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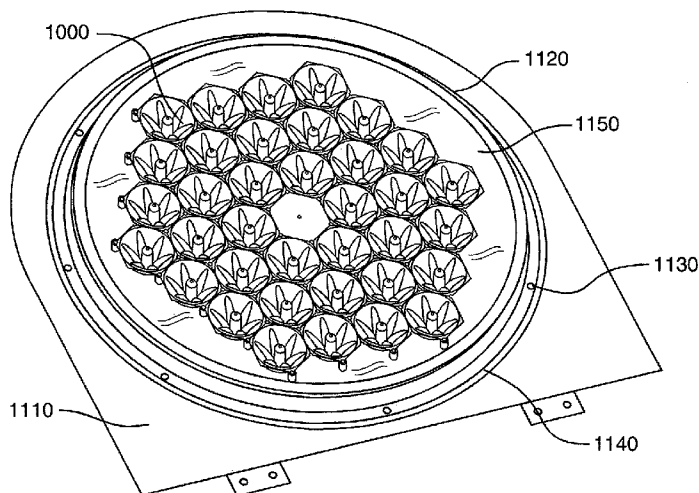


FIG. 13

(57) Abstract: A waterproof or water-resistant membrane cover (1150) for the acoustic transducer array (1000) of a sodar system. The membrane (1150) is placed over each transducer of the array (1000). The membrane (1150) may be spaced from the array (1000), held in place with a structure such as a frame (1120).

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Waterproof Membrane Cover for Acoustic Arrays in Sodar Systems

FIELD OF THE INVENTION

The present invention relates to a sonic detection and ranging (sodar) system.

BACKGROUND OF THE INVENTION

Sodar systems employ sound waves to detect atmospheric phenomena such as wind speed. A monostatic sodar operates by transmitting directional sound pulses and detecting reflected signals from a single apparatus; bistatic systems have separate transmitters and receivers. Phased-array monostatic sodars employ groups of acoustic transducers to emit and receive sound beams in different directions by electronic means. This is accomplished by varying the phase of transmitted signals from the individual transducers comprising the array and by varying the phase of the sampling process such that the transducers detect the signals reflected back from the atmosphere. The array itself remains physically motionless in operation. This approach is described in US Patent number 4,558,594, the disclosure of which is incorporated herein by reference.

The phased array approach has the benefit that the directional power density of transmitted signals, and the directional sensitivity of the array to received signals, have a primary beam width which is extremely narrow compared to what is possible with a single transducer, and which can, with appropriate electronics, be oriented in a variety of directions.

Monostatic sodar systems typically use an array of transducers arranged in a rectangular grid packing arrangement such that the transducers are aligned in rows and columns, as shown in figures 2, 4 and 5 of the 4,558,594 patent. These arrays are operated so that they emit three sequential beams, one normal to the plane of the array, and two tilted in altitude relative to the array and 90 degrees from one another in azimuth. The rectangular grid packing arrangement, with circular transducers, leaves about 27% of the array as open space, which results in non-uniformity of sound pressure across the array, leading to potential measurement errors. Also, this inherently reduces the maximum intensity of the sound pressure, which reduces the array accuracy and sensitivity. Further, the use of asymmetric sound beams results in asymmetric sensing, which causes measurement and calculation errors.

Phased arrays ideally produce controllably aimed, sharply delineated directional cones of sound when transmitting, and equivalently shaped cones of sensitivity when receiving. In reality

such arrays suffer from deficiencies. For example, the cones are not perfectly delineated by a well-defined boundary; intensity gradually drops as the angle off the main beam axis increases. Also, the cones are not perfectly shaped, but deviate from perfectly circular contours of equal sound intensity centered on the main beam axis. Further, sound transmission and reception is not entirely within the intended cones, but includes intensity outside of the intended cone of both a directionally focused and a quasi-omnidirectional nature.

The amount of sound energy radiated in undesired directions can be minimized by several techniques, including optimizing the number and physical arrangement of the individual transducers. Unfortunately it is understood that the phased array approach in and of itself cannot create a perfect directional beam. Using a practical number of transducers, the array inevitably emits sound in transmit mode, and is sensitive to sound in receive mode, in a number of directions other than the desired beam direction. For example, one or more side lobe beams are generated. Such side lobes are not as strong in transmission or sensitive in reception as the main beam, but are intense enough to degrade the performance of the sodar. These side lobes are predicted by theoretical modeling, and their existence is confirmed by experimentation.

Also, the main beam intensity does not abruptly, or even monotonically, drop to a background level as the angle of measurement deviates from the beam center axis. Instead, intensity drops to a first null, then increases somewhat from this null to a higher level, then drops to a second null, and so on. This results in the main beam being surrounded by one or more annular "rings" of sound, at angles to the main beam axis. These annular rings are also intense enough to degrade the operation performance of the sodar. Like the side lobes, these annuli are also predicted by theoretical modeling and confirmed by experimental measurement.

Further, additional signal intensity is spread out at varying small levels in all directions, likely consisting of complex combinations of the side lobes and the annular rings, as well as imperfections due to variations in transducer sensitivity, geometric accuracy of the sensor array, and variations or imperfections of other aspects of the sodar system.

Practical phased-array sodars are usually surrounded by an open-ended enclosure. Enclosures implemented in prior designs are typically fabricated from flat panel materials. Such enclosures can perform adequately as windscreens for the transducer. However, they do little, if anything, to limit the intensity of off-axis transmission and reception for the broad range of angles which are neither in the direction of the desired beam nor nearly horizontal.

The housing is sometimes lined with open-cell foam to further reduce unwanted sounds. Sound absorbing open-cell foam sheets are commonly used in recording studios, nightclubs, and other indoor applications where echo reduction is desirable. Such foams attenuate incident sound by slowing down the vibrating air within by friction. With the right combinations of density, openness, and morphology, a broad frequency spectrum of sound energy can be absorbed. The foam surface can also contribute to echo reduction by dispersing reflected sounds. Effective dispersive surfaces can range in feature size, depending on sound wavelength, from microscopic roughness to repeating shapes several inches across.

The two most common foams used for sound absorption are open cell melamine and open cell reticulated polyurethane. Both types are very susceptible to rapid degradation from weathering, especially from ultraviolet exposure, dampness, and temperature extremes. Such plastics can be made in weatherable forms, but not types that are both weatherable and useful for sound absorption. The acoustically effective foams expose large surface areas of delicate microstructure to weathering, which can lead to rapid deterioration. Protectively coating the foam surface blocks air passage, which compromises the higher frequency sound absorption desired in sodar operation.

Sound absorption material in a sodar housing benefits sodar operation in several ways. For one, it reduces the emission of stray (off-axis) acoustic energy outside of the desired sodar pulse direction. Also, it attenuates acoustic "ringing" or "reverberation" inside the enclosure following the emitted pulse. Further, it attenuates ambient and otherwise off-axis sound energy before it arrives at the transducer array in "listen" mode.

The reduction of unwanted sound, by absorption and/or blocking, benefits the operation of sodar systems by increasing signal-to-noise ratios in a process where the signals – the reflections of emitted sounds off of atmospheric turbulence and thermal gradations – are very faint. Sound emission in unwanted near-horizontal directions may be objectionable to neighbors in some locations. Reducing such unwanted emissions as a fractional ratio of the sound emitted in the desired, upward, direction has the additional benefit that stronger sound emissions in the desired direction may be possible than would otherwise be the case without effective sound absorption and blocking. This can further improve the signal-to-noise ratio of the returned signals.

The most obvious operational orientation of the array in the wind measurement application would be horizontal, as shown with array 1000 in sodar enclosure 1010, Fig. 12, as the sound beams must be transmitted in a near-vertical pattern. In this configuration the sound mirror 1020 is omitted. This orientation has, however, the serious deficiency of being subject to precipitation or windblown debris accumulating on the array and its individual transducers. Such accumulation will at best compromise system performance; at worst it may destroy the individual transducers. A practical modification of the horizontal arrangement, also used in the prior art, is to orient the array vertically or nearly vertically as shown with array 1000a, aimed at a flat, angled, surface (sound mirror) 1020 which reflects the sound beams in the desired skyward directions. This arrangement reduces the problems presented by precipitation and falling debris by making it possible to shelter the array to a considerable degree. Even with these improvements, there is a high likelihood that precipitation and debris could be blown into the array. Testing shows that raindrops will splatter off of mirror 1020, and may enter the interior cavities of the transducers. The transducers would likely exhibit reversible performance degradation as a result of such exposure, and may still exhibit long term degradation of performance or failure from this exposure. Additionally, such an array may present an attractive site for wasps, bees, or other nesting insects, which would seriously degrade system performance.

SUMMARY OF THE INVENTION

The invention benefits from an arrangement or array of acoustic transducers for a sodar system, and a system and method of operating the array to accomplish improved atmospheric detection. In one aspect, the invention contemplates grouping an array of acoustic transducers in a generally hexagonal grid packing arrangement instead of a conventional rectangular grid packing arrangement. For reasons discussed in patent application serial number 11/934,915, such a hexagonal array has advantages of its own, and it is expedient to describe the present invention in the context of a hexagonal array sodar. However, it will be readily apparent to one skilled in the art that the present housing design could be equally well adapted to other types of sodars, including conventional rectangular grid monostatic phased array sodars, in which the transducers are arranged in a rectangular grid array, and in bistatic systems. Indeed, in rectangular grid array units the benefits from the inventive shaped housing might be as great, or

greater than the benefits of a shaped housing for a hexagonal array, since such rectangular grid arrays have comparatively poorer directionality and hence more room for improvement.

In another aspect, the invention contemplates operating the transducers as a phased array operated sequentially in three orientations of rows that are 120° apart, instead of two orientations of rows that are 90° apart. This operation accomplishes three sequential sound beams with their principal axes spaced apart from one another 120° in azimuth. Preferably, the beams are each at the same elevation. The result is that the principal axes of the three beams are evenly spaced around the surface of a virtual vertically oriented cone with its apex proximate the center of the array.

Preferably, transducers with symmetric (circular) actuators and horns are employed in the housing of the invention, so that there is no inherent directionality with each transducer. One advantage is that the generally hexagonal grid packing arrangement of the array creates an array in which the area encompassed by each transducer approximates the circular shape of the transducer actuators, the transducer horns, and the acoustical dispersion patterns associated with them. This transducer packing arrangement inherently reduces the undesirable acoustic characteristics of the spaces between the horns, which improves the uniformity of sound pressures across the front of the array. Improved uniformity reduces emanations of sound beyond the perimeter of the directed beams, and symmetrically also reduces the sensitivity of the array in receive mode to off-beam sounds.

Another advantage is that the generally hexagonal transducer grid packing arrangement allows more transducers to be employed in a given area than is allowed by rectangular grid packing arrangement of the transducers, in which the transducers are aligned in rows and columns. The transducer packing density of the hexagonal array also improves the uniformity and intensity of sound pressure across the front of the array.

Another advantage is that the operation of the array that is physically symmetric along each of the azimuthal directions along which beams are propagated, with three beams orientated 120° apart, makes sodar operations based on three sequential sound beams physically symmetric. This allows the sodar enclosure to be shaped symmetrically, which in turn produces sound beams, both transmitted and received, that are shaped symmetrically. Thus, distortions created by interactions with the enclosure are inherently applied to all three orientations. This reduces measurement and calculation errors from asymmetric operation.

Yet another advantage is that the operation of the array, with three beams orientated 120° apart, allows for a maximum angle between the centers of the various beams, for any particular maximum angle between the center of any one beam and the zenith. Since increasing the angle between the various beams increases accuracy, while increasing the angle between each beam and the zenith detracts from accuracy and reliability of data capture due to atmospheric effects, this configuration has improved accuracy and data capture relative to the prior art.

Further details of transducer arrays that can be used with this invention are described in application serial number 11/934,915, filed on November 5, 2007, the disclosure of which is incorporated herein by reference.

The invention includes an open-ended structure shaped to envelop at least portions of the multiple desired beams and corresponding cones of sensitivity of the sodar. The shape is preferably formed to surround at least portions of these desired beams as closely as possible without actually impinging upon them. In the preferred embodiment the upper lip of the enclosure is rounded with a relatively large radius. The invention provides greatly improved performance over prior art flat-sided enclosures with rectangular openings; both act as windscreens to prevent wind from blowing directly on the transducer array, which would create undesirable noise that can drown out the relatively faint returned signals. However, the inventive housing does so in a way that generates less similarly undesirable noise from the wind blowing over the opening of the housing. Also, the inventive housing has benefits which the flat sided enclosures lack or which the flat sided enclosures have to a much lesser degree than the inventive housing. Also, by lining the enclosure with a sound absorbing material, sound damping is provided. This limits reverberation of the beam and reflection of the beam in undesirable directions. The enclosure also blocks sounds from near-horizontal sources when in receive mode. Such sounds may include road noise, and noises from insects and animals. These unwanted noises can seriously interfere with detecting the returned signals. Enclosures also block near-horizontal sound emanations from the arrays when in transmit mode. Such sound emanations can be objectionable. Also, if combined with a reflecting surface for the sound beams, the array can be mounted vertically, or nearly so. This provides protection to the transducer array from incident precipitation. In addition, the inventive enclosure also provides further benefits, including substantially blocking non-horizontal off-axis emanations from the

array in transmit mode, and substantially blocking reception of non-horizontal off-axis sounds from the array in receive mode.

The inventive enclosure has at least the following advantages. For one, it reduces the tendency of the phased array to emanate sound in, and be sensitive to sound from, the broad range of directions between horizontal and the intended zones of measurement, which may be close to vertical. This in turn reduces the likelihood of various common sources of measurement errors, including reception of echoes from sound transmitted to, and echoed back from, nearby trees, buildings, towers, and other structures or terrain features. The reception of noise from external sources including building ventilation systems, wildlife such as crickets and frogs, and road traffic, is also reduced. Sounds from such sources are often close to the frequency spectrum typically used by sodar (around 4000 Hz) and present highly objectionable interference to the detection of faint return signals. To a great extent such noise sources are concentrated at lower elevations outside the desired main beam, but even were they uniformly distributed in direction, substantially blocking sounds in all directions except that of the desired beam will attenuate the overall intensity of such interference. This also reduces reception of unwanted noises produced at various distances that “skip” or refract off the atmosphere, and arrive at incident angles between horizontal and vertical. It also increases the probability that the atmospheric phenomena that the reflections come from are within the intended conic volume. For some applications of sodar, most particularly for the measurement of horizontal wind velocity, accuracy critically depends on receiving echoes from the intended volume of air. It is even more critical to know with some accuracy which volume of air an echo returned from, even if that volume is not exactly, but is only approximately, the intended volume. It also decreases the likelihood, for any particular sound intensity of the main transmitted beam, of sodar emissions being an audible nuisance via reflections and scattering from lower-than-intended angles. Because of this, it is possible to transmit a more intense signal than would otherwise be possible, allowing the system to operate in conditions where the returned signal might otherwise be too weak to detect.

It is possible by adjusting the phased array parameters to set the angle of emission of the side lobe low enough that a suitable enclosure can intercept it without interfering with the main beam. Since the enclosure is lined with adequately sound-absorbing material, and the angle of

the side lobe is low, the side lobe is further attenuated by repetitive reflection off the sound absorbent enclosure walls.

The present invention contemplates using a relatively thick layer of nonwoven plastic fiber fabric (sometimes termed "felt" herein) as a sound-absorbing lining for sodar housings. The layer may comprise one or more plies of such fabric. The thickness of the felt is preferably at least about as large as one-half of the wavelength of the sound emitted by the array; this thickness ensures that any sound that reflects off of the underlying enclosure walls must travel through a thickness at least about equal to the wavelength, which increases sound damping. The use of felt to damp sound accomplishes at least the following advantages. The felt resists physical deterioration caused by exposure to ultraviolet radiation and other weathering, especially in comparison with foams. Also, the felt drains water quickly, allowing it to function during and immediately after directly incident rain. The drained damp felt also performs acoustically comparably to when it is completely dry. Further, in addition to absorbing sound that might otherwise be reflected from housing surfaces, the felt absorbs sound which might otherwise be transmitted through the walls of the enclosure. Absorption of sound which would otherwise be transmitted through the walls is most effective when the felt is continuously adhesively bonded to the interior enclosure surfaces. The felt, if of synthetic fiber, is not prone to rot, which might otherwise shorten the lifetime of a natural fiber sound absorbing material when exposed in a damp or wet environment.

This invention features a noise-reducing housing for a sodar system with a transducer array that sequentially emits and receives multiple generally conical main beams of sound along different primary axes, the housing comprising an enclosure that defines an interior volume that is essentially open to the atmosphere at the top, to emit and receive the beams, and a non-woven fiber, sound-absorbing material lining at least some of the enclosure surfaces that face the interior volume. The fiber may be synthetic. The sound-absorbing material may be made of polyester-based fibers. The fibers are preferably of a plurality of different diameters. The housing may further comprise an adhesive that bonds the sound-absorbing material to the enclosure surfaces. The adhesive may be a continuous film applied to the sound-absorbing material. The portions of the enclosure that are contacted by a beam may be essentially entirely covered with the sound-absorbing material.

The enclosure may comprise one or more upwardly-directed sidewalls. The enclosure may further comprise a lip at the top of at least a portion of at least one sidewall. The top of the lip may be rounded about its longitudinal axis, to inhibit sound from being refracted as it leaves the housing. The rounding of the top of the lip may be essentially partially circular. The sound emitted by the array may have a defined wavelength in air, and the radius of curvature of the lip rounding may be at least about as large as the wavelength of the emitted sound.

At least some of the inside surfaces of the enclosure may be shaped to closely conform to at least portions of each of the beams. Inside surfaces of the enclosure may be generally partially elliptical in cross section, to closely conform to a conical beam contour. The inside surfaces of the enclosure that are generally partially elliptical in cross section may be angled from the vertical, to define an inside surface that itself defines a portion of the surface of a cone that is slightly angled from the vertical. The angle may be about ten degrees, or more specifically, essentially 11.2 degrees. The lip may comprise a plurality of partially elliptical lip segments, each segment generally lying along a said angled conical surface. Each of the lip segments may be unitary with at least a portion of the inside surface of the enclosure. The housing may further comprise a generally partially conical passage section located between the array and the enclosure. The housing may further comprise a drainage opening to allow detritus and precipitation to exit the enclosure. The transducers comprising the array may be mounted in a generally vertical plane, and the main beams reflected to and from the atmosphere by an angled sound-reflecting surface located within the housing.

The array may comprise a plurality of individual sound transducers, for emitting sound into the atmosphere and for sensing emitted sound that has been reflected by the atmosphere, in which the transducers are arranged in a generally planar, generally hexagonal grid packing arrangement. The array may comprise a series of rows of tightly-packed essentially identical transducers, with the transducers in adjacent rows offset from one another, in a direction orthogonal to the row longitudinal axes, by about half (more specifically $\sqrt{3}/2$), essentially the width of a transducer. The transducers may define a generally hexagonal perimeter shape.

The transducers making up a row may be operated in unison at essentially the same frequency, with the operation of each sequential row uniformly phase-shifted relative to the immediately preceding row, to create beams that are tilted in altitude relative to the plane of the transducers. The row-to-row phase shift is about sixty degrees. The beam angular width may be

about five degrees from the beam main axis to the beam half power point. There may be three beams that are sequentially created, each such beam defining a main beam axis, wherein the three beam main axes are at essentially the same altitude of about 10 degrees from the normal to the plane of the transducers. The three beams may be oriented at about 120° angles to each other in azimuth.

The invention also features a noise-reducing housing for a phased array monostatic sodar system with a transducer array that emits and receives at least three generally conical main beams of sound along different primary axes spaced from one another about 120 degrees in azimuth, the housing comprising at least three upwardly-directed sidewalls that define a volume between them that is essentially open to the atmosphere at the top, to emit and receive the beams, the sidewalls each defining an inside surface that itself defines a portion of the surface of a cone that is essentially vertical or slightly angled from the vertical, a non-woven fiber sound-absorbing material lining at least some of the inside surfaces of the sidewalls, and a lip comprising at least three semi-elliptical upper lip segments, one segment at the top of each sidewall, such that the lip defines a multi-lobed curved perimeter at the top of the volume that closely conforms to the conical shape of each of at least three main beams at the location of the lip.

This invention features a membrane cover (a thin, flexible cover that at least partially acts as a barrier to water, snow, ice, dust and insects) for the transducer array, the membrane being generally transparent to sound (at least at the frequency of interest) such that it passes sound without an unacceptable level of diminution or other detrimental effect, while either fully or partially protecting the transducers from precipitation and the like. A single membrane can cover the entire array, or smaller membranes may cover individual transducers, or groups of transducers. In one embodiment, the invention features a device for protecting the transducer array of a sodar system, comprising a membrane placed spaced from the array, and structure that holds the membrane in place relative to the array. The membrane is preferably placed close to the array. The membrane may be held a distance of about one quarter to one half of the sodar wavelength from the array. The membrane may be a film. The film may be made from polyethylene. The film may be heated after installation with a source of hot air so as to cause the film to shrink and become taut, reducing wrinkles which might adversely affect performance. The film may be less than about 0.004 inches thick. The structure that holds the membrane may

comprise a frame. The structure may further comprise two-sided adhesive tape that holds the membrane to the frame, and an overwrap of cloth adhesive tape which protects and trims the edge of the membrane and strengthens the attachment of the membrane to the frame.

Also featured is a device for protecting the transducer array of a sodar system, comprising a membrane held a distance of about one quarter to one half of the sodar wavelength from the array, and a frame that holds the membrane in place relative to the array.

Further featured is a phased array monostatic sodar system, comprising a transducer array that sequentially emits and receives multiple generally conical main beams of sound along different primary axes, an enclosure that defines an interior volume that is essentially open to the atmosphere at the top in which the array is located, to emit and receive the beams, wherein at least the opening shape closely conforms to the conical shape of at least a portion of each of the main beams, a membrane placed proximate the array, and structure that holds the membrane in place relative to the array. The structure may comprise a frame. The membrane may be held a distance of about one quarter to one half of the sodar wavelength from the array. The membrane may be made from polyethylene film.

The system may further comprise a non-woven fiber, sound-absorbing material lining at least some of the enclosure surfaces that face the interior volume. The fiber may be synthetic. The sound-absorbing material may be made of polyester-based fibers of a plurality of different diameters. The system may further comprise an adhesive that bonds the sound-absorbing material to the enclosure surfaces. The portions of the enclosure that are contacted by a beam are preferably essentially entirely covered with the sound-absorbing material. The sound emitted by the array has a defined wavelength in air, and the sound-absorbing material may have a thickness of at least about one-half of that wavelength. The main sound beams define first nulls, and the sound-absorbing material may essentially fully cover the inside surfaces of the enclosure that are exposed to a sound beam, and the inside surfaces of the sound-absorbing material may lie approximately at the first null of a main sound beam.

At least some of the inside surfaces of the enclosure may be generally partially elliptical in cross section, to closely conform to a conical beam contour. The inside surfaces of the enclosure that are generally partially elliptical in cross section may be angled from the vertical, to define an inside surface that itself defines a portion of the surface of a cone that is slightly angled from the vertical. The enclosure may further comprise a lip comprising a plurality of

partially elliptical lip segments, each segment generally lying along a said angled conical surface.

The transducers comprising the array are preferably mounted in a generally vertical plane and the main beams are reflected to and from the atmosphere by an angled sound-reflecting surface located within the enclosure. The array may comprise a plurality of individual sound transducers, for emitting sound into the atmosphere and for sensing emitted sound that has been reflected by the atmosphere, in which the transducers are arranged in a generally planar, generally hexagonal grid packing arrangement. The array may comprise a series of rows of tightly packed essentially identical transducers, with the transducers in adjacent rows offset from one another, in a direction orthogonal to the row longitudinal axes, by about $\sqrt{3}/2$ the width of a transducer. There may be three beams that are sequentially created, each such beam defining a main beam axis, wherein the three beam main axes are at essentially the same altitude of about 10 degrees from the normal to the plane of the transducers. The three beams are preferably oriented at about 120° angles to each other in azimuth.

In another embodiment the invention features a phased array monostatic sodar system, comprising a transducer array that sequentially emits and receives at least three generally conical main beams of sound along different primary axes spaced from one another about 120 degrees in azimuth, each beam defining a first null spaced from its main axis, in which the transducers comprising the array are mounted in a generally vertical plane, an angled sound-reflecting surface that reflects the main beams to and from the atmosphere, a membrane placed proximate the array, structure that holds the membrane in place relative to the array, a housing comprising three upwardly-directed sidewalls that define a volume between them that is essentially open to the atmosphere at the top, to emit and receive the beams, the sidewalls each defining an inside surface that itself defines a portion of the surface of a cone that is essentially vertical or slightly angled from the vertical, a lip comprising three partially-elliptical upper lip segments, one segment at the top of each sidewall, such that the lip defines a three-lobed curved perimeter at the top of the volume that closely conforms to the conical shape of a portion of each the three main beams at the location of the lips, rounded fillet areas at the intersections of the sidewalls, a generally horizontal partially conical passage section located between the array and the sidewalls, and non-woven fiber sound-absorbing material essentially fully covering the inside

surfaces of the sidewalls and the passage section, wherein the inside surfaces of the sound-absorbing material lie approximately at the first null of each of the main sound beams.

The use of a membrane cover for the transducer array accomplishes several advantages. For one, the membrane cover prevents or at least inhibits blown water, splattered water, mist, and snow from reaching the transducers. This will for each transducer keep or inhibit moisture from entering the "phase plugs," the slots that allow sound pressure to pass from the cavity in front of the vibrating speaker cone to the speaker's radiating horn. In an implementation of piezo-electric based "tweeter" actuators, the cone material is of formed paper, which is fairly hygroscopic. Long exposure to moisture will soften the paper, and weaken the adhesive bond to the piezo element which excites the cone's vibration. Both effects can lead to degradation in performance or destruction of the transducers. In the preferred implementation the cone material is of formed polycarbonate plastic sheet. Even in this preferred implementation, moisture entering through the phase plugs can significantly degrade the performance of the speaker by damping the motion of the cone, by blocking the passage which forms the path for the sound to travel from the cone to the horn through the phase plugs. Moisture trapped within the transducer may freeze, causing permanent damage to the transducer. With or without such freezing, moisture trapped within the transducer may also leak into the electronics enclosure, adversely affecting the sensitive circuits.

Another advantage is that the membrane cover prevents or at least inhibits the collection of dust on or inside the transducer elements. The dust may not be destructive in small quantities, but gradual accretion of significant quantities, in the small air space between the vibrating cone and the transducer body containing the phase plugs, will permanently degrade the transducers' performance. Also, the membrane cover seems to smooth and unify the shape of the emitted beams, which improves the performance of the sodar by reducing stray emissions that can reflect off of objects or air movement in unintended directions. In the preferred embodiment of the invention, this improvement is modest, due to several other innovations that also reduce stray emissions: hexagonal element packing, sound absorbing materials, and an optimally shaped enclosure. In other sodar systems without such features, the performance enhancement could be more significant.

Yet another advantage is that the membrane cover prevents or at least inhibits moisture and dust from penetrating the array face, and entering the space behind it, which may contain

electronics and electromechanical components that could be compromised by the contamination. Further, it protects against insects nesting in or on the array.

BRIEF DESCRIPTION OF THE DRAWINGS

Various other objects, features and advantages of the present invention will become fully appreciated as the invention becomes better understood when considered in conjunction with the accompanying drawings, in which like reference characters designate the same or similar parts throughout the several views, and wherein:

Figure 1 is a perspective view of a thirty six-transducer element array for use with an embodiment of the invention;

Figures 2A, 2B and 2C schematically depict three beams created by operation of the array of Fig. 1 in accordance with an embodiment of the invention. In these figures the beam is depicted at a much smaller scale than the array itself, for the sake of clarity;

Figs. 3A-3C schematically depict simplified versions of the three beams emanating from a horizontal phased array without the enclosure of the invention, each beam surrounded by its two closest annular "wake" rings, and each beam with its principal side lobe;

Figures 4A, 4B and 4C show the array element rows that are sequentially operated in order to produce the beams of Figs. 2A, 2B and 2C, respectively;

Figure 5 is a schematic block diagram of a system for operating a transducer array in accordance with the invention;

Figures 6A and 6B are different perspective views, and Figure 6C is a top view, of the preferred embodiment of the sodar enclosure of the invention;

Figure 6D is a cross-sectional view of the enclosure shown in Figs. 6A-6C, detailing the sound beam path;

Figure 6E is a view similar to that of Fig. 6C schematically depicting the three sound beams;

Figs. 7A-7C depicts three equivalent beams to those of Figures 3A-3C, respectively, emanating from a phased array with the preferred embodiment of the enclosure of the invention, showing that the side lobes of each beam and the majority of the annular rings have been eliminated by the enclosure, leaving only artifacts of the annular rings;

Fig. 8 is a composite of plotted normalized magnitudes of computer-modeled emissions from a prior art rectangular grid transducer packing arrangement 32-element phased array,

wherein the emitter elements are modeled as point sources and all elements are in phase with each other, such as to produce a main beam perpendicular to the plane of the array;

Figs. 9A-9D are graphical "mosaic" summaries of sound intensity measurements taken over an approximately hemispherical matrix of positions over a prototype of the preferred embodiment of a thirty-six element hexagonal grid packing arrangement array which was programmed to emit the beams shown in Figs 3A-3C. Figs. 9A and 9B show the measured sound pressures over the array placed horizontally, operating with no enclosure. Figures 9C and 9D show the same measurements made over the same array installed in the preferred embodiment of the inventive enclosure as shown in Figs. 6A-6E;

Figure 10 is a top view of an alternative placement of the transducer array in an enclosure of the same general design as that shown in Figs. 6A-6E;

Figure 11 is a graph showing signal attenuation versus number of one-half inch plies, from testing of the sound-absorbing material used in the preferred embodiment of the invention;

Figure 12 is a schematic cross sectional diagram of a generic sodar system, used to illustrate the horizontal and vertical array orientations that are typically used in sodar systems;

Figure 13 shows the preferred embodiment of the inventive membrane cover in place over a transducer array;

Figure 14 shows the membrane cover of Fig. 13;

Figures 15A and 15B are plots of the response relative to frequency of two transducers used in the preferred embodiment of the array of the invention, showing the effects of the dropwise addition of water; and

Figures 16A and 16B are similar plots of the same tests run on the same speakers after overnight drying.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Monostatic sodars employ sequential, directed beams of sound as part of their operation. Individual acoustic transducers typically emanate sound in a wide wavefront approximating the surface of a sphere, rendering them unsuitable for sodar use without a focusing mechanism. Array 10 of closely packed and evenly spaced transducers, Fig. 1, can accomplish focusing by producing a complex interfering pattern of wavefronts that effectively creates a principal beam that is narrower than that of an individual transducer. The angular spread of the beam is related to the number of transducers in the array: more transducers generally can create a narrower

beam. Arrays of thirty-two to sixty transducers are usually adequate to produce beams that are narrow enough for sodar applications; array 10 has thirty-six transducers 12. Each transducer 12 has a circular actuator and horn. Transducers 12 are closely packed along a number of parallel rows (seven such rows in the non-limiting preferred embodiment of the invention shown in Fig. 1), with the transducers in adjacent rows offset from one another in a direction orthogonal to the rows by about one half (more specifically $\sqrt{3}/2$) of a transducer diameter. This arrangement is termed herein a generally hexagonal grid packing arrangement.

Each transducer is preferably of hexagonal overall perimeter shape, closely circumscribing a circular active horn region of about 3 inches in diameter. The transducer is based on a standard piezo-electric horn "tweeter" element modified in external shape to facilitate the generally hexagonal grid packing arrangement. The paper cone of the transducer can be replaced with a plastic cone (preferably polycarbonate or Mylar (which is a biaxially-oriented polyethylene terephthalate film) or equivalent, to improve the weather-resistance of the apparatus. Transducers 12 are provided with connectors for convenient installation and replacement in the apparatus. The transducer is designed to operate efficiently as both a transmitter and receiver of sound at the approximately 4000 Hz (more specifically 4425 Hz) operating frequency preferred for the apparatus. The size of the transducers is such that the phased array technique can create beams of sound with good directionality using a reasonable number of transducers. Other shapes and types of transducer elements are not as efficiently assembled into hexagonal arrays, do not operate efficiently as both transmitter and receiver at the desired operating frequency, and are not as suitable for installation in an apparatus operating in an exposed environment.

The generally hexagonal external shape of the array, and the generally hexagonal grid packing arrangement of the array, also permits the directional control necessary to steer beams without mechanical devices. Beam steering is accomplished by driving the transducers in a sequence of parallel rows, with the transducers within each row driven in phase with each other, and each of the rows driven at the same wavelength but with successive, equal phase shifts row-to-row. If there is no phase shift between rows, the principal beam is emitted along an axis that is orthogonal to the plane of the array. As phase shift is introduced, the interference pattern changes such that the beam is directed at altitudes that are no longer vertical (assuming the array is horizontal). Also, the beam is orthogonal to the axes along which the transducers making up

each of the rows lie. Thus, by driving the transducers in rows of differing relative orientation, beams can be created that are directed along desired azimuthal directions.

Array 10 is comprised of a series of rows of closely-packed transducers. Each transducer has a generally hexagonal perimeter shape. This perimeter closely circumscribes the active transducer region, which is circular. The hexagonal perimeter primarily exists to facilitate assembling the array. There may be some additional advantage if the active transducer region itself were hexagonal, effectively eliminating all dead (i.e., non sound producing) area in the array. Similarly, a square transducer with a square active horn area, along with the transducers in adjacent rows offset by about one-half of the transducer width in accordance with the invention, could provide some (but not all) of the benefits of this invention as compared to the prior-art rectangularly arranged arrays. The array itself preferably has a generally hexagonal perimeter as shown in Fig. 1.

The generally hexagonal grid packing arrangement makes each active element of the array occupy a hexagonal area that is only about 10% greater than the actual area occupied by the circular shape of each transducer horn. Thus, only about 10% of the array area is not involved in sound production or sensing. This is contrasted with a prior art rectangular grid array element arrangement, in which each circular transducer occupies a square area that is about 27% greater than the actual area occupied by the circular transducer horn. The generally hexagonal grid packing arrangement of the array minimizes the area of the entire array that does not contribute to the desired interference pattern, nor to the uniformity of the sound pressure across the array. The air motion in the regions between the circular transducers can also create interference patterns that create sound emanations in other directions than the intended beams. The undesired emanations reduce the ability of the sodar system to resolve the directions of the beams, thus reducing its measurement performance. The undesired emanations can also radiate horizontally enough to strike trees and other adjacent objects, creating echoes of similar or greater magnitude than the reflections off the atmospheric phenomena from the intended beams.

The generally hexagonal array of the invention is physically symmetric about six radial axes spaced sixty degrees apart. This can be accomplished with two or more transducers in each of the six outer rows making up the six sides of the hexagon; thus the minimum number of transducers is seven. Also, the transducers are closely packed in the array, with adjacent parallel rows of the array having their axes offset by $\sqrt{3}/2$ (approximately 0.866) times the transducer

width. The generally hexagonal grid packing arrangement allows operation to sequentially produce from three to six generally conical beams that emanate along principal beam axes that are generally symmetrical around and lie on the surface of a virtual vertical cone having its apex located on an axis that is normal to the center of the array. The preferred embodiment creates three such beams spaced 120° apart. The beams are at a favorable altitude that is determined by the manner of operation. Such beams are schematically depicted in Figs. 2A-2C. This depiction is highly schematic, as the bottom of the beam is more like a circle roughly the size of the array. The effective length of the beam is about 400 times the diameter of the array. The operation of the array to produce such beams is schematically illustrated in Figs. 4A-4C. A schematic block diagram of a system for accomplishing this operation is shown in Figure 5.

For example, in order to produce beam 1 that is schematically shown in Fig. 2A, transducers 16, 22, 28 and 33 making up row 1 (see Fig. 4A) are driven with a particular waveform; transducers 10, 17, 23, 29 and 34 making up row 2 are driven by the same waveform with a phase shift of n ; row 3 with a phase shift of $2n$ from row 1; row 4 shifted by $3n$ from row 1; row 5 by $4n$; row 6 by $5n$; and row 7 by $6n$. Beam 2 is produced as shown in Fig. 4B by shifting the first row 120° in a clockwise fashion, such that the first row includes transducers 1, 2, 3 and 4, with rows 2-7 indicated in the drawing, and operating the array in the same fashion. Beam 3 is likewise produced as shown in Fig. 4C by again shifting the first row 120° in a clockwise fashion, such that the first row includes transducers 21, 27, 32 and 36 with rows 2-7 also indicated in the drawing and again operating the rows in the same fashion.

System 150, Fig. 5, accomplishes this operation with signal generator 152 that supplies signals to phase control and switching control 154, which supplies the appropriate transducer drive signals to array 156 of transducers 1-N. The echo signals received by transducer array 156 are routed to receiver 158 and processor 160, which outputs atmospheric information that can be derived from a sodar system. The derivation of atmospheric information from sodar signals is known in the art, for example as set forth in US Patent 4,558,594.

System 150 can be accomplished as all hardware, or a combination of hardware and firmware, as would be apparent to one skilled in the art. Preferably, system 150 is accomplished with hardware, except that all of signal generator 152, portions of phase and switching control 154, and all of processing 160 are implemented as firmware within microprocessors and a DSP chip.

As the transducer arrangement of array 10 is symmetric with respect to each of the six sides of the hexagonal array, the three beams are essentially identical to one another, the only difference being the azimuthal direction of the beams' main axes. Up to six such beams could be created.

Horn-shaped enclosure 100, Figs. 6A-6E, is similarly symmetrically shaped, defining three identically-shaped lobes 102, 104 and 106 spaced 120° apart about central vertical axis 105 of enclosure 100. In enclosure 100, array 10 is preferably positioned vertically, behind access door 122 and directly facing flat sound-reflecting surface 110 that is 45° from vertical so that it acts as a sound mirror. See the cross-sectional view of Fig. 6D. This arrangement acoustically approximates the same array 10 being positioned horizontally at the center bottom of the enclosure, as shown in the top view of an alternative embodiment, Fig. 10. The vertical array position shown in Fig. 6D inhibits the transducers from collecting water, ice, snow, or debris.

In one non-limiting embodiment, each transducer is about three inches in diameter, and the array is operated at frequencies corresponding to wavelengths of approximately 3 inches. A typical frequency may be 4425 Hz. Sounds near this wavelength have been found to both reflect from and travel through turbulence and thermal gradations in the atmosphere, a compromise that is essential to sodar operation. With the preferred array made up of thirty six transducers in seven rows, the phase shift from row to row is about 60 degrees, (or, about 3.75×10^{-5} sec) which accomplishes an essentially vertical beam tilted at about ten degrees (more specifically at 11.2 degrees) in altitude from the normal to the plane of the transducers, and with a main beam angular width of about five degrees measured from the main beam axis to the half power point. The beam power drops to about zero at a null that is located at about ten degrees from the beam main axis (a total beam width of about twenty degrees). Preferably, each of the three lobes of housing 100 defines an inner surface that lies at about the location of this null. As the enclosure is lined with sound-absorbing material, this inner surface is defined as the inner surface of the sound-absorbing material. This allows the full main beam to be utilized in atmospheric sensing while helping to intercept and thus squelch both unwanted emanations that are not part of the main beam, and unwanted return signals that are not reflections of the main beam. Alternatively, the inner surface of the enclosure can lie closer to the main axes of the beams, which will create narrower, less powerful beams.

The preferred embodiment of the array as shown in Fig. 1 has thirty-six transducers; there

is no transducer at the center of the array, although there could be. This is primarily due to the electronics in the preferred embodiment, which were designed around integrated circuits that are generally used for surround sound applications. These circuits each have 3 left and 3 right channels-- for a total of six each. So each sixty-degree segment of the array can be neatly handled by one of these circuits, for a total of six geometrically and electronically identical subdivisions of the transmitting circuit. Adding the 37th transducer to the center of the array thus adds substantial complexity to the transmitting circuit design, as well as to the firmware. Testing indicated that the center speaker doesn't have a substantial impact on the directionality of the unit-- at best it might increase directionality by 3%, while it increases cost and complexity of the electronic equipment by perhaps as much as 17%. Accordingly, leaving the center speaker out is an appropriate trade-off between cost and functionality.

The preferred embodiment of the enclosure of the invention is comprised of a structure 100, Figs. 6A-6E, shaped to partially envelop with some accuracy the multiple desired beams and corresponding cones of sensitivity of the sodar. Interior sidewalls 128, 129 and 130 are partially conical, each circumscribing approximately half of a main beam, and located at the first null, as described below. These walls are preferably lined with a sound absorbing material. For example, as shown in Fig 6D, the interior of sidewalls 128 and 129 shown in the drawing are lined with one or more layers of sound absorbing material 181. The generally conical wall 133 that is very close to array 10 is also lined with material 181.

The preferred lining is a single layer of 1½" thick white felt, which is a non-woven material made from polyester fibers of varying diameters and provided by National Non-Woven Fiber Inc. of Easthampton, Massachusetts, or an equivalent such as more than one layer of this material, a different total thickness of this material, or a different non-woven material such as a natural-fiber felt. The preferred felt-like material can be made of various types of synthetic fibers, such as polyester, polyethylene, polypropylene, or nylon. The fibers are of various deniers, typically ranging between 0.8 and 100 denier. The material is a carded web that is cross-laid and needle punched. The material can be stiffened as desired by heat setting or additive treatment. The thickness is about 1.6". The weight is about 72 ounces per square yard. The material comprises about 80% void volume. The differing fiber sizes and large amount of void space provide excellent sound damping in the frequency range of interest of around 4000 Hz. The material is preferably adhered to essentially all of the inside faces of the housing that

are exposed to a sound beam using an appropriate pressure-sensitive adhesive film that is applied to one face of the felt material. Test results of this preferred lining material are set forth below. Enclosure 100 is designed such that the surface of the absorbing felt material is coincident with the predicted and experimentally verified first major "null" position of the beam/cone. See Fig. 8 and its description, below. The thickness of the felt is preferably at least about as large as one-half of the wavelength of the sound emitted by the array; this thickness ensures that any sound that reflects off of the underlying enclosure walls must travel through a thickness at least about equal to the wavelength, which increases sound damping. The use of felt to damp sound accomplishes at least the following advantages.

Upper lip 108 of housing 100 is preferably rounded with a large radius, preferably equal to or larger than the wavelength of the transmitted sound. Three identical semi-elliptical upper lip segments tie the structure together by being bolted to threaded inserts in the enclosure body 116 at six positions 112, and to pairs of threaded inserts at three positions 114. The lip sections essentially lie along the intersection of a horizontal plane and each of the three angled cones that are defined by the first nulls of the three sound beams. Enclosure lifting and/or anchoring eyebolts can be threaded into inserts at locations 114. Alternatively, a satellite or cellular antenna 142 can be mounted at one location 114.

Since the beams of a single-array sodar emanate from the surface of a single phased array 10, but in different directions, their conic profiles overlap spatially near the array. This means that the enveloping structure has an unusual "fluted" shape as shown in the drawings. If the shape were extended vertically, it would become a three-horned enclosure joined at the base. Since the height of such a structure would be impractical, the fluted shape is best for the desired portability of the sodar system. The enclosure wall making up each of the three flutes generally defines a semi-circle in cross section; since the cones are tilted from the vertical, the horizontal cross section is elliptical. The cones all emanate from array 10, taking into account 45° reflector 110. In the preferred embodiment, the structure has an overall height, from bottom of the mounting base 146 to the tops of the lips of approximately 74 inches. The width measured to outside of lip 108 at the widest point between any two flutes is approximately 70 inches.

Figure 6E shows the top of the structure. Overlapping areas 125, 126 and 127 show the approximate cross sections of the beams where they exit the opening in the top of the structure. Areas 125, 126 and 127 indicate the cross sections for beams 1, 2 and 3 respectively. As is

apparent from the illustrations, these sections substantially overlap in the central area of the structure, but each beam has a non-overlapping area which forms the fluted shape of the structure. The central cavity of the structure is substantially the union of three overlapping conic sections, 128, 129 and 130 shown in figure 6C for beams 1, 2, and 3 respectively to allow the three conical beams to pass unimpeded from the structure. Radiused surfaces or fillets 131 are provided so as to allow conic sections 128, 129, and 130 to join without a sharp corner. Such a sharp corner would be undesirable due to manufacturing and structural considerations, and might introduce undesirable diffraction of off-axis sound which would otherwise be properly intercepted by the structure. In Figure 6E areas 132 which result from these radii constitute the areas of the opening of the structure which are not needed by any of the three beams. Since these areas 132 are quite small, the harm caused by their presence is small compared to the benefits of the radii 131 discussed above.

The enclosure's effectiveness is limited by the openings created by the intersections of the cones that form its shape. In the case of any particular beam, the housing fails to intercept the off-axis signals for that beam that happen to fall within the main directions of the two other beams (for example the portions of areas 126 and 127 which do not overlap area 125 fail to intercept some of the off axis sounds of beam 1, and similarly for beams 2 and 3). Such off-axis signals are predominately remnants of the generally annular rings surrounding the main beam. The first two of these rings are shown in Figs. 3A-3C. The ring fragments remaining after the enclosure wall intercepts a portion (about half) of each ring are shown in Figs. 7A-7C.

Two O'clock beam 20, Fig. 3A comprises main beam 21, and undesirable portions comprising side lobe 24, and first and second annular rings 22 and 23, respectively. When enclosure 100 is used, beam 20 is partially circumscribed such that side lobe 24 is squelched, as are the outer portions (about half) of annular rings 22 and 23, leaving ring fragments 22a and 23a, Fig. 7A. Ten O'clock beam 30, Fig. 3B comprises main beam 31, and undesirable portions comprising side lobe 34, and first and second annular rings 32 and 33, respectively. When enclosure 100 is used, beam 30 is circumscribed such that side lobe 34 is squelched, as are the outer portions (about half) of annular rings 32 and 33, leaving ring fragments 32a and 33a, Fig. 7B. Six O'clock beam 40, Fig. 3C comprises main beam 41, and undesirable portions comprising side lobe 44, and first and second annular rings 42 and 43, respectively. When enclosure 100 is used, beam 40 is circumscribed such that side lobe 44 is squelched, as are the

outer portions (about half) of annular rings 42 and 43, leaving ring fragments 42a and 43a, Fig. 7C.

The remaining ring fragments are of a relatively well-defined intensity and direction, and come from a near vertical direction where any response is almost certainly from clear air, which will return a comparatively weak signal, and not from trees, buildings or other potentially interfering structures which would return a strong, and potentially disruptive, signal. Also, they are fairly close to the desired main beam and essentially symmetrical between the various beams. Because of these factors, it is possible to estimate the contribution of the annular ring fragments to the overall main beam and mathematically correct for any error in estimation of wind speed or other atmospheric properties which these they might otherwise introduce. The annular ring fragments for each beam combine with that main central beam in a way that simply biases the effective beam to be slightly more vertical that would be expected from the main central beam alone. Such a bias can be accounted for in the calculation of the horizontal wind speed.

In the preferred embodiment, the housing is assembled from a small number of thermoplastic (polyethylene) parts custom molded (e.g. by rotational molding) to shape for the application. However, since large portions of the housing consist of partially conic sections, in an alternative embodiment the majority of the housing could also be fabricated by forming flat stock such as suitably damped sheet metal, sheet plastic, composite material sheet or plywood into developable conic sections. Further alternative embodiments are possible in which the housing is fabricated from a large number of flat surface components to approximate the shape of the desired cavity shape, or from foam or other bulk solid materials cut to the desired shape.

Theoretical prediction and analytic testing show that the geometry of the lip, or upper edge of the housing structure, should not be a sharp edge. Theory suggests that forming a rounded lip at the upper edge of the structure, where the radius of curvature of the lip is large, for example greater than or equal to the wavelength of the transmitted sound, substantially eliminates any problems with refracted or reflected sound. Experimental measurement confirms this. The lip can be integral with the sidewalls (i.e., the top of the sidewalls) or can be a separate structure, as shown in the drawings.

In the preferred embodiment, the phased array of the sodar is mounted vertically for protection from precipitation, and a diagonally oriented aluminum plate serves as a reflector, or "mirror," to orient the beams into the desired near-vertical directions. In the preferred

embodiment, this mirror is suspended by the housing and structurally reinforces it. However, other embodiments are possible where the reflecting surface is of other materials, where the reflecting surface is mounted independently of the housing, where the reflecting surface does not reinforce the housing, or even (with loss of some, but not all, benefits of the invention) where the reflecting surface is omitted, and a phased array directly facing upwards is surrounded by a somewhat simpler housing. Horizontal mounting of array 10 in enclosure 100a is shown in Fig. 10.

In the preferred embodiment, the housing envelops accurately the shape of the conic beams as they travel approximately horizontally from the phased array to the mirror, and also envelops the beam shape as it reflects off the mirror and out the top of the housing. Surface 133, shown in figure 6D surrounds the three conical sound beams immediately following their emission from array 10. This surface encloses the union of the volume taken up by the three beams. The shape of surface 133 is essentially a conical section. More specifically, preferably its shape is an extension of the three-lobed fluted shape of the interior of the enclosure, reflected off of the sound mirror at the location of surface 133. Immediately after exiting array 10, the beams overlap substantially enough that the difference in shape between three overlapping cones and a single essentially conical shape is not very pronounced, and surface 133 could, in fact, be formed as a simple conical section surface with little difference in performance. Although the extent of surface 133 is not large, its proximity to array 10 is such that it is of more significant importance in intercepting side lobes 24, 44 and (especially) 34 than its size would suggest.

Other embodiments are possible where the shape of the housing does not continuously follow the shape of the beams. In an extreme case, the housing could have an arbitrary, for example rectilinear, shape with only the opening at the top contoured to the cross-section of the beams as they exit the housing, for example through use of the same lip as in the preferred embodiment. To perform as well as the preferred embodiment, such a rectilinear housing would require superior sound absorbent material to damp internal beam reflections.

In the preferred embodiment, the housing is equipped with an opening, or scupper (134 in figure 6D) at the lower end of the reflector, below the vertically mounted phased array, sized to provide a passage for rainwater, leaves and other detritus to exit the housing. Further, for cold climate installations, the reflector may be optionally equipped with a heating system (not shown) to melt any snow or ice that might accumulate, and allow this precipitation to also exit the

scupper in liquid form. This can be accomplished electrically, or by including a propane tank as a fuel source for the heating system in area 145 behind door 144. Other embodiments are possible, for example without any provision for allowing the exit of detritus where such is unlikely to accumulate, or by provision of a suitable screen that is sufficiently transparent to sound over the opening of the housing to inhibit detritus from entering the housing in the first place.

In the preferred embodiment, the housing is employed with a hexagonal phased array that transmits three beams angled off vertical spaced at 120° angles from each other in azimuth. However, other embodiments are possible where the housing is fitted to other phased array architectures, including a more conventional rectangular grid packing arrangement phased array transmitting one directly vertical beam and two angled beams oriented at a 90° angle to each other in azimuth, as detailed in US Patent 4,558,594. In this latter case, the overall performance of the system will be inferior to the preferred embodiment with three or more symmetric beams. However, the inventive housing, with a lip that defines two or more generally partially elliptical lip segments, and preferably with walls that fall at the first null of each of the three beams, will be of considerably greater value due to the significantly poorer directional performance of the prior art rectangular grid array relative to the hexagonal grid array of the preferred embodiment.

In the preferred embodiment the hexagonal phased array is mounted such that one of the three beams leaves the reflector angled in an azimuth direction opposite the array, and the other two beams are oriented in azimuth reflecting generally back over the array at 60° angles resulting in a most compact overall size. Where size is a less significant concern, other embodiments are possible.

Fig. 8 is a composite of plotted normalized magnitudes of computer-modeled emissions from a prior art 32-element rectangular grid packing arrangement phased array, wherein the emitter elements are modeled as point sources and all elements are in phase with each other, such as to produce a main beam perpendicular to the plane of the array. The magnitudes are plotted against tilt angle from vertical, which is the center of the beam. The different plots each represent a predicted beam intensity as a function of tilt angle, as measured along different angles from the array rows, 0 (or 90°) degrees being in line with the rows, 45° degrees being diagonal to them. In all of these cases, the model predicts the main beam dropping off abruptly to a first null at about 10 degrees of tilt angle. The intensity increases again at a greater

angle to produce first annular ring 61, then second annular ring 62, and so on, as shown in the figure. The inside surfaces of the inventive enclosure are preferably positioned immediately outside of the first null position at about ten degrees from the main beam axis, to block the formation and emission of all but the desired main beam.

Figures 9A and 9B show results of testing a bare hexagonal phased array transducer of the preferred embodiment herein. Figures 9C and 9D show results from testing the same transducer array mounted within the preferred embodiment of the inventive housing shown in the drawings. The prototype used in this series of experiments was manufactured from plywood and sculpted foam, but otherwise matched the design of the molded plastic preferred embodiment housing described above.

The system was tested in transmitter mode, emitting pulsed sound signals at 4425 Hz, a typical operating frequency for sodar systems. A computerized instrumentation system consisting of a scanning array of microphones was used to map the emission patterns of the bare phased transducer array (Figs. 9A and 9B) and the emission pattern from the array mounted within the housing (Figs. 9C and 9D).

For each run the data was normalized to a signal strength of 1.00 at the center of the main beam 41 in Figs. 9A and 9C, and 31 in Figs. 9B and 9D. Coordinate transforms were carried out to map the data into a spherical coordinate system centered in the instrument's frame of reference, and contours of equal sound intensity ("i" in the figure) were plotted.

Data was collected for the case in which the beam emanates from the instrument in the azimuth direction opposite the position of the array (referred to as the "6 O'clock beam") and also for the case in which the beam emanates in the direction 120° counter-clockwise viewed from above from the first case (referred to as the "2 O'clock beam"). These data are shown in Figures 9A and 9C, and 9B and 9D, respectively. No data was taken for the third ("10 O'clock") azimuth direction. Due to the bilateral symmetry of the enclosure, the "2 O'clock" and "10 O'clock" beams will be mirror images, otherwise identical to the limits of experimental accuracy.

Inspection of Figure 9A shows that the bare array produces a side lobe 44 (at 0 degrees) greater than 0.4 times the intensity of the main beam; this side lobe is shown in Fig. 3C. This harmful beam is eliminated entirely by the housing (see Fig. 9C), as it is at a very low altitude of around 25 degrees and so strikes the housing walls and is absorbed by the sound-absorbent wall

lining. Also, in the bare array data, the annular ring predicted by theory is apparent as a region 42 of signal intensity approaching 0.3 times the intensity of the main beam within an area 47 approaching 0.2 times the intensity of the main beam. Due to the plotting projection and experimental data variability, the ring shape is considerably distorted. As expected, portions of this ring remain in the housing data (42a Fig. 9C), but area 47 of the annular ring is greatly attenuated in size and intensity as is the overall intensity of the ring relative to the bare array data. Similarly figure 9B shows side lobe 34 and a significant annular ring 32, 37 for the bare array 2 O'clock case. Side lobe 34 and the major area 37 approaching 0.2 times main beam strength in the bare array case, Fig. 9A are virtually eliminated in the housing case, Fig. 9D. The area of the annulus approaching 0.3 times main beam strength, 32, Fig. 9B, is greatly reduced in the housing data (area 32a shown in Fig. 9D) relative to the bare array data of 9B. In the bare array data of Figs. 9A and 9B, a number other minor regions of undesirable off-axis sound are apparent, e.g., regions 48 and 38. These areas are virtually absent when the housing is introduced, Figs. 9C and 9D. Figure 9 thus summarizes the experimental evidence that the inventive enclosure functions as predicted.

Experimentation showed that when the enclosure wall surfaces are located approximately coincident with the position of the first null, the intensity of the main beam is largely unaffected. Thus, the phased array operates better within the enclosure than in free air. The wall surfaces could be located somewhat closer to the central axis of the beams, which would reduce the overall beam power, but may be acceptable, depending upon the application. Alternatively, locating the beams somewhat further from the axis would cause the inclusion of wake rings, which would also degrade performance, but may be acceptable, again depending on the application.

The preferred felt sound absorbing fabric material was tested for environmental durability as follows. An approximately 3 inch square sample of the felt material was affixed to a vertical south facing surface exposed to the weather in Amherst, Massachusetts. This sample showed no visible or tactile signs of deterioration over a one-year period. A similar sample of acoustic foam such as Type AF-1 polyurethane foam from Acoustical Solutions Inc. mounted adjacent showed significant deterioration. The surface of the foam became brittle to a depth of about 1/10" from the surface. Gently touching this surface layer caused it to crumble into a fine powder. The brittle surface layer developed within a few weeks of exposure. It appears as though this layer

protects the underlying foam from further degradation, until it is brushed off. Once brushed off, a new brittle layer develops within a few weeks. The poor performance of the foam at the test site is likely better than what would be expected at potential sites for the sodar apparatus, where wind and other environmental factors might cause the brittle layer to slough off without ever becoming thick enough to protect the underlying foam. Testing confirms that the felt is suitable for long-term outdoor exposure, while acoustic foam is not.

Also, the sound absorbing qualities of the preferred material and alternative materials that were likely to resist weathering were tested. The materials chosen for testing were a combination of materials manufactured to be sound absorbent, as well other available materials that might be expected to have suitable sound absorbent and water shedding properties that are important for the housing lining material used in the invention. The materials tested were:

1. Truck bed liner fabric: An approximately ¼” thick pile fabric woven from coarse polyester fiber supplied by Wise Industries of Old Hickory, TN, normally used as the exposed surface of their “Bedrug” brand name pickup truck bed liners.
2. Sintered Glass tiles: 1” thick “Reapor” brand name sound absorbent sintered glass tiles manufactured by RPG Diffusor Systems, Inc of Upper Marlboro, MD.
3. Fiberglass insulation material: 1” thick uncoated fiberglass sheet sold as a sound absorbing material; McMaster-Carr Stock #55075T21.
4. Natural fiber welcome mat: A natural fiber (probably jute) woven welcome mat purchased from a local home-improvement store.
5. Heavy welcome mat cut: A natural fiber (probably jute) deep cut pile welcome mat purchased from a local home improvement store.
6. ½” thick white “felt”: This is the material used in the preferred embodiment herein. It is a non woven fabric (a felt material) made from polyester fibers of varying diameters and provided by National Nonwovens Inc. of Easthampton, MA.
7. Vee foam: “Auralex Studiofoam Wedges” brand name acoustic foam supplied by True Sound Control Division of Metro Music, Bayville, NJ.

The measured amplitudes of reflected 4425 Hz tones from test materials were compared with reflections from a non-absorptive surface. The following Table 1 summarizes the test results:

Table 1

Description of reflector surface material	Approximate Normalized	
	Thickness (inches)	Reflected Signal
Bare reflector (non absorptive)	n/a	1.00
Single layer "truck bed liner" fabric	0.2	0.87
Two layers "truck bed liner" fabric	0.4	0.71
Three layers "truck bed liner" fabric	0.6	0.54
Sintered glass tiles	1	0.51
Fiberglass insulation material	~1	0.46
Four layers "truck bed liner" fabric	0.8	0.43
Light natural-fiber "welcome mat"	~0.8	0.43
Five layers "truck bed liner" fabric	1	0.41
Six layers "truck bed liner" fabric	1.2	0.40
Seven layers "truck bed liner" fabric	1.4	0.38
Heavy welcome mat cut	~1.2	0.35
Single layer 1/2" white felt	0.5	0.34
Eight layers "truck bed liner" fabric	1.6	0.33
Heavy natural-fiber "welcome mat"	~1.2	0.25
Two layers 1/2" white felt	1	0.21
Vee foam flat side up, alone	~1	0.15
Vee foam flat side up, on top of "truck bed liner" fabric	~1.2	0.14
Three layers 1/2" white felt	1.5	0.11
Vee foam flat side up, alone	2	0.07
Four layers 1/2" white felt	2	0.06

Experimental Notes:

1. Measured reflected signal, normalized to signal with bare reflector - about 17 Volts AC microphone output.
2. Sound source: 32-element tweeter array, all tweeters driven in parallel. (Approximately 20° beam)
3. Source frequency: 4425 Hz.
4. Subsequent testing showed that the three layers of 1/2" white felt served as an excellent proxy in the above testing for the 1 1/2" thick white felt.

There are several pertinent findings:

- Certain materials that are industrially rated for good broadband sound absorption are not as effective as expected at the test frequency, which is typical in sodar use. (e.g. fiberglass, sintered glass.)
- Sound absorption effectiveness increased with increasing material thickness. Performance improvement diminished at greater thicknesses. See Figure 11, which is a plot of the sound-absorbing performance of one or more plies of the one-half inch thick white felt material.
- The felt, made up of several diameters of polyester fiber, performed almost as well by thickness as high quality sound absorbing foam.

The results of testing of the preferred white felt material are depicted in Fig. 11, which shows that 1.5" of the material (three, 0.5" layers) reduced sound reflection by about 89%.

The felt was tested for water retention and acoustic performance in different stages of saturation with water, to reflect outdoor conditions. It was found that:

- When nearly vertical, the felt drained water rapidly from fully saturated to merely damp. When used with the preferred enclosure described herein, the material will be on a surface that is about ten degrees from the vertical.
- Draining would abruptly stop when the visible water level (corresponding to the level below which the void space in the felt was essentially water saturated) in the felt dropped to about an inch up from the bottom of the material.
- The amount of water retained in the felt was reducible by orienting the felt such that it did not have a horizontal bottom edge. For example, by rotating a vertical square

sample of the felt such that one of its corners was pointing straight down, the felt drained water until its visible level dropped to about an inch from this corner.

- The amount of water retained after draining in this rotated vertical position was about the same as the weight of the felt.
- The residual retained water in the damp felt disappeared slowly by evaporation.
- The damp felt's sound absorbing qualities (at 4425 Hz) were not reduced by more than 25% from its dry state.
- An assembly of multiple pieces of felt material in edge-to-edge contact performed in the above respects as if the assembly were a single piece of felt. Water drained rapidly from all pieces, collecting only in the bottom of the lowest piece of felt in the contiguous assembly.

The preferred embodiment of the array membrane cover of the invention is shown in Figs. 13 and 14. This aspect of the invention may be accomplished in a system and method of protecting the sodar acoustic actuator array with a membrane 1150 placed over array 1000. Membrane 1150 may be held in place over array 1000 by stretching it over a frame 1120 surrounding the front of the array 1000. Frame 1120 is fixed to array mounting plate 1110 by fasteners 1130. The combination of the frame, a gasket material 1140 between frame 1120 and mounting plate 1110, and membrane 1150, effectively waterproofs the array without excessively compromising its dry weather performance.

In the preferred embodiment of the invention, the frame is spun aluminum, and the membrane is a thin plastic film held on the frame with a layer of double-sided adhesive tape between the frame and the film and an overwrapping layer of cloth adhesive tape to protect and trim the attachment of the film to the frame. This embodiment facilitates easy replacement of the membrane, which may be necessary as part of routine maintenance. The membrane is essentially acoustically transparent (or at least sufficiently acoustically transparent for the needs of the sodar system), and may be optically transparent, translucent or opaque.

Alternative implementations could use a molded plastic frame, or a metal or plastic form integrated into the array mounting plate. A snap-on trim ring, or an elastic rubber band could also be used to hold on the membrane. Alternatively, the membrane might be molded or otherwise fashioned with an integral frame ring.

The membrane is preferably suspended a short distance in front of the array face. This is preferably between a quarter and a half wavelength at the normal operating frequency of the array, which also corresponds to between a quarter and a half of the actuator spacing. In the preferred embodiment of the invention, the actuators are hexagonally packed at 3 inch spacing, and the operating frequency is approximately 4,500 Hz. Other membrane-array spacing distances, square array orientation, and operating frequencies are also possible.

In the preferred embodiment of the invention, the membrane itself is a polyethylene film material commonly used to make inexpensive interior storm windows. The material is tough, weatherable, and can be shrunk taut with the application of hot air from, for example, a hair drier. Other materials, including other plastics, such as EPDM, weatherproof fabrics, composite materials, or even metal foil membranes may be acceptable alternatives if material stiffness, thickness and density are such that the material is substantially transparent to the passage of sound at the sodar apparatus' operating frequency and beam angle relative to membrane normal. For example, an acceptable membrane material may comprise a screen material, such as mosquito netting fabric, which might significantly block water droplets and would certainly protect against nesting insects. Such a netting material passes sound in large part by letting the sound (vibrating air) pass through the pores in the weave, as opposed to the manner in which a film transmits sound, by being vibrated by the air on one side, and as a result exciting the same vibration in the air on the other side. In general terms, any full or partial barrier to water droplets that is also sufficiently transparent to sound might serve the function of the membrane of the invention.

The suitability of thin (less than 0.004") polyethylene film, and its optimal spacing from the array, were both determined experimentally. Various water-vapor permeable and impermeable materials were tested, including thin, woven, coated and uncoated, plastic fabrics. All tested materials except the thin film attenuated emitted signals from the array relative to no covering to an unacceptable extent. Open-weave materials that block or at least sufficiently inhibit water infiltration may be appropriate membrane materials. The thin polyethylene film apparently mildly smoothed the shape of the emitted beam. We have speculated that the film has such low mass that the sound waves emitted by the array at the tested frequency produce vibrations in the film that in turn produce sound waves on its other face. That is, the film is to a sufficient extent essentially transparent to sound at the test frequencies. It is also possible that

the captive air mass in the space between the film and the array face somehow aids in integrating the multiple convergent individual emissions from the transducers into a more uniform wave front.

Initial testing for material selection and proof-of-concept was only performed with the array in transmit (speaker) mode, not in receive (microphone) mode. This methodology was developed from earlier array testing that demonstrated that the shape and relative intensity of the emitted beams and directional patterns of receive mode sensitivity are very similar. Subsequent field testing with prototype and production equipment equipped with the inventive membrane shows good performance in both transmit and receive mode. There may be minor degradation in performance relative to that of a dry instrument not equipped with the inventive membrane, however the performance with the membrane in place is certain to be superior to that of an otherwise identical instrument in which the transducers have been temporarily or permanently degraded by the ingress of water droplets into the small and critically dimensioned internal cavities forming the internal sound path between the internal moving element of the transducer and the radiating horn of the transducer.

Testing was undertaken to determine the effect of water infiltration on transducer performance. As a first experiment, two polycarbonate cone speakers were wetted gradually and run through a series of speaker test cycles. Their responses were recorded and are displayed in Figures 15A and 15B. The polycarbonate cone tweeter speakers were tested using a frequency sweep program in which the speaker was sent a sinusoidal signal at frequencies between 3800 Hz and 5500 Hz in steps of 10 Hz. A microphone in an echo resistant chamber captured the response of each speaker. The magnitude of the FFT of the digital microphone signal was then summed and plotted as V_{rms} . If more than 10% of this plot falls outside of pre-determined pass bands, the speaker is deemed a failure. The pass bands were developed from high and low limits of visible trends seen in the bulk of the speakers tested over time using the test cycle. This method assures quality control in the speakers used in the arrays.

Speakers 1 and 2 were first run through the speaker test dry, to establish a baseline. The data is plotted in Figures 15A and 15B, respectively. Then a single drop of water was dropped into the center of the speaker horn, so that it would fall down towards the speaker cone. After each drop the speaker was run through the test again. This was done until the speakers began to fail. Speaker 2 was fully soaked afterwards, by pouring a large amount of water into the horn,

and then tipped over to drain. The speakers were then left inside overnight to dry. The next day they were each run through the same test regimen again several times, with the results shown in Figs. 16A and 16B.

The effect of water quickly showed in the speakers' response, Figs. 15A and 15B. After each drop, the magnitude of the response became smaller and the response curve more erratic. After 4 to 5 drops, the speakers were audibly performing worse and began failing the test criteria. The fully immersed speaker (speaker 2) was very muffled and performed terribly.

After drying overnight, the speakers still were not performing as they did during the original dry run. Speaker 1, which was not fully soaked, had variable performance over several runs, but all within the test limits (Fig. 16A). Runs 4 and 5 were more consistent but had lower response than the original dry run, before any water was dropped into the speaker. It seems likely that the vibrations of the cone as the transducer was operated helped to evaporate the remaining water on the cone. The fully soaked speaker 2 had a response (Fig. 16B) that was much lower than its original run, when dry, with the first two runs below the low test limit. As with the other speaker, though, it started to become more consistent with each additional run, but did not return to its original dry response performance after six test runs.

These data show that the speakers can be easily put out of acceptable operation by water dripping into the cone. It is possible that this damage is irreversible, but given the steady improvement as a formerly-wetted speaker is run through successive test cycles, it seems more likely that it takes a while to dry sufficiently to return to normal operation. Accordingly, while a membrane that completely blocks water infiltration seems best, a membrane that inhibits water infiltration rather than absolutely blocking it may be acceptable, as the transducers may be able to handle some minor intermittent water infiltration and still quickly return to normal operation.

In the preferred embodiment, the membrane is mounted to, and used in conjunction with, a transducer array mounted approximately vertically and where the sound beams are reflected off an adjacent sound mirror surface as described above. With suitable alternative membrane materials, alternative embodiments are possible where the membrane is attached to a horizontally mounted transducer array, which transmits beams skywards without need for a reflecting surface. Further alternative embodiments are possible where the transducer is mounted in a housing with a reflecting mirror, and the entire skyward facing opening of the housing is protected by a

membrane. Another option is to mount individual membranes over the open face of each transducer, or to cover groups of adjacent transducers with individual membranes.

As to a further discussion of the manner of usage and operation of the present invention, the same should be apparent from the above description. Accordingly, no further discussion relating to the manner of usage and operation will be provided.

With respect to the above description then, it is to be realized that the optimum dimensional relationships for the parts of the invention, to include variations in size, materials, shape, form, function and manner of operation, assembly and use, are deemed readily apparent and obvious to one skilled in the art, and all equivalent relationships to those illustrated in the drawings and described in the specification are intended to be encompassed by the present invention.

Therefore, the foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention.

What is claimed is:

1. A device for protecting the transducer array of a sodar system, comprising:
a membrane placed spaced from the array; and
structure that holds the membrane in place relative to the array.
2. The device of claim 1 in which the membrane is placed close to the array.
3. The device of claim 2 in which the structure comprises a frame.
4. The device of claim 3 in which the structure further comprises two-sided adhesive tape that holds the membrane to the frame.
5. The device of claim 4 in which the structure further comprises an overwrap of cloth adhesive tape which protects and trims the edge of the membrane and strengthens the attachment of the membrane to the frame.
6. The device of claim 2 in which the membrane is held a distance of about one quarter to one half of the sodar wavelength from the array.
7. The device of claim 1 in which the membrane is made from polyethylene film.
8. The device of claim 7 in which the film is heated after installation with a source of hot air so as to cause the film to shrink and become taut, reducing wrinkles which might adversely affect performance.
9. The device of claim 7 in which the film is less than about 0.004 inches thick.
10. A device for protecting the transducer array of a sodar system, comprising:
a membrane held a distance of about one quarter to one half of the sodar wavelength from the array; and
a frame that holds the membrane in place relative to the array.
11. A phased array monostatic sodar system, comprising:
a transducer array that sequentially emits and receives multiple generally conical main beams of sound along different primary axes;
an enclosure that defines an interior volume that is essentially open to the atmosphere at the top in which the array is located, to emit and receive the beams, wherein at least the opening shape closely conforms to the conical shape of at least a portion of each of the main beams;
a membrane placed proximate the array; and
structure that holds the membrane in place relative to the array.
12. The system of claim 11 in which the structure comprises a frame.

13. The system of claim 12 in which the membrane is held a distance of about one quarter to one half of the sodar wavelength from the array.
14. The system of claim 11 in which the membrane is made from polyethylene film.
15. The system of claim 11 further comprising a non-woven fiber, sound-absorbing material lining at least some of the enclosure surfaces that face the interior volume.
16. The system of claim 15 in which the fiber is synthetic.
17. The system of claim 16 in which the sound-absorbing material is made of polyester-based fibers of a plurality of different diameters.
18. The system of claim 17 further comprising an adhesive that bonds the sound-absorbing material to the enclosure surfaces.
19. The system of claim 15 in which the portions of the enclosure that are contacted by a beam are essentially entirely covered with the sound-absorbing material.
20. The system of claim 19 in which the sound emitted by the array has a defined wavelength in air, and in which the sound-absorbing material has a thickness of at least about one-half of that wavelength.
21. The system of claim 19 in which the main sound beams define first nulls, the sound-absorbing material essentially fully covers the inside surfaces of the enclosure that are exposed to a sound beam, and wherein the inside surfaces of the sound-absorbing material lie approximately at the first null of a main sound beam.
22. The system of claim 19 in which at least some of the inside surfaces of the enclosure are generally partially elliptical in cross section, to closely conform to a conical beam contour.
23. The system of claim 22 in which the inside surfaces of the enclosure that are generally partially elliptical in cross section are angled from the vertical, to define an inside surface that itself defines a portion of the surface of a cone that is slightly angled from the vertical.
24. The system of claim 23 in which the enclosure further comprises a lip comprising a plurality of partially elliptical lip segments, each segment generally lying along a said angled conical surface.
25. The system of claim 11 in which the transducers comprising the array are mounted in a generally vertical plane and the main beams are reflected to and from the atmosphere by an angled sound-reflecting surface located within the enclosure.

26. The system of claim 25 in which the array comprises a plurality of individual sound transducers, for emitting sound into the atmosphere and for sensing emitted sound that has been reflected by the atmosphere, in which the transducers are arranged in a generally planar, generally hexagonal grid packing arrangement.

27. The system of claim 26 in which the array comprises a series of rows of tightly-packed essentially identical transducers, with the transducers in adjacent rows offset from one another, in a direction orthogonal to the row longitudinal axes, by about $\sqrt{3}/2$ the width of a transducer.

28. The system of claim 27 comprising three beams that are sequentially created, each such beam defining a main beam axis, wherein the three beam main axes are at essentially the same altitude of about 10 degrees from the normal to the plane of the transducers.

29. The system of claim 28 in which the three beams are oriented at about 120° angles to each other in azimuth.

30. A phased array monostatic sodar system, comprising:

- a transducer array that sequentially emits and receives at least three generally conical main beams of sound along different primary axes spaced from one another about 120 degrees in azimuth, each beam defining a first null spaced from its main axis, in which the transducers comprising the array are mounted in a generally vertical plane;

- an angled sound-reflecting surface that reflects the main beams to and from the atmosphere;

- a membrane placed proximate the array;

- structure that holds the membrane in place relative to the array;

- a housing comprising three upwardly-directed sidewalls that define a volume between them that is essentially open to the atmosphere at the top, to emit and receive the beams, the sidewalls each defining an inside surface that itself defines a portion of the surface of a cone that is essentially vertical or slightly angled from the vertical;

- a lip comprising three partially-elliptical upper lip segments, one segment at the top of each sidewall, such that the lip defines a three-lobed curved perimeter at the top of the volume that closely conforms to the conical shape of a portion of each the three main beams at the location of the lips;

- rounded fillet areas at the intersections of the sidewalls;

a generally horizontal partially conical passage section located between the array and the sidewalls; and

non-woven fiber sound-absorbing material essentially fully covering the inside surfaces of the sidewalls and the passage section, wherein the inside surfaces of the sound-absorbing material lie approximately at the first null of each of the main sound beams.

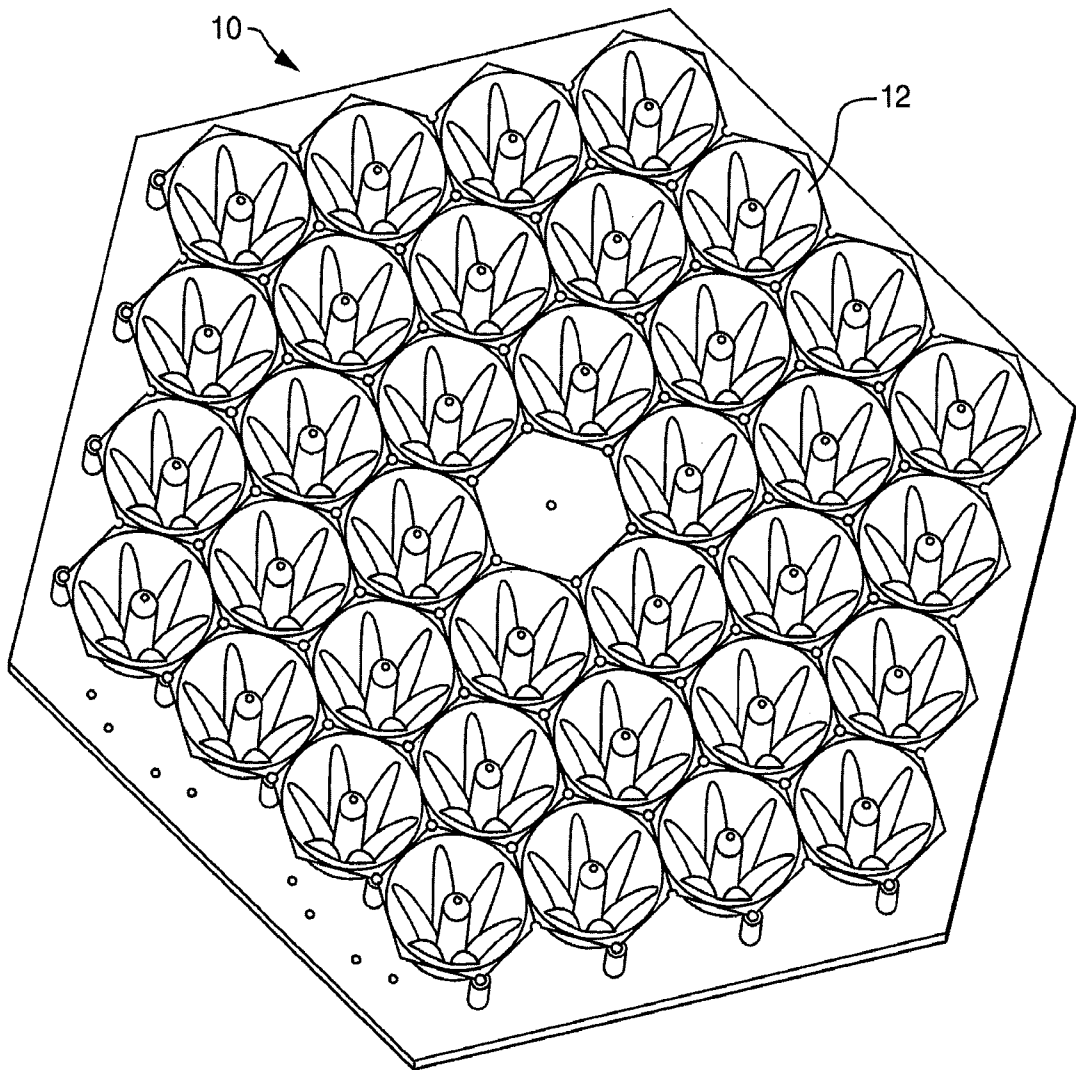


FIG. 1

2/23

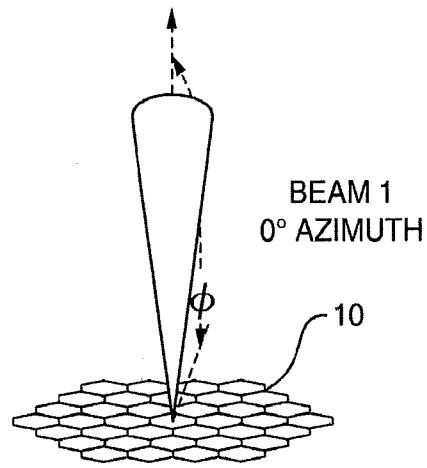


FIG. 2A

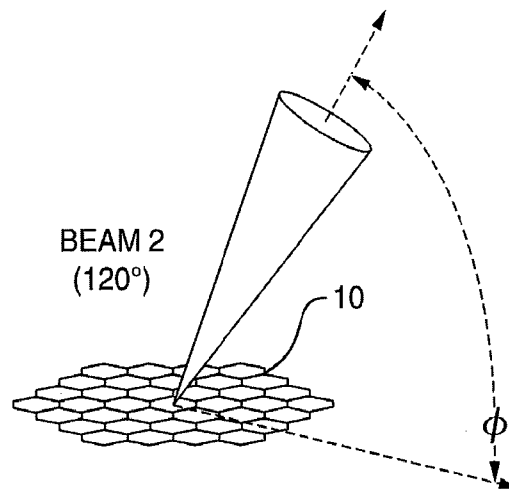


FIG. 2B

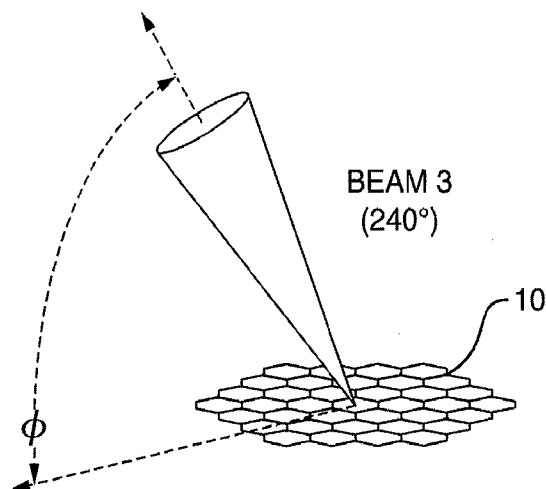


FIG. 2C

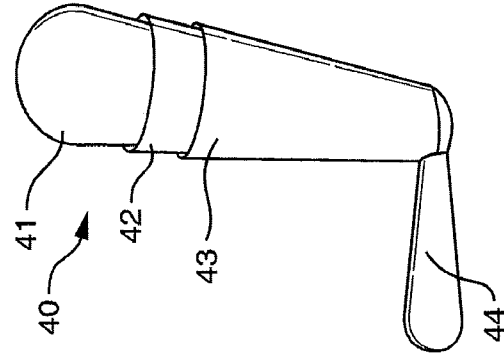


FIG. 3C

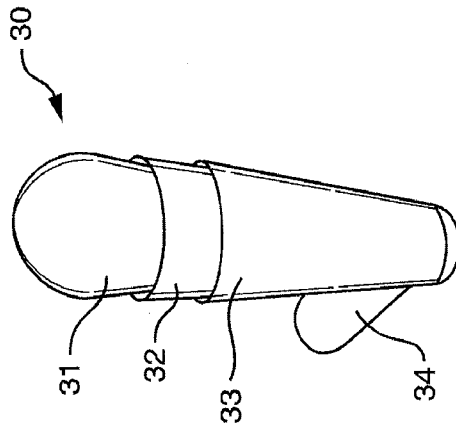


FIG. 3B

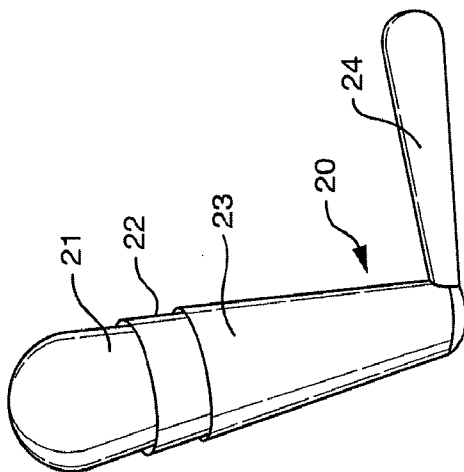


FIG. 3A

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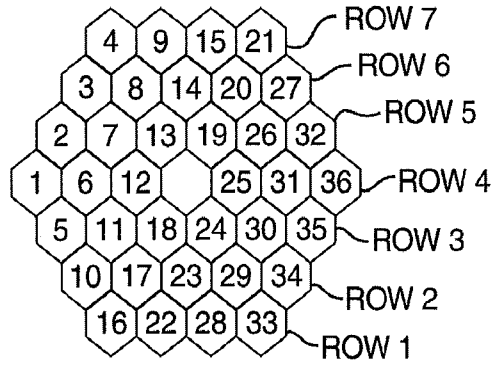


FIG. 4A

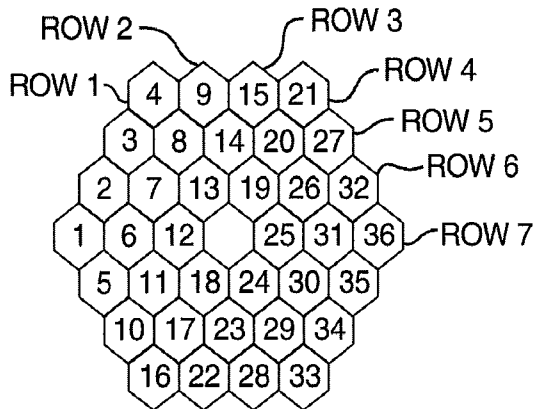


FIG. 4B

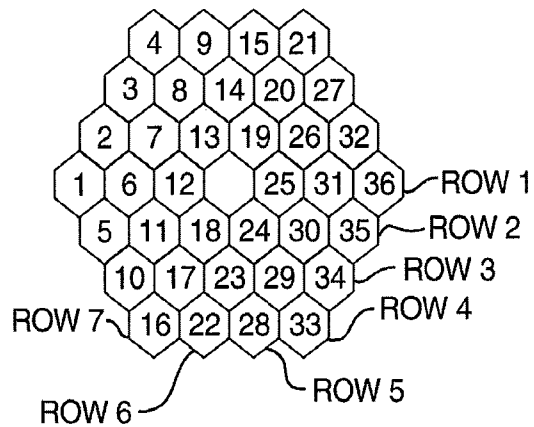


FIG. 4C

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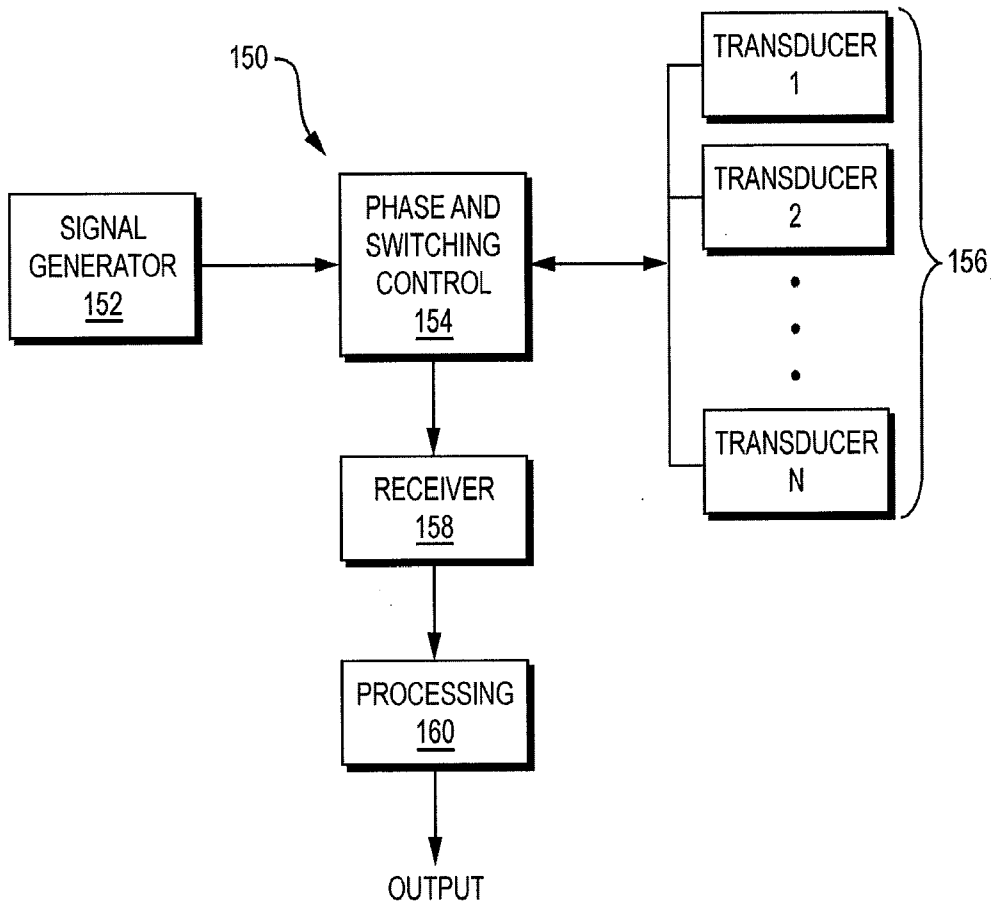


FIG. 5

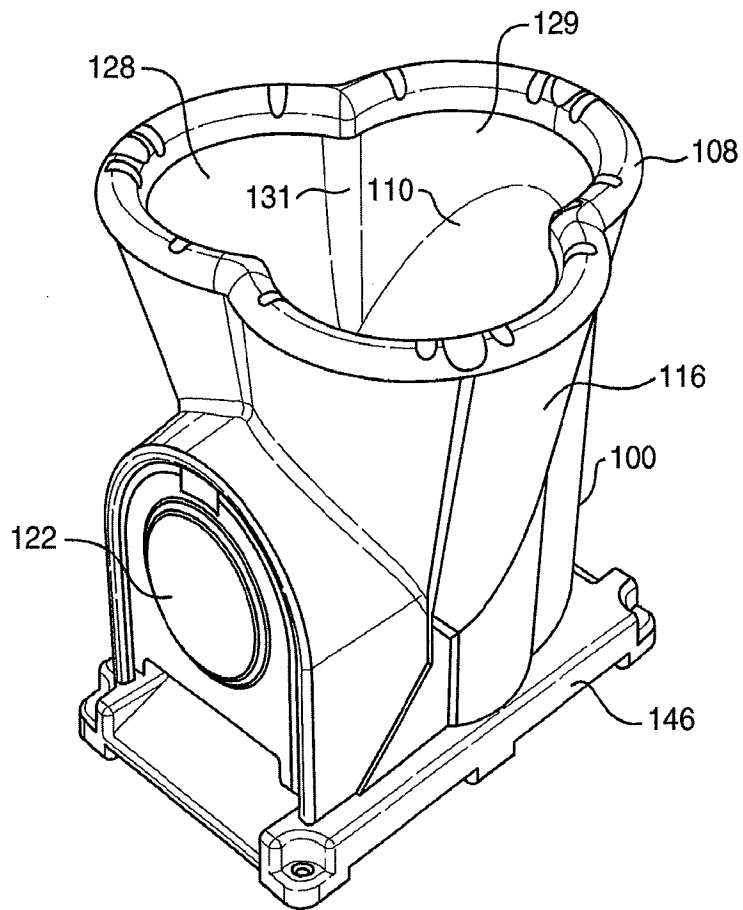


FIG. 6A

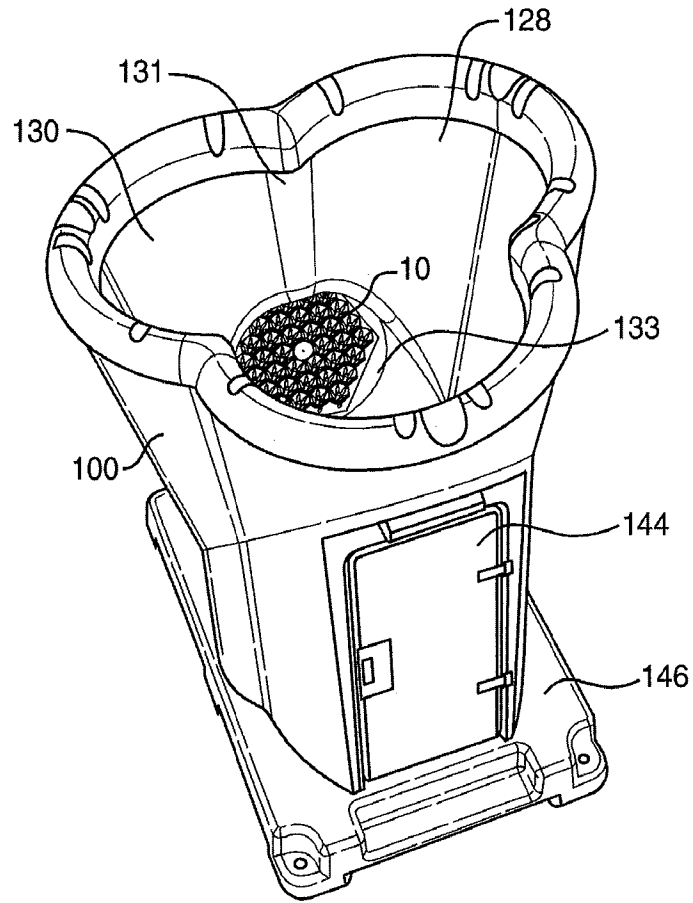


FIG. 6B

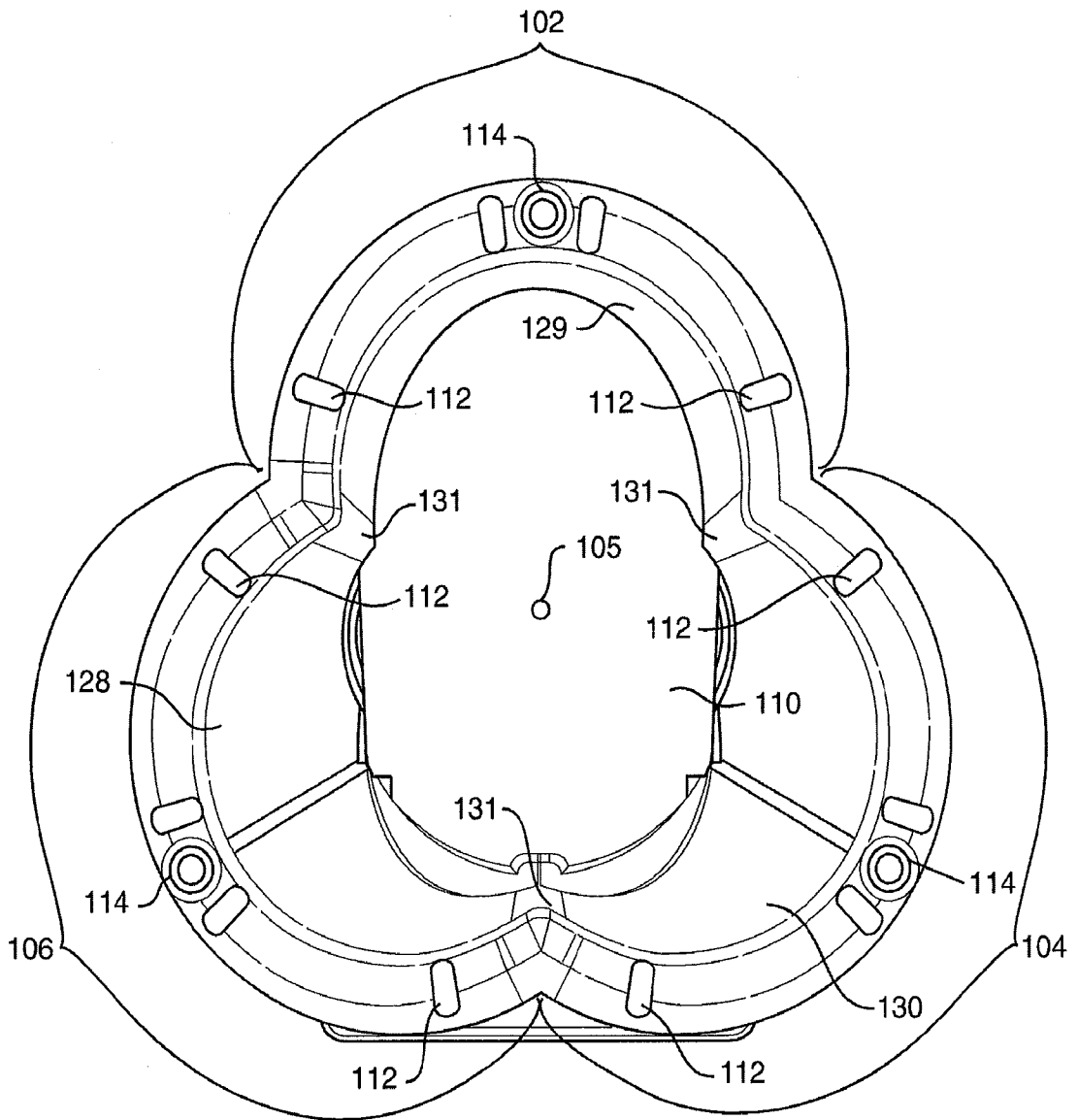


FIG. 6C

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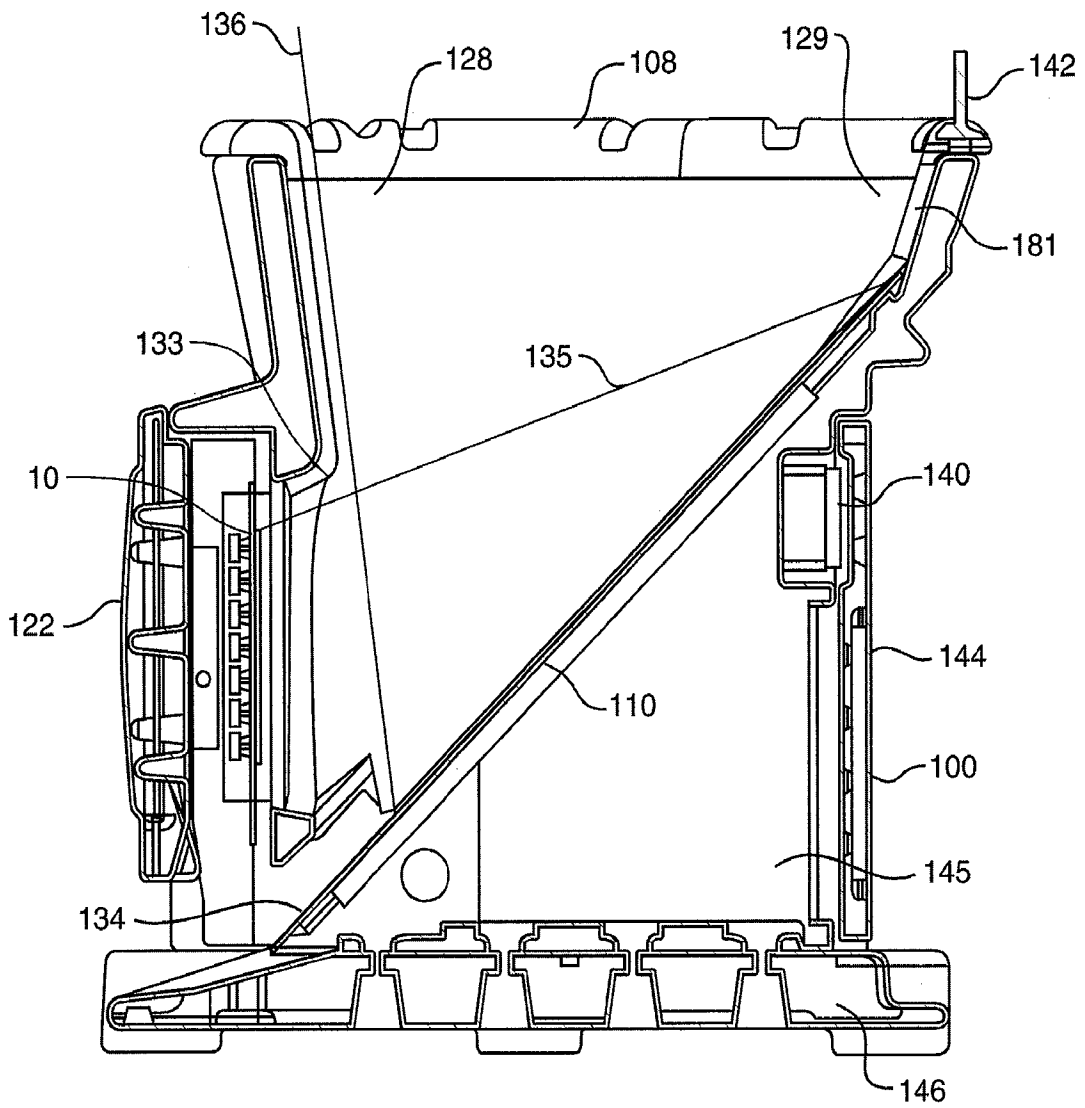


FIG. 6D

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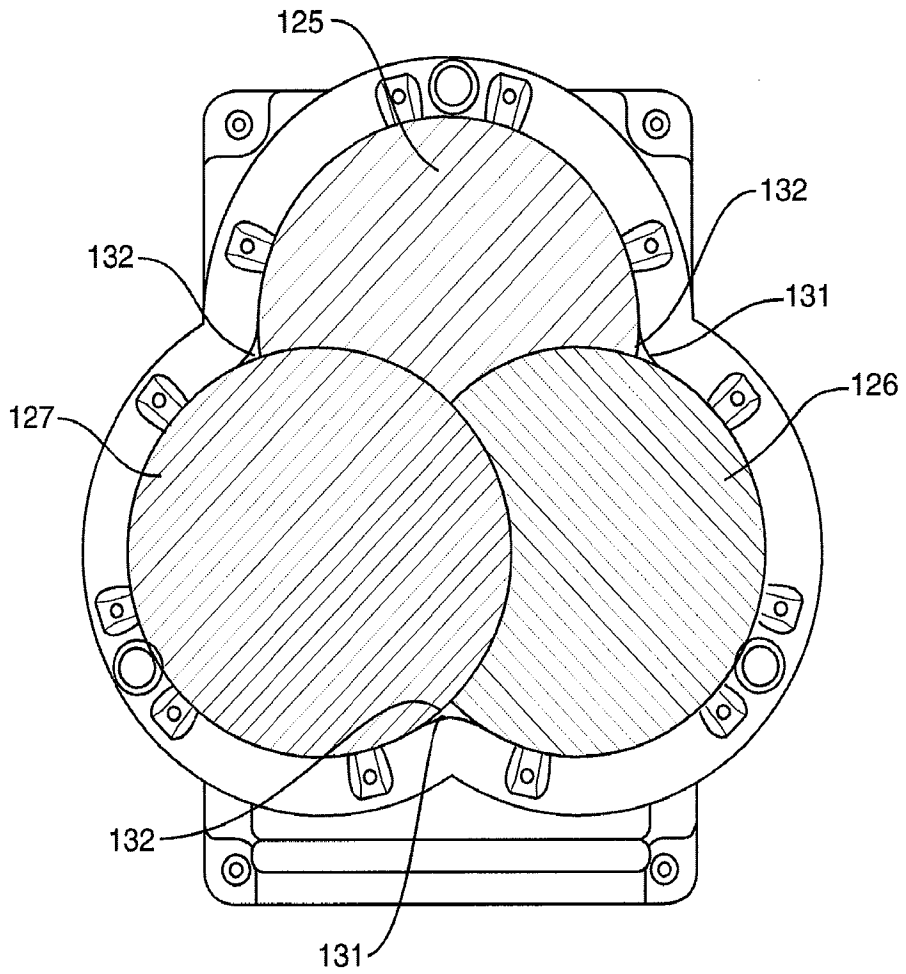


FIG. 6E

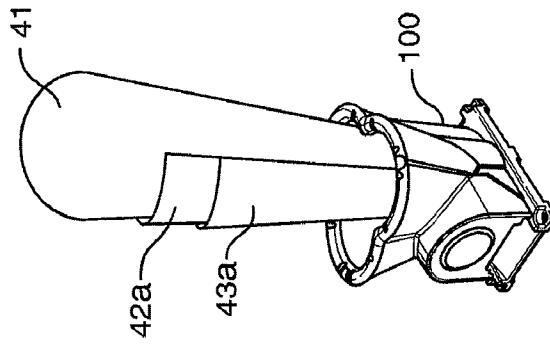


FIG. 7C

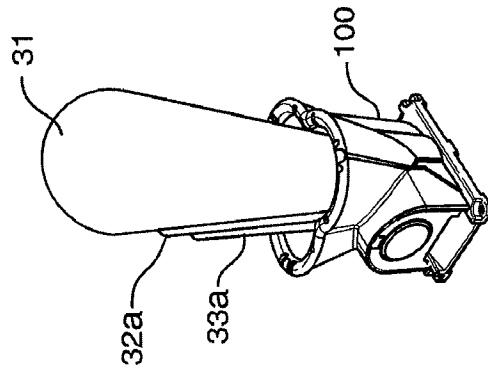


FIG. 7B

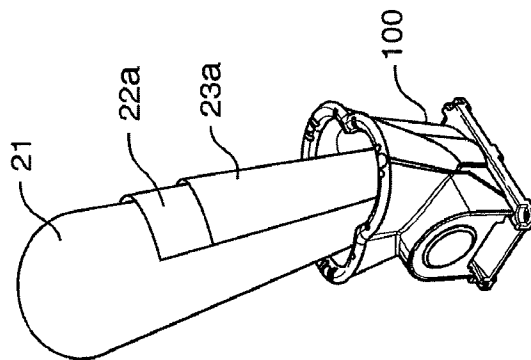


FIG. 7A

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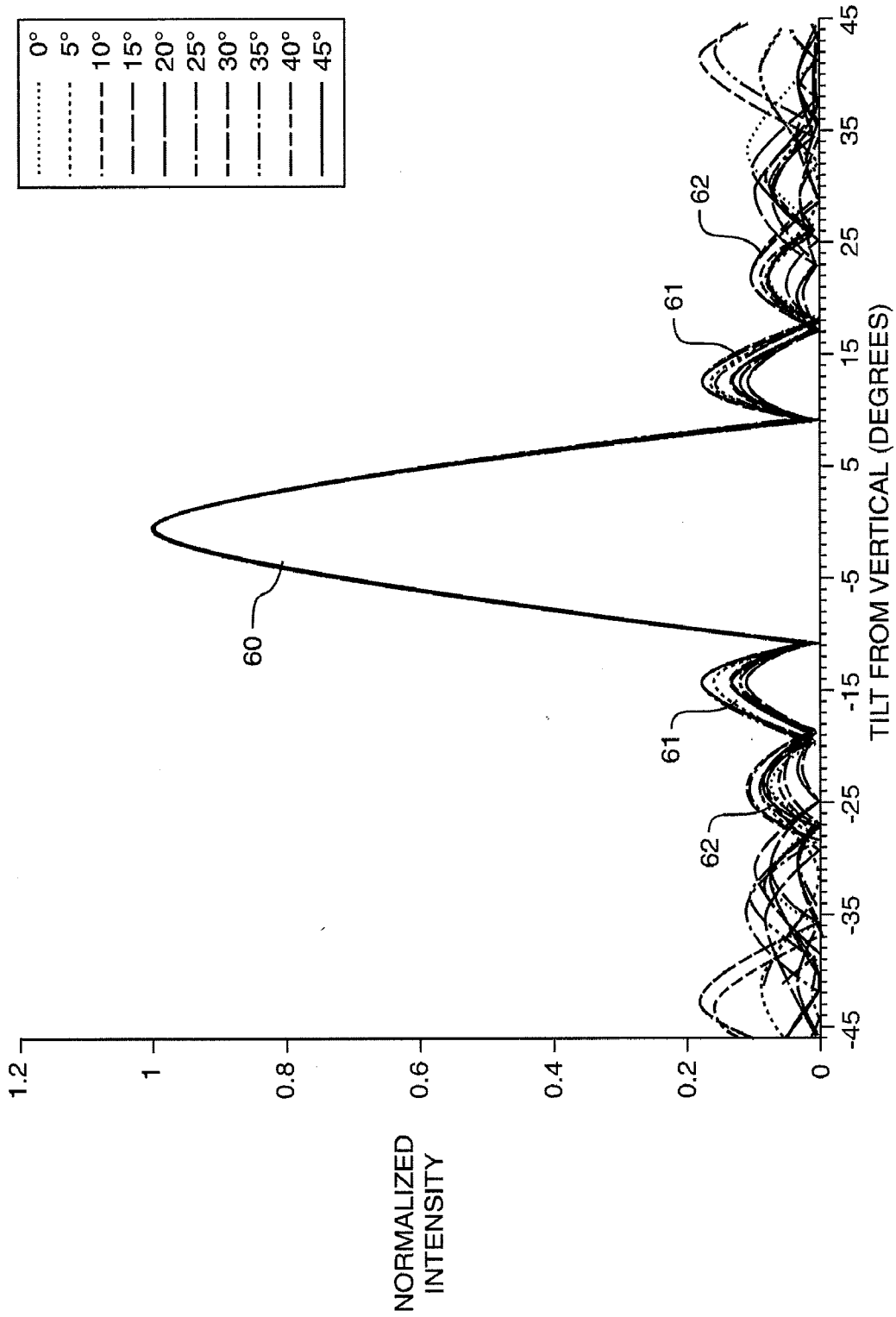


FIG. 8

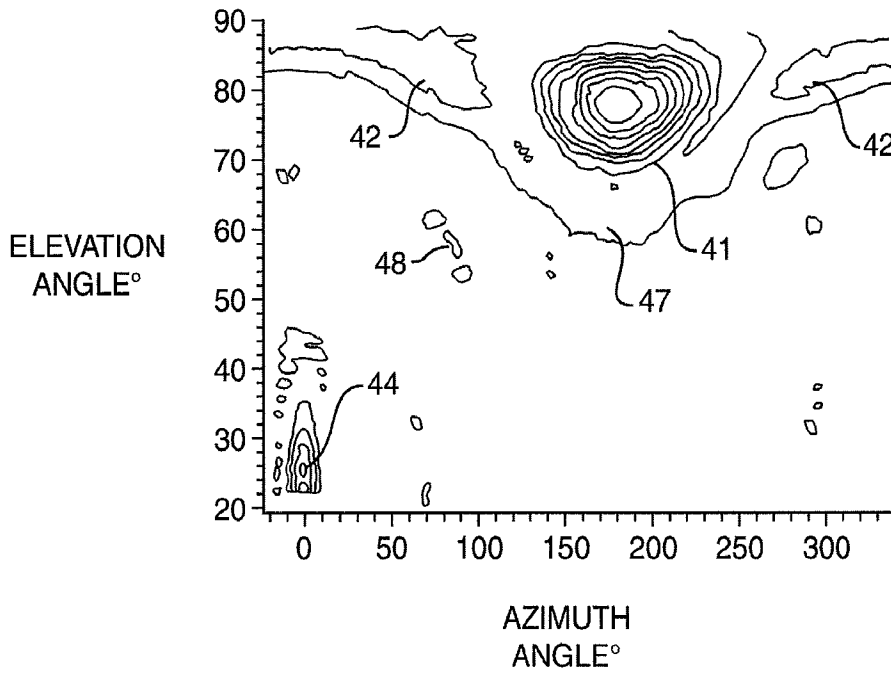


FIG. 9A

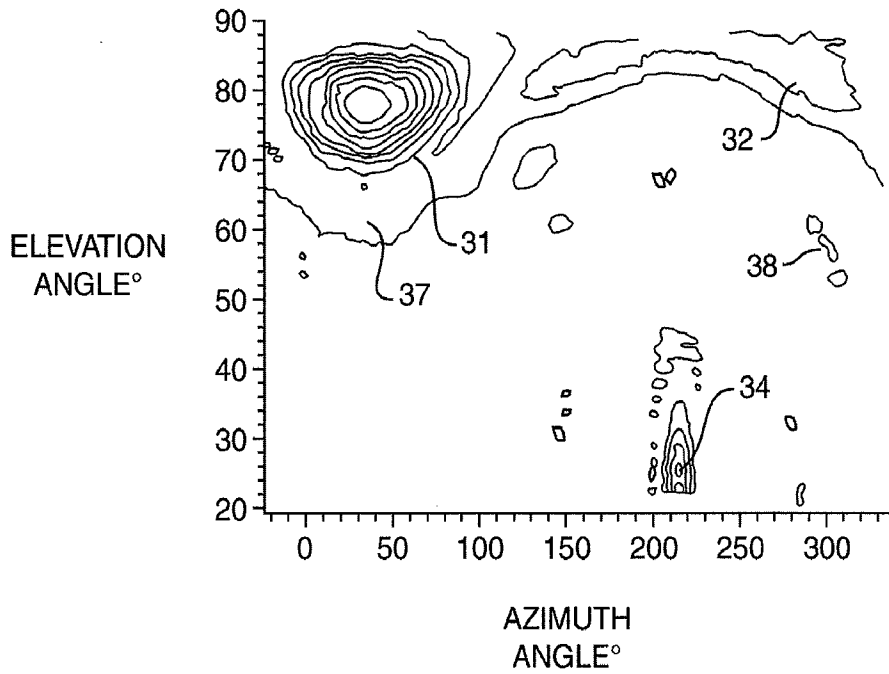


FIG. 9B

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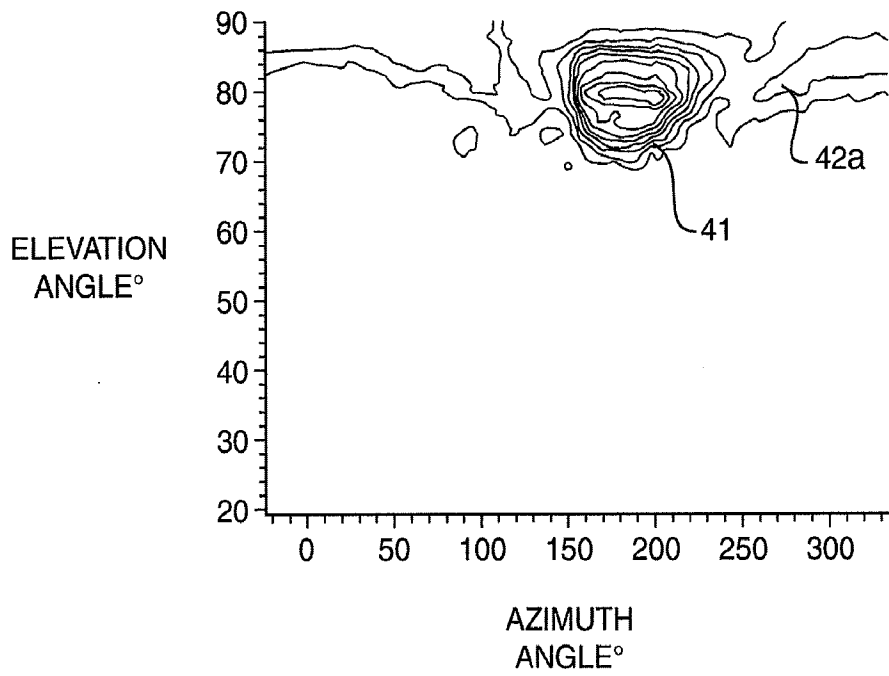


FIG. 9C

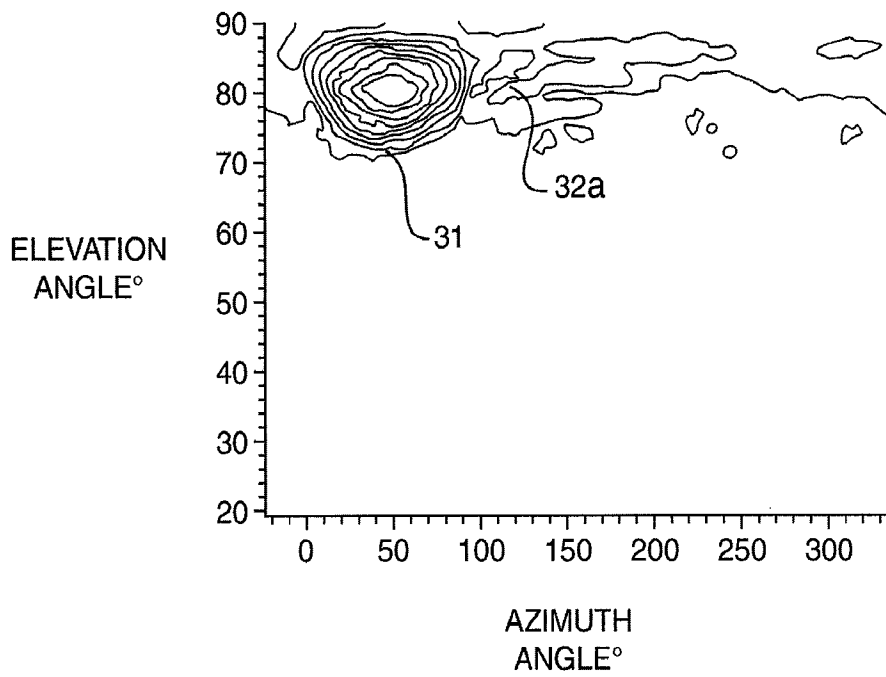


FIG. 9D

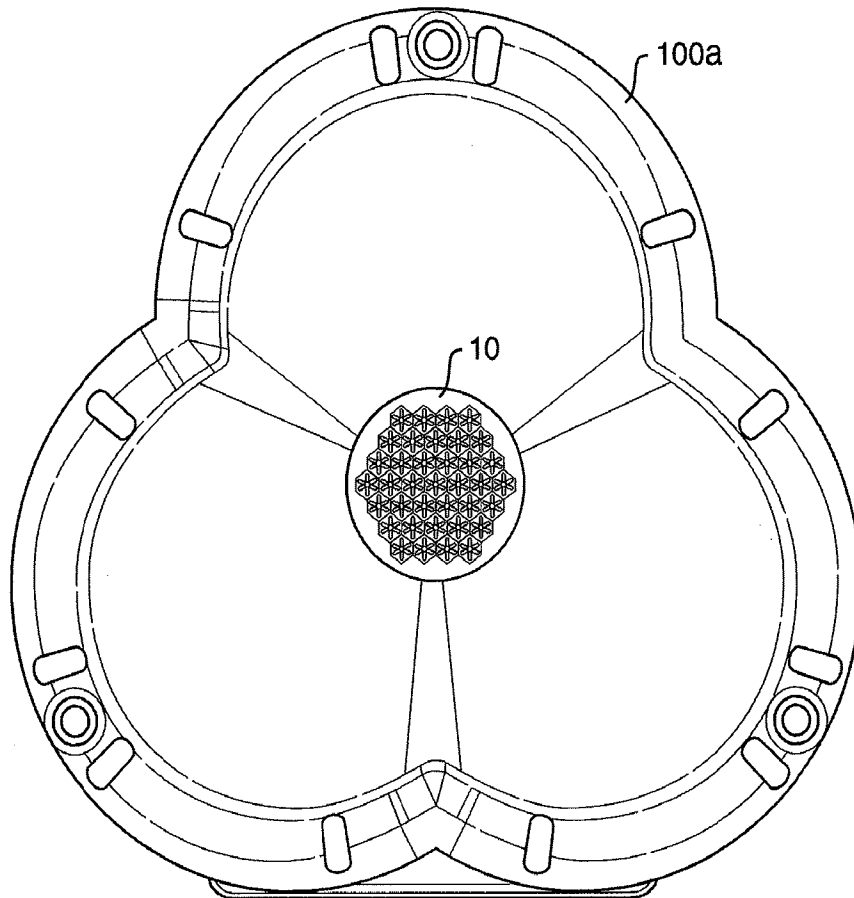


FIG. 10

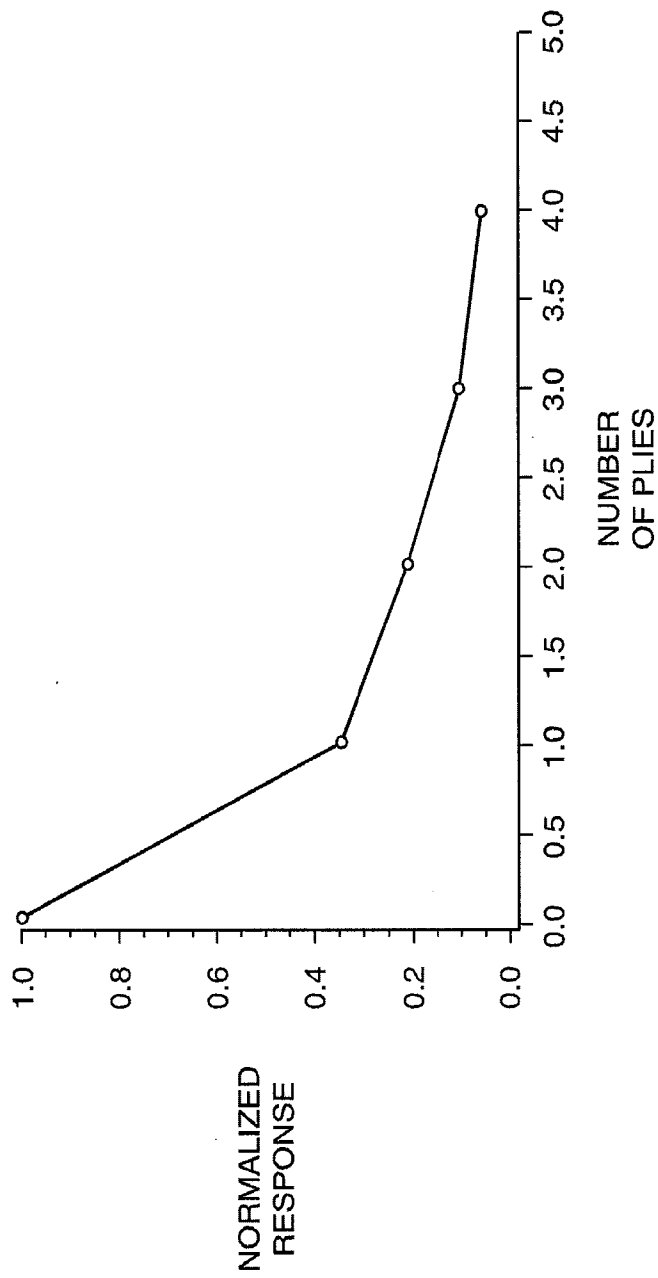


FIG. 11

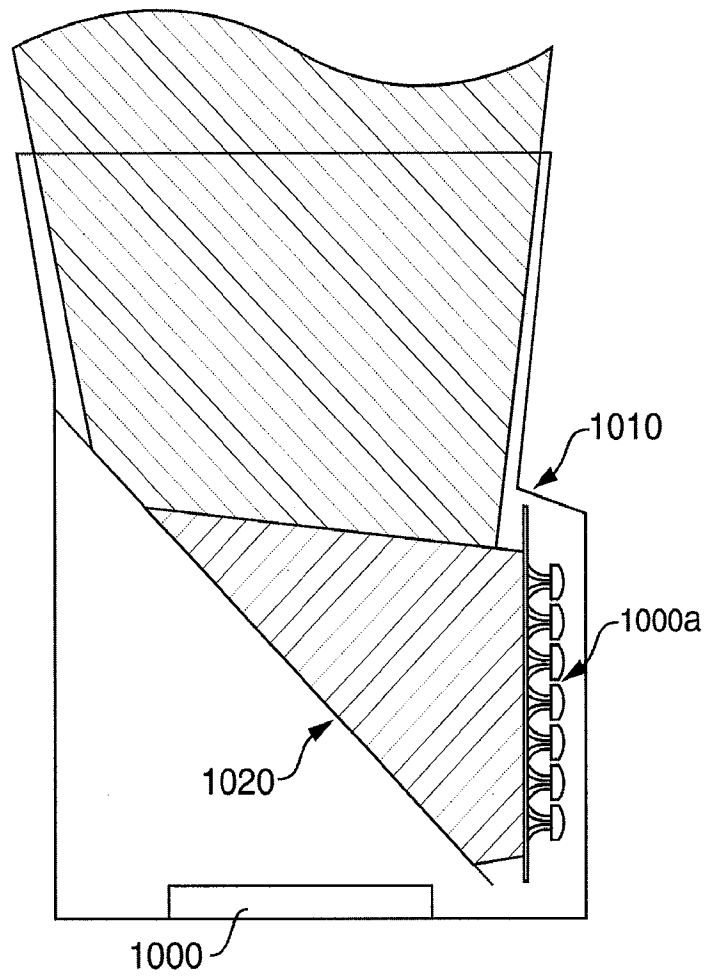


FIG. 12
PRIOR ART

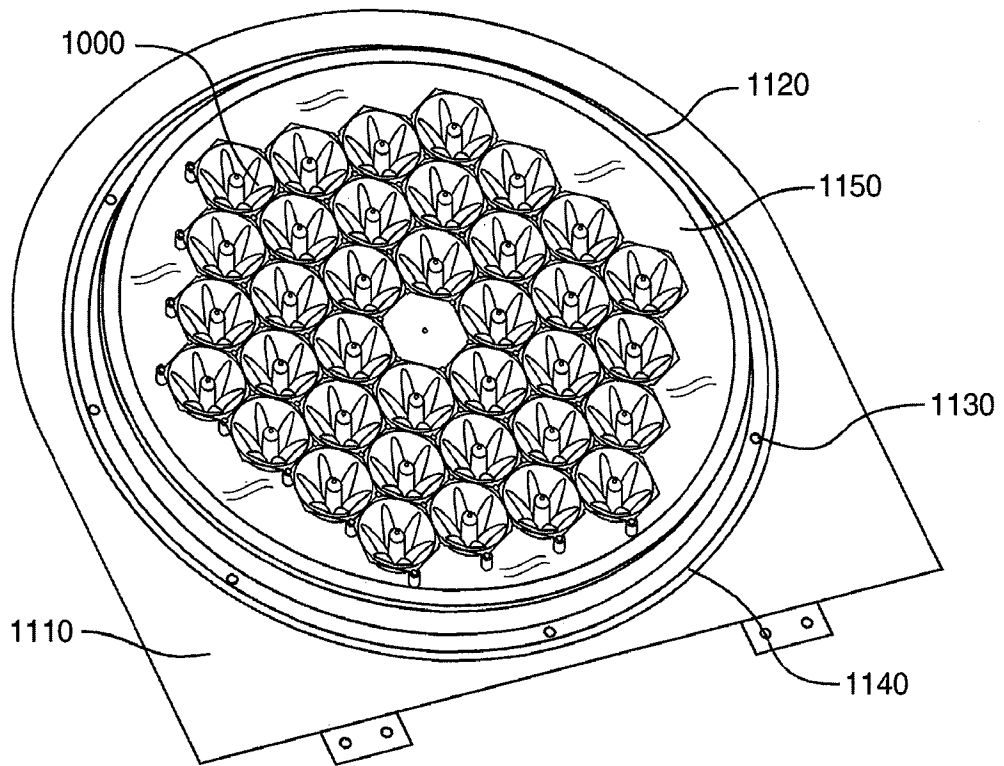


FIG. 13

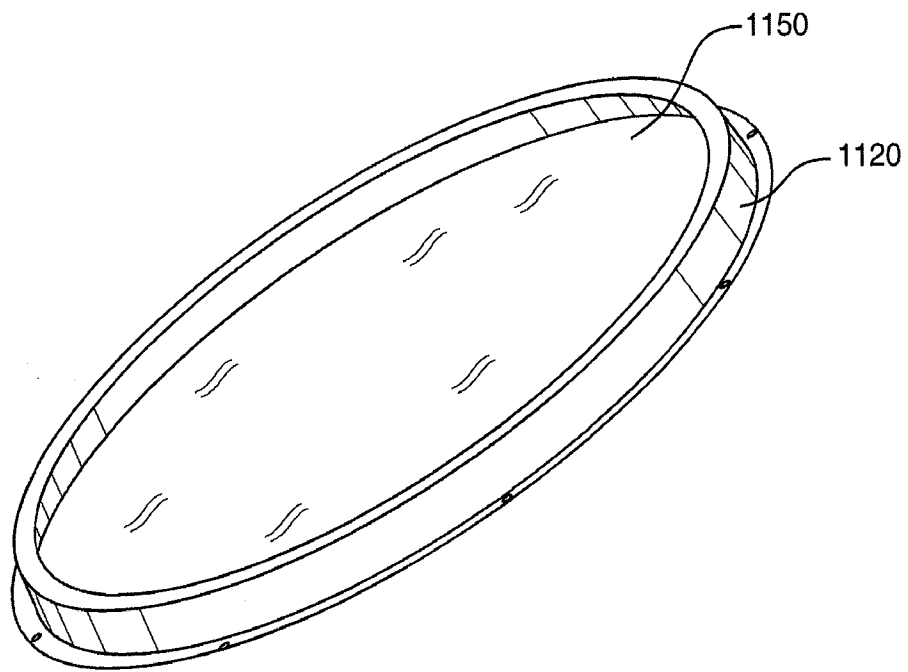


FIG. 14

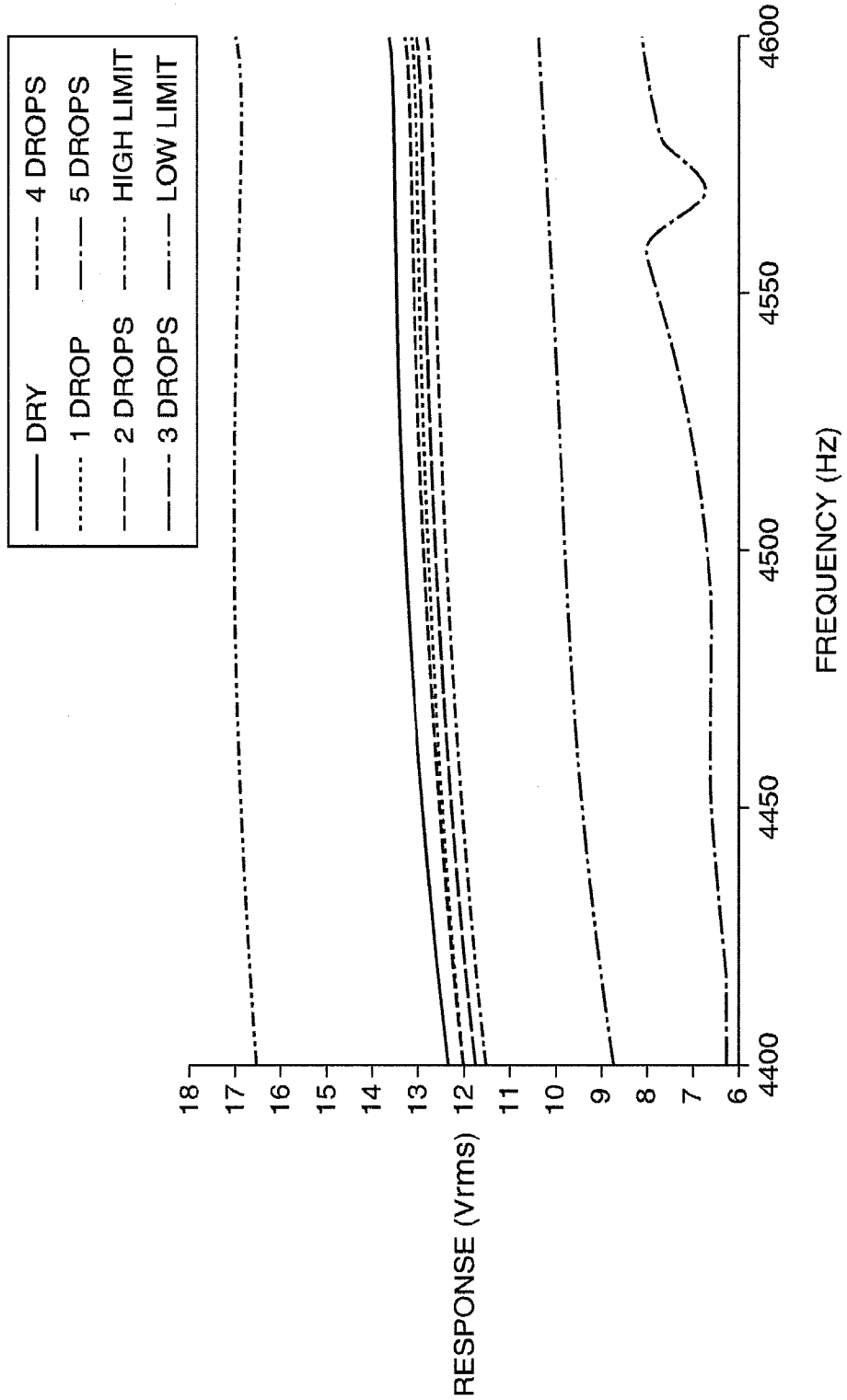


FIG. 15A

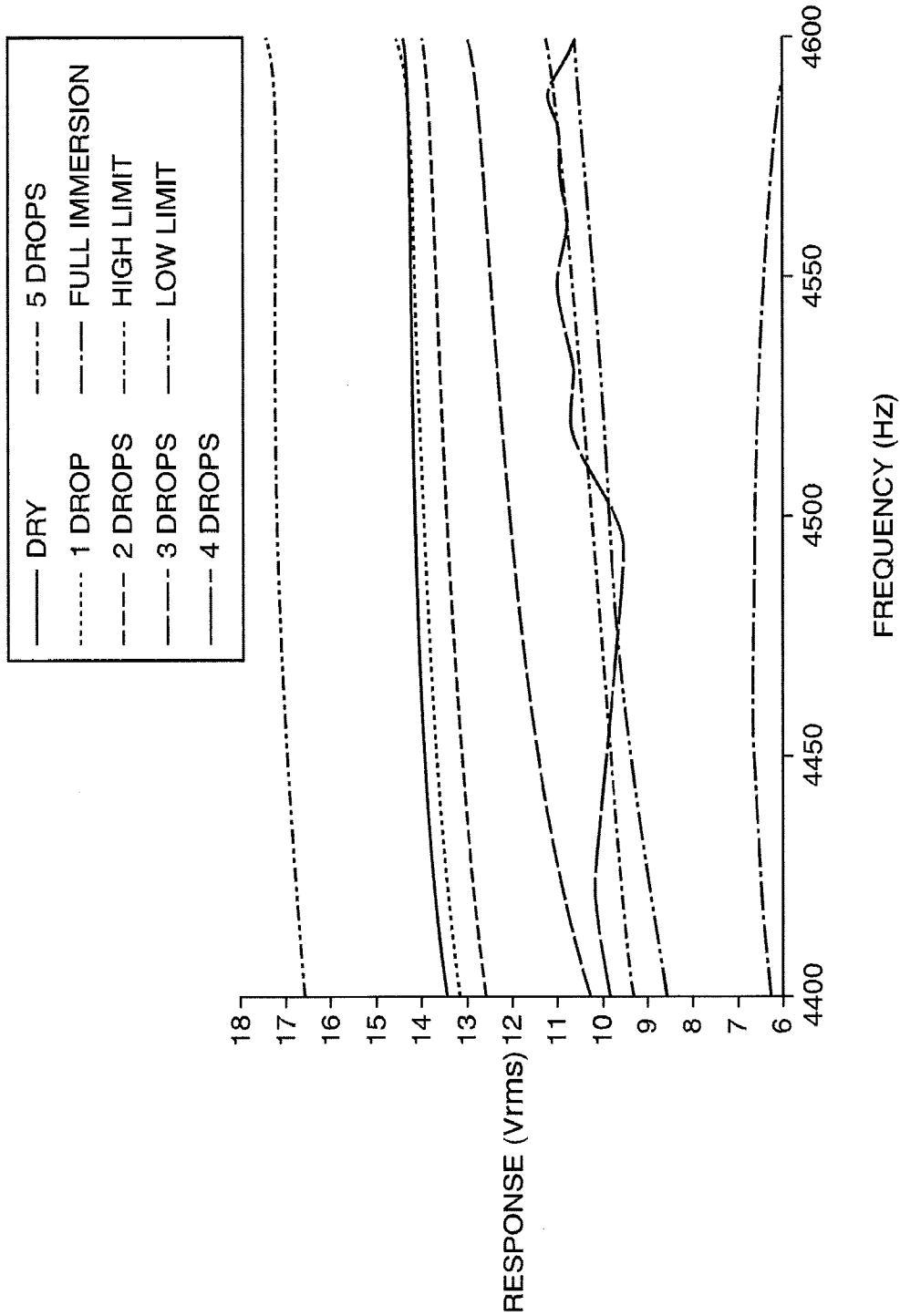


FIG. 15B

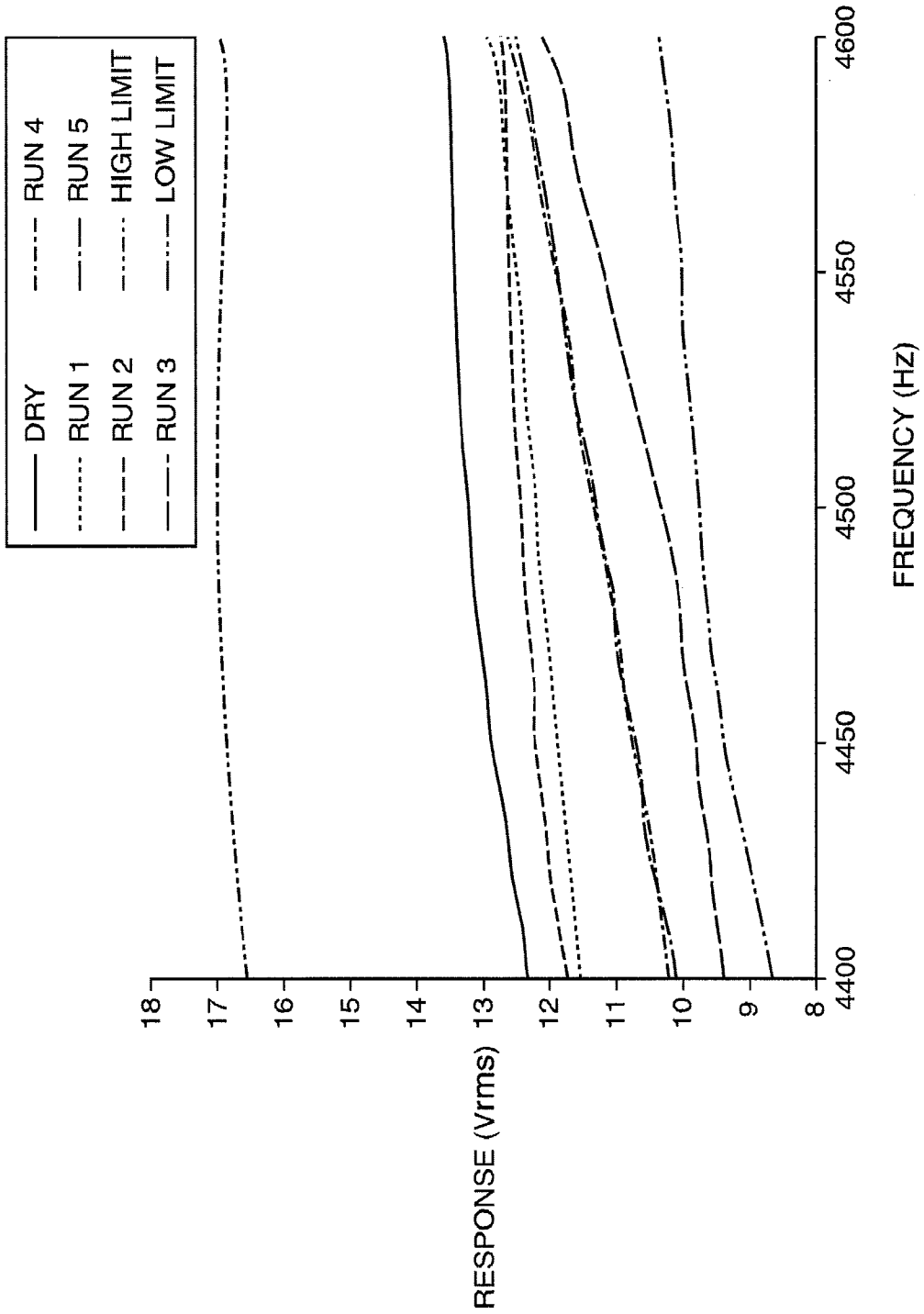


FIG. 16A

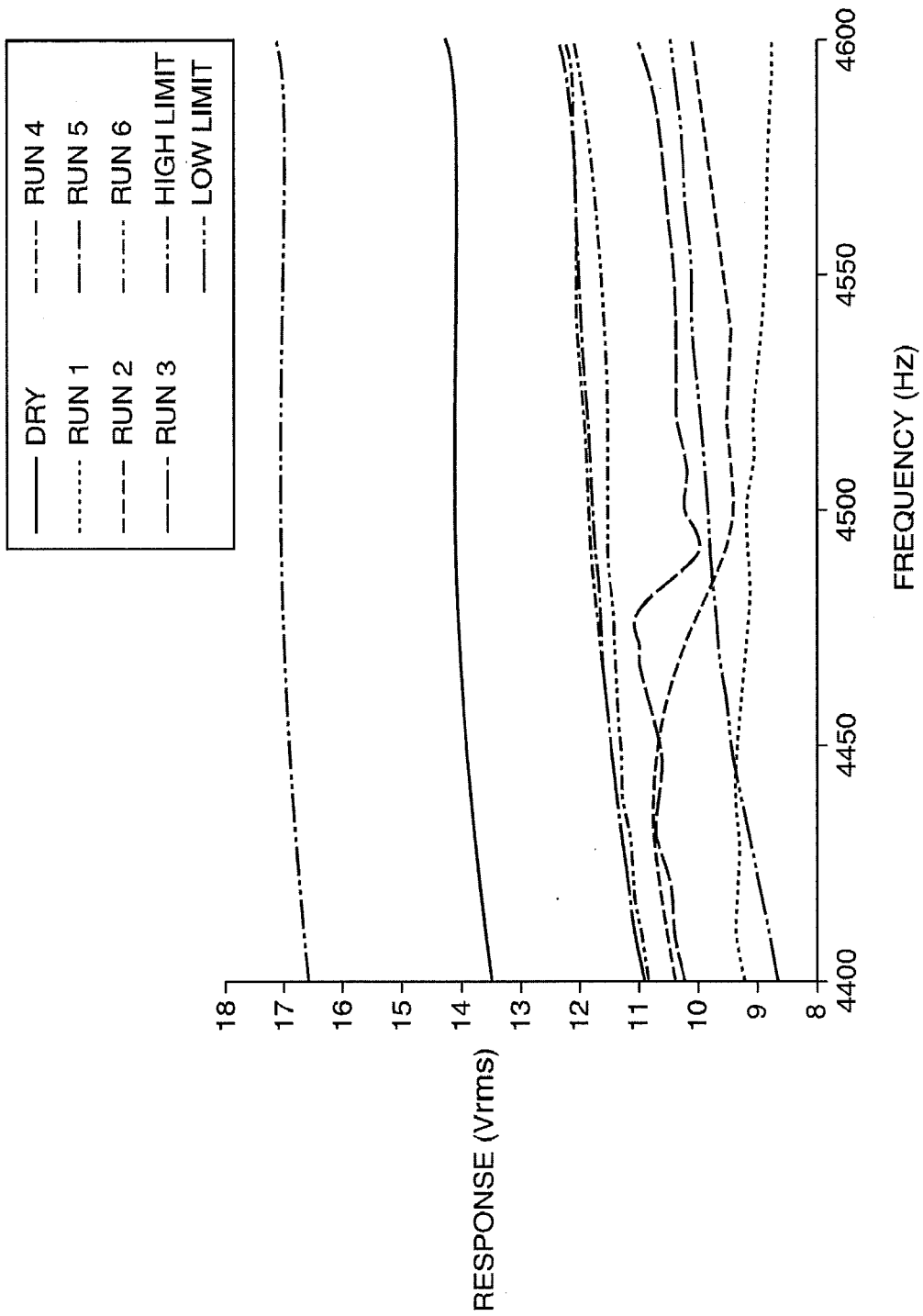


FIG. 16B