New

A SUMMARY

OF

RESEARCHES IN SOUND:

CONDUCTED IN THE SERVICE OF

THE UNITED STATES LIGHT-HOUSE BOARD,

BY

JOSEPH HENRY,

DURING THE YEARS 1865 TO 1877.

[FROM THE SMITHSONIAN REPORT FOR 1878.]

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RESEARCHES IN SOUND:

WITH SPECIAL REFERENCE TO FOG-SIGNALING.

By Joseph Henry.

[From the Annual Reports of the U. S. Light-House Board.]

PREFATORY NOTE.

[The series of investigations undertaken by the late Professor Henry in the interest of the light-house service, embracing not only observations more than usually laborious and extended, with regard to the atmospheric conditions affecting the propagation of sound to a distance, but varied and elaborate experimental inquiries, as well, with reference to the most efficient character and form of sonorous instruments for fog-signaling purposes, commenced as far back as the year 1865, and continued to the last year of his life.

These important investigations, though in the language of an official report, they "have resulted in giving us a fog-signal service conceded to be the best in the world,"[*] have hitherto received so little publicity and attention, owing to the purely official character and channel of their presentation, that their collection and republication here (in advance of of a possible edition of Henry's collected works), appears to be called for in the interests of science, as well as of a just appreciation of the value of his prolonged researches.

The first part, extracted from the Appendix to the Light-House Report for 1874, comprises a preliminary statement and an account of observations and experiments made by the author, from 1865, at New

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[*] Executive Document No. 94, Forty-fifth Congress, second session, Senate, p. 2. This is a report to the Hon. Secretary of the Treasury, made since Professor Henry's death. To a similar effect, may be quoted an official statement made five years earlier. In 1873, Major George H. Elliot, of the Light-House Board, commissioned to make a tour of inspection of European light-house establishments, presented the results of his observations abroad in a very able and elaborate report, published by the Senate in 272 octavo pages, with numerous illustrations. In his preliminary report to the Board, dated September 17, 1873, he concludes, that while there are "many details of construction and administration which we can adopt with advantage," (from the British and French light-house systems,) "there are many in which we excel. Our shore fog-signals, particularly, are vastly superior, both in number and power." (Executive Document No. 54, Forty-third Congress, first session; Senate, p. 12.)

Haven, Conn., to 1872, at Portland, Me. The second part is a communication made to the "Philosophical Society of Washington" (of which he was the president) December 11, 1872, embracing a discussion of some abnormal phenomena of sound, and is extracted from the Bulletin of the Society, vol. ii, appendix ix. The third part, forming the latter portion of the Appendix to the Light-House Report for 1874, comprises investigations extending from 1873, at Whitehead Station, off the coast of Maine, to 1874, at Sandy Hook, New Jersey. The fourth part, extracted from the Appendix to the Light-House Report for 1875, comprises his investigations for that year. And the fifth part, from the Appendix to the Light-House Report of 1877, embraces his latest observations during September and October of the year 1877.

These papers necessarily are more fragmentary, and at the same time involve more recapitulation than would have been the case, could they have received the revision of their distinguished and lamented author. It has however been considered more just to reproduce these contributions in this form, than to attempt either a compilation of extracts, or a condensation of their substance in the form of an abstract.]

S. F. BAIRD.

RESEARCHES IN SOUND.

INTRODUCTION.*

FOG.

Among the impediments to navigation none perhaps are more to be dreaded than those which arise from fogs, and consequently the nature of this impediment and the means which may be devised for obviating it are objects of great interest to the mariner. Fogs are in all cases produced when cold air is mingled with warm air saturated with moisture. In this case the invisible vapor of the warmer air is condensed by the cold into minute particles of liquid water, which, by their immense number and multiplicity of reflecting surfaces, obstruct the rays of light in the same way that a piece of transparent glass when pounded becomes almost entirely opaque and is seen by reflection as a white mass. So greatly does a dense fog obstruct light, that the most intense artificial illumination, such as that produced by the combustion of magnesium, by the burning of oxygen and hydrogen in contact with lime, and that produced between the charcoal points of a powerful electrical apparatus, are entirely obscured at comparatively short distances. Even the light of the sun, which is far more intense than that of any artificial illumination, is so diminished by a single mile of dense fog that the luminary itself becomes invisible. Recourse must therefore be had to some other means than that of light to enable the mariner to recognize his position on approaching the coast when the land is obscured by fog.

The only means at present known for obviating the difficulty is that of employing powerful sounding instruments which may be heard at a sufficient distance through the fog to give timely warning of impending danger. Investigations therefore as to the nature of sound and its applications to fog-signals become an important object to those in charge of aids to navigation. Such investigations are of special importance in connection with the light-house service of the United States. The northeastern coast of the United States on the Atlantic, and the entire western coast on the Pacific, included in our territory, are subject, especially during the summer months, to dense fogs, which greatly impede navigation, as well as endanger life and property.

The origin of the fogs on our coast is readily explained by reference to a few simple principles of physical geography. In the Atlantic Ocean there exists a current of warm water proceeding from the Gulf of Mexico, between Cuba and Florida, which flows along our coast to the lati-

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* From the Report of the Light-House Board, for 1874.

tude of about 35°, and then turning gradually to the eastward, crosses the Atlantic and impinges against the coast of Northern Europe. Throughout its entire course, on account of the immense capacity of water for heat, the temperature of the stream is greater than that of the ocean on either side. In addition to this stream, the Atlantic Ocean is traversed by another current of an entirely opposite character, one of cold water, which, coming from the arctic regions down Davis's Strait, is thrown, by the rotation of the earth, against our coast, passing between it and the Gulf-stream, and sinking under the latter as it approaches the southern extremity of the United States.

These conditions are those most favorable to the production of fogs, since whenever the warm air, surcharged with moisture, is blown from the Gulf-stream over the arctic current and mingles with the cold air of the latter, a precipitation of its vapor takes place in the form of fog. Hence, especially in summer, when the wind in the eastern part of the United States is in a southeasterly direction, fogs prevail. As we proceed southerly along the coast, the fog-producing winds take a more easterly direction.

A somewhat similar circulation in the Pacific Ocean produces fogs on the western coast of the United States. In this ocean a current of warm water, starting from the equatorial regions, passes along the shores of China and Japan, and, following the general trend of the coast, turns eastward and continues along our shore. The northern part of this current being warmer than the ocean through which it passes, tends to produce dense fogs in the region of the Aleutian Islands and the coast of Alaska. As this current descends along the American coast into lower latitudes it gradually loses its warmth, and soon assumes the character, in regard to the water through which it passes, of a comparatively colder stream; and to this cause we would attribute the prevalence of fogs on the coast of Oregon and California, which are most prevalent during the spring and early summer, with wind from the northwest and west.

From what has been said, it is evident that the fogs in the Aleutian Islands occur chiefly in summer, when southwesterly winds prevail and mingle the moist air from the warm current with the colder air of the more northerly latitude. In winter, the wind being from the north chiefly, the moist air is driven in an opposite direction, and dense fogs therefore at this season do not prevail.

In regard to the fogs on the coast of Maine, the following interesting facts were furnished me by the late Dr. Stimpson, formerly of the Smithsonian Institution and of the Chicago Academy of Sciences, who had much experience as to the weather during his dredging for marine specimens of natural history in the region of Grand Manan Island, at the entrance of the Bay of Fundy.

"So sharply marked," says Dr. Stimpson, "is the difference of temperature of the warm water from the Gulf-stream and that of the polar current, that in sailing in some cases only a few lengths of a ship the temperature of the water will change from 70° to 50°. The fog frequently comes rolling in with the speed of a race-horse; in some cases while dredging, happening to turn my eyes to the south, a bank of fog has been seen approaching with such rapidity that there was scarcely time in which to take compass-bearing of some object on shore by which to steer, before I would be entirely shut in, perhaps for days together." He also mentions the fact that it frequently happened during a warm day, while a dense fog existed some distance from the shore, close in to the latter there would be a space entirely clear; this was probably due to the reflection and radiation of the heat from the land, which converted the watery particles into invisible vapor.

Dr. Stimpson has also noticed another phenomenon of some interest. "When a dense fog, coming in regularly from the sea, reaches the land, it gradually rises in the atmosphere and forms a heavy, dark cloud, which is frequently precipitated in rain." This rising of fog is not due, according to the doctor, to a surface-wind from the west pressing under it and buoying it upward, since the wind at the time is from the ocean. It is probably due to the greater heat of the land causing an upward current, which, when once started, by its inertia carries the cloud up to a region of lower temperature, and hence the precipitation. The height of the fog along the coast is not usually very great, and can be frequently overlooked from the mast-head. The deception as to size and distance of objects as seen in a fog is also a remarkable phenomenon when observed for the first time. A piece of floating wood at a little distance is magnified into a large object, and after much experience the doctor was not able to overcome the delusion. It is said that the sailors in the Bay of Fundy prefer of two evils a fog that remains constant in density to one that is variable, although the variation may be toward a greater degree of lightness, on account of the varying intensity producing a varied and erroneous impression of the size and distance of the object seen through it. It is also his impression that sound can be heard as well during fog as in clear weather, although there is a delusion even in this, since the source of sound, when seen, appears at a greater distance than in a clear atmosphere, and hence the sound itself would appear to be magnified.

Fogs also exist on the Mississippi, especially on the lower portion of the river. They are of two classes, those which result from the cooling of the earth, particularly during the summer in clear nights, with wind probably from a northerly direction, followed by a gentle, warm wind from the south surcharged with moisture, and the other induced by the water of the river, which, coming from melting snow of northern regions, is colder than the air in the vicinity. The air over the river being thus cooled below the temperature of a gentle wind from the south, the moisture of the latter is precipitated. This fog, which occurs in the last of winter, during the spring, and beginning of summer, is very dense, but is confined entirely to the atmosphere above the river, while the other class of fog exists over the land as well.

FOG-SIGNALS.

The importance of fog-signals as aids to navigation, especially on the northeastern portion of our coast, of which the shore is exceedingly bold and to the approach of which the sounding-line gives no sure indication, has been from the first an object of special attention.

At the beginning of the operations of the Light-House Board such instruments were employed for producing sound as had been used in other countries; these consisted of gongs, bells, guns, horns, &c. The bells were actuated by clock-machinery, which was wound up from time to time and struck at intervals of regular sequence by which their position might be identified. The machinery, however, by which these bells were struck was of a rude character and exceedingly wasteful of power, the weight continuing to descend during the whole period of operation, including the successive intervals of silence. This defect was remedied by the invention of Mr. Stevens, who introduced an escapement arrangement, similar to that of a clock, which is kept in motion by a small weight, a larger one being brought into operation only during the instant of striking.

Bell-buoys were also introduced at various points. These consisted of a bell supported on a water-tight vessel and rung by the oscillation of the waves, but all contrivances of this kind have been found to be untrustworthy; the sound which they emit is comparatively of feeble character, can be heard at but a small distance, and is frequently inefficient during a fog which occurs in calm weather. Besides this, automatic fog-signals are liable to be interfered with by ice in northern positions, and in all sections to derangement at times when no substitute can be put in their place, as can be in the cases of the bells rung by machinery under the immediate control of keepers. A signal which is liable to be interrupted in its warnings is worse than no signal, since its absence may give confidence of safety in the midst of danger, and thus prevent the necessary caution which would otherwise be employed.

Guns have been employed on the United States coast, first under the direction of General Bates, engineer of the twelfth district, at Point Bonita, San Francisco Bay, California. The gun at this station consisted of a 24-pounder, furnished by the War Department. The necessary arrangements being made, by the construction of a powder-house, and laying of a platform, and employment of a gunner, notice to mariners was given that after the 8th of August, 1856, a signal-gun would be fired every hour and half-hour, night and day, during foggy or thick weather. The first year, with the exception of eighty-eight foggy days, omitted for want of powder, 1,390 rounds were fired. These consumed 5,560 pounds of powder, at a cost of $1,487, pay of gunner and incidentals excluded. The following year the discharges were 1,582, or about one-eleventh of the number of hours and half-hours of the whole time. The fog-gun was found to answer a useful purpose; vessels by the help of it alone having come into the harbor during a fog at night, as well as in the day, that otherwise could not possibly have entered. This signal was continued until it was superseded by a bell-boat. A gun was also used at West Quoddy Head, near the extreme eastern part of Maine. It consisted of a short piece, or carronade, 5 feet long, with a bore of 5¼ inches, charged with four pounds of blasting-powder. The powder was made up in cartridges and kept in chests in the work-house. The gun was only fired on foggy days, when the steamboat running between Boston and Saint John, New Brunswick, was approaching the light-house from the former place. In going in the other direction the signal was not so much required, because in the former case (of approach) the vessel had been for some time out of sight of land, and consequently its position could not be so well known. The firing was commenced with the hearing of the steamer's whistle as she was approaching, and as the wind during the fog at this place is generally from the south, the steamer could be heard five or six miles. The firing was continued as frequently as the gun could be loaded until the steamer answered by a signal of three puffs of its whistle. The number of discharges was from one to six, the latter exhausting a keg of powder valued at $8. The keeper of the light-house acted as gunner, without compensation other than his salary. The cost of powder was paid by the steamboat company. The report of the gun was heard from two to six miles.

This signal has been abandoned,—because of the danger attending its use,—the length of the intervals between the successive explosions,—and the brief duration of the sound, which renders it difficult to determine with accuracy its direction.

The lamented General Bache, of the Light-House Board, adopted a very ingenious plan for an automatic fog-signal, which consisted in taking advantage of a conical opening in the coast, generally designated a blow-hole. On the apex of this hole he erected a chimney which terminated in a tube surmounted by a locomotive-whistle. By this arrangement a loud sound was produced as often as a wave entered the mouth of the indentation. The penetrating power of the sound from this arrangement would not be great if it depended merely on the hydrostatic pressure of the wave, since this, under favorable circumstances, would not be more than that of a column of water 20 feet high, giving a pressure of about 10 pounds to the square inch. The effect however of the percussion might add considerably to this, though the latter would be confined in effect to a single instant. In regard to the practical result from this arrangement, which was continued in operation for several years, it was found not to obviate the necessity of producing sounds of greater power. It is however founded on an ingenious idea, and may be susceptible of application in other cases.

EXPERIMENTS BY PROFESSOR ALEXANDER, IN 1855.

The Light-House Board was not content with the employment alone of the fog-signals in ordinary use, but directed a series of experiments in order to improve this branch of its service. For this purpose the board employed Prof. J. H. Alexander, of Baltimore, who made a report on the subject, which was published among the documents. The investigations of Professor Alexander related especially to the use of the locomotive steam-whistle as a fog-signal, and in his report he details the results of a series of experiments in regard to the nature and adjustment of the whistle, the quantity of steam necessary to actuate it, with suggestions as to its general economy and management. He found, what has since been fully shown, that the power of the sound depends upon the pressure of the steam in the boiler, and the pitch upon the distance between the circular orifice through which the steam issues, and the edge of the bell. He appears however to be under an erroneous impression that the sound is produced by the vibrations of the metal of the goblet or bell, while in fact this latter portion of the apparatus is a resounding cavity, which, as I have shown in subsequent experiments, may be constructed of wood as well as of brass, in order to produce the same effect. Mr. Alexander also mentions the effect of the wind in diminishing the penetrating power of sound when in an adverse direction, either directly or approximately. He also recommends the adoption of an automatic pump to supply the boilers with water, and also to open and shut the valves at the proper intervals for blowing the whistle. He states that the location of a sound can be determined more precisely in the case of loud, high sounds than in that of feebler or lower ones. On this point I am not prepared to concur with him in experiments of my own. In all cases however loud sounds are more desirable than feebler ones, in order that they may be heard at a greater distance above the noise of the surf and that of the wind as it passes through the spars and rigging of vessels.

The board however at this time were not prepared to adopt these suggestions, and an unsuccessful attempt to use a steam-boiler, rendered abortive by the incapacity of the keeper to give it proper attendance, discouraged for a time efforts in this line.

Previous to the investigations of Mr. Alexander, at the expense of the Light House Board, Mr. Daboll, of New London, had for several years been experimenting on his own account with reference to a fog-signal. His plan consisted in employing a reed trumpet, constructed after the manner of a clarionet, and sounded by means of air condensed in a reservoir, the condensation being produced by horse-power operating through suitable machinery. Although the sound of this was more penetrating than that of bells, still the expense and inconvenience of the maintenance of a horse, together with the cost of machinery, prevented its adoption. Mr. Daboll however after this presented to the board a modification of his invention, in which a hot-air engine of Ericsson's patent was substituted as the motive-power, instead of the horse; and the writer of this report, as chairman of the committee on experiments in behalf of the board, examined this invention and reported in favor of its adoption. The other members of the committee made an unfavorable report, on the ground that fog-signals were of little importance, since the mariner should know his place by the character of his soundings in all places where accurate surveys had been made, or should not venture near the coast until the fog was dissipated. The board however established Daboll trumpets at different stations, which have been in constant use up to the present time.

PART I.—INVESTIGATIONS FROM 1865 TO 1872.*

EXPERIMENTS NEAR NEW HAVEN, IN 1865.

The subject of sound, in connection with fog-signals, still continued to occupy the attention of the board, and a series of investigations was made in October, 1865, at the light-house near New Haven, under the direction of the writer of this report, in connection with Commodore, now Admiral, Powell, inspector, and Mr. Lederle, acting engineer of the third district.

The principal object was to compare the sound of bells, of steam-whistles, and other instruments, and the effect of reflectors, and also the operation of different hot-air engines. For this purpose the committee was furnished with two small sailing-vessels. As these were very imperfectly applicable, since they could not be moved without wind, the writer of the report devised an instrument denominated an "artificial ear," by which the relative penetrating power of different sounding bodies could be determined and expressed in numbers by the removal of the observer to a comparatively short distance from the point of origin of the sound. This instrument consisted of a conical horn, made of ordinary tinned sheet-iron, the axis of which was about 4 feet in length, the diameter of the larger end 9 inches, and tapering gradually to 1¾ of an inch at the smaller end. The axis of this horn was bent at the smaller end in a gentle curve, until the plane of the section of the smaller end was at right angles to the perpendicular section of the larger end, so that when the axis of the trumpet was held horizontally and the larger section vertically, then the section of the smaller end would be horizontal. Across the smaller end a thin membrane of gold-beater's skin was slightly stretched and secured by a thread. On this membrane fine sand was strewn. To protect the latter from disturbance by the wind, it was surrounded by a cylinder of glass, cut from a lamp-chimney, the upper end of which was covered with a plate of glass; and, in the improved condi-

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* From the Report of the Light-House Board, for 1874.

tion of the instrument, with a magnifying lens, with which to observe more minutely the motions of the sand. To use this instrument in comparing the relative penetrating power of sound from different sources. as for example from two bells, the axis being held horizontal, the mouth was turned toward one of the bells, and the effect causing agitation of the sand, was noted. The instrument was then removed to a station a little further from the bell, and the effect again noted, the distance being increased, step by step, until no motion in the sand could be observed through the lens. This distance, being measured in feet or yards, gave the number indicating the penetrating power of the instrument under trial. The same experiment was immediately repeated, under the same conditions of temperature, air, wind, &c., with the other sounding apparatus, and the relative number of yards indicating the distance, taken as the penetrating powers of the two instruments. It should be observed, in the use of this instrument, that it is intended merely to concentrate the rays of sound, and not to act as a resounding cavity; since in that case the sound, in unison with the resounding note, would produce effect at a greater distance than one in discord.

The indications of this instrument were compared with the results obtained by the ear in the use of the two vessels, and in all cases were in exact accordance; and it was accordingly used in the following investigations, and has been found of great service in all subsequent experiments on the penetration of sound.

The only precaution in using it is that the membrane shall not be of such tension as to vibrate in unison with a single sound or its octaves; or, in other words, that the instrument must be so adjusted by varying the length of the axis or the tension of the membrane that it shall be in discordance with the sounds to be measured, and only act as a condenser of the sonorous waves.

The first experiments made were with regard to the influence of reflectors. For this purpose a concave wooden reflector had been prepared, consisting of the segment of a sphere of 16 feet radius, and covered with plaster, exposing a surface of 64 square feet. In the focus of this, by means of a temporary railway, a bell or whistle could be readily introduced or withdrawn. The center of the mouth of the bell was placed in the horizontal axis of the reflector. This arrangement being completed, the sound of the bell, with and without the reflector behind it, was alternately observed. Within the distance of about 500 yards the effect was evidently increased, as indicated by the motion of the sand on the membrane, but beyond this the difference was less and less perceptible, and at the limit of audibility the addition of the reflector appeared to us entirely imperceptible. This result was corroborated by subsequent experiments in which a whistle was heard nearly as well in the rear of a reflector as before it. It would appear from these results that while feeble sounds, at small distances, are reflected as rays of light are, waves of powerful sound spread laterally, and even when projected from the mouth of a trumpet, tend at a great distance to embrace the whole circle of the horizon.

Upon this and all the subsequent experiments, as it will appear, the principle of reflection as a means of re-enforcing sound is but slightly applicable to fog-signals. It is evident however that the effect will be somewhat increased by augmenting the size of the reflector, and by more completely inclosing the source of sound in a conical or pyramidal reflector.

Another series of experiments was made to ascertain whether the penetration of the sound was greater in the direction of the axis of the bells, or at right angles to the axis; or, in other words, whether the sound was louder in front of the mouth of a bell or of its rim. The result of this experiment was considered of importance, since, in one of the light-houses, a bell has been placed with the plane of its mouth at right angles to the horizon, instead of being placed, as usual, parallel to the same. The effect on the sound in these two positions was similar to that produced by the bell with a reflector, the noise being greater at a short distance with the mouth toward the observer than when the rim was in the plane of the ear. At a distance however, the difference between the two sounds was imperceptible. In practice therefore it is of very little importance whether the axis of the bell is perpendicular or parallel to the horizon.

The first fog-signal examined in this series of experiments was a double whistle, improperly called a steam-gong, designed principally for a fire-alarm and for signals for the commencement of working-hours in large manufacturing establishments. It consisted of two bells of the ordinary steam-whistle on the same hollow axis, mouth to mouth, with a flat, hollow cylinder between them, through the upper and lower surface of which the circular sheets of steam issue, the vibration of which produces the sound. In the instrument under examination, the upper bell was 20 inches in length of axis, and 12 inches in diameter, and the lower-whistle was of the same diameter, with a length of axis of 14 inches. The note of the shorter bell was a fifth above that of the longer. This arrangement gave a melodious sound, unlike that of the ordinary locomotive-whistle, and on that account had a peculiar merit. The sound was also very loud, and, according to testimony, had been heard under favorable circumstances more than twenty miles. It however required a large quantity of steam to give it its full effect, and the only means to obtain an approximate idea as to this quantity was that afforded by observing its action on a boiler of a woolen manufactory near Newport. It was here blown with a pressure of at least 75 pounds. From theoretical considerations however, it might be inferred that its maximum penetrating power would be not greater than that of a single whistle using the same amount of steam, and this theoretical inference was borne out by the subsequent experiments of General Duane. But from the strikingly distinctive character of its tone it has, in our opinion, an advantage over a single whistle expending an equal quantity of steam.

The fact that the vibration of the metal of the bell had no practical effect on the penetrating power of the sound was proved quite conclusively by winding tightly around each bell, over its whole length, a thick cord, which would effectually stop all vibration. The penetration of the sound produced under this condition was the same as that with the bells free. It is true, the latter produces a difference in the quality of the tone, such as that which is observed in a brass instrument and that of one of wood or ivory. The inventor was not aware that the sound produced was from the resonance of the air within the bell, and not from the metal of the bell itself, and had obtained a patent, not only for the invention of the double whistle, but also for the special compound of metal of which it was composed.

Another apparatus proposed to be used as a fog-signal was presented for examination by the Marine Signal Company, of Wallingford, Conn. It consisted of a curved tube of copper nearly in the form of the letter C, and was supported on an axis passing through the center of the figure. An ordinary bell-whistle was attached to each extremity of the tube, the instrument being placed in a vertical position and partially filled with water, then made to oscillate on its center of support. By this means the air was drawn in at one end and forced out through the whistle at the other. The motion being reversed the air was drawn in at the end through which it had just made its exit and forced out through the whistle at the other. By rocking the instrument, either by hand or by the motion of the vessel, a continued sound could be produced. The motive-power in the former case was muscular energy, and the experiments which were made at this time, as well as all that have been made subsequently, conclusively prove that the penetrating power of the sound for practical use as a fog-signal depends upon the intensity of the motive-energy employed. No instrument operated through levers and pumps by hand-power is sufficient for the purpose.

One of these instruments with two 4-inch whistles gave a sound, as indicated by the artificial ear, the power of which was about one-tenth of that of a steam-trumpet. It was supposed however that this instrument would be applicable for light-ships; and that if extended entirely across the vessel, and armed with whistles of large size, it would be operated by the rolling of the vessel, and thus serve to give warning in time of thick weather. But as it frequently happens that fog exists during a calm, this invention could not be relied upon to give warning in all cases of danger. Besides this, the ordinary roll of a ship is not sufficient to produce a hydrostatic pressure of more than five or six pounds to the square inch, which is insufficient to give an effective sound. It has however been proposed to increase the power by using quicksilver instead of water; but, besides the first cost of this material, and the constant loss by leakage and oxidation, the tendency to affect the health of the crew is an objection to the introduction of this modification of the apparatus into light-ships.

The other instruments which were subjected to trial were an ordinary steam-whistle and a Daboll trumpet. The bell of the whistle was 6 inches in diameter, 9 inches in height, and received the sheet of steam through an opening of one-thirtieth of an inch in width; was worked by a pressure of condensed air of from 20 to 35 pounds per square inch, and blown once in a minute for about five seconds. The air was condensed by a Roper engine of one-horse power. The penetrating power of the sound was increased by an increase in the pressure of the air, and also the pitch. The tone however of the instrument was lowered by increasing the distance between the orifice through which the circular sheet of air issued at the lower rim of the bell or resounding cavity. To prove conclusively that the bell performs the part of a mere resounding cavity, a wooden one, on a subsequent occasion, was substituted for that of metal without a change in the loudness or the pitch of the sound.

The penetrating power of the whistle was compared with a Daboll trumpet, actuated by an Ericsson engine of about the same power; the reservoir for the condensed air of each machine was furnished with a pressure-gauge, and by knowing the capacity of the condensing pumps and the number of strokes required to produce the pressure, the relative amount of power was determined. The result was that the penetrating power of the trumpet was nearly double that of the whistle, and that an equal effect was produced at the same distance by about one-fourth of the power expended in the case of the latter. It must be recollected however, that the whistle sends sonorous waves of equal intensity in every direction, while the greatest power of the trumpet is in the direction of its axis. This difference however is lessened on account of the spreading of the sound to which we have before alluded.* The whistle was blown, as we have said, with a pressure of from 20 to 35 pounds, while the trumpet was sounded with a pressure of from 12 to 15 pounds. In the case of the whistle, the pressure in the reservoir may be indefinitely increased with an increase in the penetrating power of the sound produced, while in the case of the trumpet a pressure greater than a given amount entirely stops the blast by preventing the recoil of the vibrating tongue; this being made of steel, in the larger instruments 2½ inches wide and 8 inches long, would receive a pressure of steam, at only 10 pounds to the square inch, of 200 pounds, tending to press it into the opening and to prevent its recoil, this circumstance limits, as it were, the power of a trumpet of given dimensions. It is however well fitted to operate with a hot-air engine, and is the least expensive in fuel of any of the instruments now employed. The whistle is the simpler and easier of management, although they both require arrangement of machinery in order that they may be operated automatically.

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* It is worthy of note however that in the case of a sound having primarily an axial direction, the subsequent lateral diffusion must result in enfeebling the whole sphere of expanding sound-waves in a more rapid ratio than the square of the distance.

It is a matter of much importance to obtain a hot-air engine of sufficient power, and suitable for working fog-signals of all classes. This will be evident when we consider the difficulty in many cases of obtaining fresh water for producing steam, and the expense of the renewal of the boilers in the use of salt-water, as well as that of the loss of power in frequently blowing out the latter, in addition to the danger of the use of steam by unskillful attendants.

The merits of the two engines however under consideration could not be fully tested by the short trial to which they were subjected during these experiments. The principal objection to the Ericsson engine was the size of the fly-wheel and the weight of the several parts of the machine; the Roper engine was much more compact, and appeared to work with more facility, but from the greater heat imparted to the air the packing was liable to burn out and required to be frequently renewed. Although at first the impression of the committee was in favor of the Roper engine, yet in subsequent trials of actual practice it was found too difficult to be kept in order to be employed for light-house purposes, and its use has consequently been abandoned; another hot-air engine has been employed by the board, the invention of a Mr. Wilcox, which has also been discontinued for a similar reason. I was assured by the person last named, a very ingenious mechanician, that when the several patents for hot-air engines expired, a much more efficient instrument could be devised by combining the best features of each of those now in use.

For determining the relative penetrating power of these instruments, the use of two vessels had been obtained, with the idea of observing the sound simultaneously in opposite directions.

Unfortunately however the location which had been chosen for these experiments was of a very unfavorable character in regard to the employment of sailing-vessels and the use of the artificial ear. It was fully open to the ocean only in a southerly direction, navigation up the bay to the north being limited to three and a half miles, while on shore a sufficient unobstructed space could not be obtained for the proper use of the artificial ear. With these obstructions and the necessity of beating against the wind, thereby constantly altering the direction of the vessel, exact comparisons were not possible, yet the observations made were sufficiently definite to warrant certain conclusions from them as to the relative power of the various instruments submitted to examination.

The following is a synopsis of the observations on four different days. Before giving these however, it is necessary to observe that at each stroke of the piston of the hot-air engine a loud sound was produced by the blowing off of the hot air from the cylinder, after it has done its work. In the following statement of results the noise thus produced is called the exhaust. On the first day but one set of observations was made, the vessel's course being nearly in the line of the axis of the trumpet. The order of penetrating power was as follows: 1, trumpet; 2, exhaust; 3, bell; these instruments being heard respectively at 5⅛, 3½, and 2 miles. The whistle was not sounded.

The second day simultaneous observations were made from two vessels sailing nearly in opposite directions. The results of the observations made on the vessel sailing in a southerly direction were very irregular. The trumpet was heard at 3⅝ miles and lost at 4⅜ miles with the wind slightly in favor of the sound, and heard at 6¼ miles with the wind somewhat against the sound; it was heard even at 7⅝ miles from the masthead, though inaudible from the deck. In all these cases the position of the vessel was nearly in line with the axis of the trumpet.

The whistle and exhaust were heard at 7¼ miles with a feeble opposing wind, and lost at 6¼ miles when the force of the wind became greater.

The order of penetration in this series of observations was: 1, trumpet and gong; 2, whistle; 3, exhaust.

In the case of the vessel sailing northward, its course being almost directly against the wind and in the rear of the trumpet, all the sounds were lost at less distances than in the case of the other vessel. The observations showed very clearly the effect of the wind, the bell at a certain distance being heard indistinctly with a strong opposing wind and more and more plainly as the wind died away. The trumpet was heard only as far as the whistle, the vessel being in the rear of it.

The third day observations were made from the two vessels, both however sailing to the south. From the vessel sailing at right angles to the direction of the wind the order of penetration was: 1, trumpet; 2, whistle; 3, exhaust; 4, bell.

In the case of the other vessel the opposing effect of the wind was greater, and the sounds were heard to a less distance; the order was: 1, trumpet; 2, whistle; 3, exhaust; 4, bell; 5, rocker.

On the fourth day two trips were made by the same vessel in the course of the day, one being northward and the other southward. In the first case the trumpet was lost at 3⅛ miles, the vessel being nearly in its rear; in the second case, the wind being almost directly opposed to the sound, the large bell was heard at 1⅛ miles, and lost at ⅞ of a mile, probably due to increase of the force of the wind; the trumpet was was lost at 3½ miles.

In all these observations, owing to the unfavorable conditions of the locality, and the direction of the wind, we were unable to obtain any satisfactory observations on sound moving with the wind. In all cases the results were obtained from sounds moving nearly against the wind, or at right angles to it. From the results of the whole it appears that the sound was heard farther with a light opposing wind than with a stronger one, and that it was heard farthest of all at right angles to the wind. From this latter fact, however, it should not be inferred that in this case sound could be heard farther at right angles to the wind than with the wind, but that in this direction the effect of the wind was neutralized. The results also exhibited, in a striking manner, the divergency of sound from the axis of the trumpet, the trumpet being heard in the line of its axis in front at 6 miles and behind at 3, the wind being nearly the same in both cases.

All the observations were repeated on land with the artificial ear as far as the unfavorable condition of the surface would permit. Although the limit, as to distance, at which the sand might be moved was not in most cases observed, yet the relative degree of agitation at a given distance established clearly which was the most powerful instrument, the result giving precisely the same order of penetration of the different instruments as determined by direct audition.

During this series of investigations an interesting fact was discovered, namely, a sound moving against the wind, inaudible to the ear on the deck of the schooner, was heard by ascending to the mast-head. This remarkable fact at first suggested the idea that sound was more readily conveyed by the upper current of air than the lower, and this appeared to be in accordance with the following statement of Captain Keeney, who is commander of one of the light-house vessels, and has been for a long time on the banks of Newfoundland in the occupation of fishing: "When the fishermen in the morning hear the sound of the surf to the leeward, or from a point toward which the wind is blowing, they take this as an infallible indication that in the course of from one to five hours the wind will change to the opposite direction from which it is blowing at the time." The same statement was made to me by the intelligent keeper of the fog-signal at Block Island. In these cases it would appear that the wind had already changed direction above, and was thus transmitting the sound in an opposite direction to that of the wind at the surface of the earth.

Another remarkable fact bearing on this same point is established by the observations of General Duane. At Cape Elizabeth, 9 miles southeasterly from the general's house, at Portland, is a fog-signal consisting of a whistle 10 inches in diameter; at Portland Head, about 4 miles from the same city, in nearly the same direction, is a Daboll trumpet. There can be no doubt, says the general, that those signals can be heard much better during a heavy northeast snow-storm than at any other time. "As the wind increases in force, the sound of the nearer instrument, the trumpet, diminishes, but the whistle becomes more distinct; but I have never known the wind to blow hard enough to prevent the sound of the latter from reaching this city." In this case, the sound comes to the city in nearly direct opposition to the course of the wind, and the explanation which suggested itself to me was that during the continuance of the storm, while the wind was blowing from the northeast at the surface, there was a current of equal or greater intensity blowing in an opposite direction above, by which the sound was carried in direct opposition to the direction of the surface current. The existence of such an upper current is in accordance with the hypothesis of the character of a northeast storm, which sometimes rages for several days at a given point on the coast without being felt more than a few miles in the interior, the air continuously flowing in below and going out above. Indeed, in such cases a break in the lower clouds reveals the fact of the existence above of a rapid current in the opposite direction.

The full significance, however, of this idea did not reveal itself to me until in searching the bibliography of sound I found an account of the hypothesis of Professor Stokes in the Proceedings of the British Association for 1856,* in which the effect of an upper current in deflecting the wave of sound so as to throw it down upon the ear of the auditor, or directing it upward far above his head, is fully explained. This subject will be referred to in the subsequent parts of the report, in the attempt to explain various abnormal phenomena of sound which have been observed during the series of investigations connected with the Light-House Board.

During these investigations an attempt was made to ascertain the velocity of the wind in an upper stratum as compared with that in the lower. The only important result however, was the fact that the velocity of the shadow of a cloud passing over the ground was much greater than that of the air at the surface, the velocity of the latter being determined approximately by running a given distance with such speed that a small flag was at rest along the side of its pole. While this velocity was not perhaps greater than six miles per hour, that of the shadow of the cloud was apparently equal to that of a horse at full speed.

During this and subsequent investigations, inquiries were made in regard to the effect of fog upon sound, it being a subject of considerable importance to ascertain whether waves of sound, like the rays of light, are absorbed or stifled by fog. On this point, however, observers disagree. At first sight, from the very striking analogy which exists in many respects between sound and light, the opinion largely prevails that sound is impeded by fog; although observers who have not been influenced by this analogy have, in many instances, adopted the opposite opinion, that sound is better heard during a fog than in clear weather. For instance, the Rev. Peter Ferguson, of Massachusetts, informs me that from his own observations, sound is conveyed farther in a fog than in a clear air. He founds this opinion on observations which he has made on the sound of locomotives of several railways in passing over bridges at a distance. Unfortunately, the question is a difficult one to settle, since the effect of the wind, in order to arrive at a true result, must be carefully eliminated. Captain Keeney, who has previously been mentioned, related the following occurrence, in the first part of which he was led to suppose that fog had a very marked influence in deadening sound, though in a subsequent part he came to an opposite conclusion: He was sailing during a dense fog, with a slight wind bear-

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* Report of British Association, 1856; Abstracts, p. 22.

ing him toward a light-vessel, the locality of which he expected to find by means of the fog-signal. He kept on his course until he thought himself very near the ship, without hearing the stroke of the bell. He then anchored for the night, and found himself next morning within a short distance of the light-vessel, but still heard no sound, although he was assured when he got to it that the bell had been ringing all night. He then passed on in the same direction in which he had previously sailed, leaving the light-vessel behind, and constantly heard the bell for a distance of several miles, the density of the fog not perceptibly diminishing. In this case it is evident that the deadening of the sound was not due to the fog, but, as we shall hereafter see, in all probability to the combined action of the upper and the lower currents of air.

On returning to Washington the writer took advantage of the occurrence of a fog to make an experiment as to the penetration of the sound of a small bell rung by clock-work, the apparatus being the part of a moderator-lamp intended to give warning to the keepers when the supply of oil ceased. The result of the experiment was contrary to the supposition of absorption of the sound by the fog, but the change in the condition of the atmosphere as to temperature and the motion of the air, before the experiment could be repeated in clear weather, rendered the result not entirely satisfactory.

EXPERIMENTS AT SANDY HOOK IN 1867.

The next series of experiments was made from October 10 to October 18, 1867, under the direction of the writer of this report, in connection with General Poe, engineer-secretary of the Light-House Board, Commodore (now Admiral) Case, then inspector of the third light-house disdistrict, and Mr. Lederle, acting engineer of the same district.

The principal object of these investigations was to compare different instruments, and to ascertain the improvements which had been made in them since the date of the last investigations, especially the examination of a new fog-signal called the siren, and the comparison of it with the Daboll trumpet, although other investigations were made relative to the general subject of sound in relation to fog-signals. The locality chosen was Sandy Hook, a narrow peninsula projecting northward, about five miles into the middle of the Lower Bay of New York, and almost at right angles to its coast, having a width of about half a mile. Near the northern point on the east shore a temporary building was erected for the shelter of the engines and other instruments.

The comparisons in regard to penetrating power were made by the use of the artificial ear, heretofore described, by carrying this off a measured distance until the sand ceased to move. This operation was much facilitated by previous surveys of members of the Engineer Corps, who had staked off a straight line parallel with the shore, and accurately divided it into equal distances of 100 feet.

On account of the character of the deep and loose sand, walking along this distance was exceedingly difficult, and, to obviate this, a carriage with broad wheels, drawn by two horses, was employed. An awning over this vehicle protected the observer from the sun, and enabled him, without fatigue and at his ease, to note the agitations of sand on the drum of the artificial ear, the mouth of which was directed from the rear of the carriage toward the sounding instrument.

For these and other facilities we were indebted to General Humphreys, Chief of the Engineer Bureau, who gave orders to the officer in charge of the military works at Sandy Hook to afford us every aid in his power in carrying on the investigation.

The instruments employed were—

1st. A first-class Daboll trumpet (the patent for which—since the death of Mr. Daboll, is owned by Mr. James A. Robinson,) operated by an Ericsson hot-air engine. It carried a steel reed 10 inches long, 2¾ inches wide, and ½ inch in thickness at the vibrating end, but increasing gradually to an inch at the larger extremity. This was attached to a large vertical trumpet curved at the upper end into a horizontal direction and furnished with an automatic arrangement for producing an oscillation of the instrument of about 60° in the arc of the horizon. Its entire length, including the curvature, was 17 feet. It was 3½ inches at the smaller end and had a flaring mouth 38 inches in diameter. The engine had a cylinder 32 inches in diameter, with an air-chamber of 4½ feet in diameter and 6 feet long, and was able to furnish continually a five-second blast every minute at a pressure of from 15 to 30 pounds.

2d. A siren, originally invented by Cagniard de Latour, and well known to the physicist as a means of comparing sounds and measuring the number of vibrations in different musical notes. Under the direction of the Light-House Board, Mr. Brown, of New York, had made a series of experiments on this instrument in reference to its adoption as a fog-signal, and these experiments have been eminently successful. The instrument as it now exists differs in two essential particulars from the original invention of Latour: 1st, it is connected with a trumpet in which it supplies the place of the reed in producing the agitation of the air necessary to the generation of the sound; and 2d, the revolving disk, which opens and shuts the orifices producing the blasts, is driven not by the blast itself impinging on oblique openings, as in the original instrument, but by a small engine connected with the feed-pump of the boiler.

The general character of the instrument may be understood from the following description: Suppose a drum of short axis, into one head of which is inserted a steam-pipe connected with a locomotive-boiler, while the other end has in it a triangular orifice, through which the steam is at brief intervals allowed to project itself. Immediately before this head, and in close contact with it, is a revolving disk, in which are eight orifices. By this arrangement, at every complete revolution of the disk, the orifice in the head of the drum is opened and shut eight times in succession, thus producing a rapid series of impulses of steam against the air into the smaller orifice of the trumpet placed immediately in front of the revolving disk. These impulses are of such intensity and rapidity as to produce a sound unrivalled in magnitude and penetrating power by that of any other instrument yet devised.

The siren was operated by an upright cylindrical tubular boiler, with a pressure of from 50 to 100 pounds on the square inch. For this form of boiler has been subsequently substituted an ordinary horizontal locomotive-boiler with a small engine attached for feeding it and for rotating the disk, the latter being effected by means of a band passing over pulleys of suitable relative dimensions.

3d. A steam-whistle 8 inches in diameter. Through some misunderstanding a series of whistles of different diameters was not furnished as was intended.

The first experiments to be noted were those in regard to the comparison of penetrating power of the siren and the whistle, the fitting up of the Daboll trumpet not having been completed. The principal object of this however was to test again the truthfulness of the indications of the artificial ear in comparison with those of the natural ear.

An experiment was made both by means of the artificial ear on land and by actually going off on the ocean in a steamer until the sounds became inaudible to the natural ear. By the latter method the two sounds ceased to be heard at the distances of six, and twelve and a half miles, respectively. The indications of the artifical ear gave a similar result, the distance at which the sand ceased to move in one case being double that of the other. In both cases the conditions of wind and weather were apparently the same. In the case of the steamer the distance was estimated by noting the interval of time between the flash of steam and the perception of the sound.

Comparison of the Daboll trumpet and the siren.—The pressure of the hot air in the reservoir of the hot-air engine of the trumpet was about 20 pounds, and that of the steam in the boiler of the siren about 75 pounds. These pressures are however not considered of importance in these experiments, since the object was not so much to determine the relative amount of motive power employed as the amount of penetrating power produced by these two instruments, each being one of the first of its class.

1. At distance 50 the trumpet produced a decided motion of the sand, while the siren gave a similar result at distance 58. The two observations being made within ten minutes of each other, it may be assumed that the condition of the wind was the same in the two cases, and hence the numbers above given may be taken as the relative penetrating power of the two instruments.

2. Another series of experiments was instituted to determine whether a high or a low note gave the greatest penetration. For this purpose the

siren was sounded with different velocities of rotation of the perforated disk, the pressure of steam remaining at 90 pounds per square inch. The effect upon the artificial ear in causing greater or less agitation of sand was taken as the indication of the penetrating power of the different tones. The number of revolutions of the disk in a given time was determined by a counting apparatus, consisting of a train of wheels and a series of dials showing tens, hundreds, and thousands of revolutions; this was temporarily attached to the projecting end of the spindle of the revolving disk by pushing the projecting axis of the instrument into a hole in the end of the spindle.

From the whole of this series of experiments it appeared that a revolution which gave 400 impulses in a second was the best with the siren when furnished with a trumpet. On reflection however it was concluded that this result might not be entirely due to the pitch, but in part to the perfect unison of that number of impulses of the siren with the natural tone of the trumpet. To obviate this complication, a series of experiments was next day made on the penetration of different pitches with the siren alone, the trumpet being removed. The result was as follows:

The siren was sounded at five different pitches, the artificial ear being at such a distance as to be near the limit of disturbance by the sound. In this condition the lowest pitch gave no motion of sand. A little higher, slight motion of sand. Still higher, considerable motion of sand; and with a higher pitch again, no motion of sand. The best result obtained was with a revolution which gave 360 impulses in a second.

3. An attempt was made to determine the most effective pitch or tone of the steam-whistle. It was started with what appeared to be the fundamental note of the bell, which gave slight motion of sand; a higher tone a better motion; still higher, sand briskly agitated; next, several tones lower, no motion; higher, no motion; still higher, no motion. The variation in the tone was made by altering the distance between the bell and the orifice through which the steam was ejected.

The result of this experiment indicated nothing of a definite character, other than that with a given pressure there is a maximum effect produced when the vibrations of the sheet of air issuing from the circular orifice are in unison with the natural vibrations from the cavity of the bell, a condition which can only be determined in any case by actual experiment. In practice, Mr. Brown was enabled to produce the best effect by regulating the velocity until the trumpet gave the greatest penetrating power, as indicated by an artificial ear of little sensibility, in order that it might be employed for determining the relative power while the observer was but a few yards from the machine.

These experiments have been made in an apartment of less than 80 feet in length, in which the sounding apparatus was placed at one end and the artificial ear at the other, substituting fine shot instead of sand.

The experiments with the siren however indicate the fact that neither the highest nor the lowest pitch of an instrument gives the greatest penetrating power, but one of a medium character.

Another element of importance in the construction of these instruments is the volume of sound. To illustrate this, it may be mentioned that a harpsichord-wire stretched between two strings of India rubber, when made to vibrate by means of a fiddle-bow, gives scarcely any appreciable sound. We attribute this to the want of quantity in the aerial wave; for if the same wire be stretched over a sounding-board having a wide area, the effect will be a comparatively loud sound, but of less duration, with a given impulse. It was therefore suggested that the width of the reed in the Daboll trumpet, the form and size of the holes in the disk of the siren, and the circumference of the vibrating sheet of air issuing from the circular orifice of the whistle, would affect the power of the sound. The only means of testing this suggestion is by using reeds of different widths, sirens with disks of different-shaped openings, and whistles of different diameters. In conformity with this view, Mr. Brown has made a series of empirical experiments with openings of different forms, which have greatly improved the operation of the siren, while Mr. Wilcox has experimented on several forms of reeds, of which the following is the result:

The best reed obtained was $2\frac{1}{4}$ inches wide, 8 inches long in the vibrating part, $\frac{5}{8}$ inch thick at the butt, and $\frac{1}{4}$ inch thick at the free end. This sounded at a pressure of from 20 to 30 pounds. The thinner reeds gave a sound at a less pressure, from 5 to 10 pounds, the thicker at from 20 to 30 pounds. A reed $8\frac{1}{2}$ inches long in the vibrating part, 1 inch thick at the butt, $\frac{3}{4}$ inch thick at the end, and 3 inches wide, did not begin to sound until a pressure of 80 pounds was reached, then gave a sound of a dull character. Another reed of the same width, $\frac{5}{8}$ inch thick at the butt, and $\frac{7}{16}$ inch at the end, and same length, gave a sound at 75 pounds pressure, but still dull and of little penetrating power. These reeds were evidently too heavy in proportion to their elasticity. These were made without the addition of a trumpet, and therefore to produce the best result when used with a trumpet, the latter must be increased or diminished in length until its natural vibrations are in harmony with those of the former, as will be seen hereafter. General Duane has also made experiments on whistles of different diameters, of which the result will be given.

Another consideration in regard to the same matter is that of the amplitude of the oscillations of the tongue or steel reed in its excursion in producing the sound; the time of oscillation remaining the same, that is, the pitch, the amplitude will depend upon the elasticity of the reed, the power to surmount which will again depend upon the pressure of steam in the boiler, and hence we might infer that an increase of pressure in the boiler with an increase of the elasticity of the reed, everything else being the same, would produce an increase in penetrating power. From the general analogy of mechanical effects produced by motive power, we may denote the effect upon the ear by the expression mv^2, in which m expresses the mass or quantity of air in motion, and v the velocity of the particles in vibration.

If this be the expression for the effect upon the ear, it is evident that in case of a very high note the amplitude of the vibration must be so small that the effect would approximate that of a continued pressure rather than that of distinct alternations of pressure, giving a vibrating motion to the drum of the ear.

4. Next, experiments were made to determine the penetrating power in the case of the siren under different pressures of steam in the boiler. The experiments commenced with a pressure of 100 pounds. The pressure at each blast was noted by two observers, and to compare these pressures with the indications of the sand, the time of the blasts was also noted.

The following are the results:

Pressure.	Relative distances at which the sand ceased to move.
100	61
90	59
80	58
70	57
60	57
50	56
40	55
30	53
20	51

From this series of experiments, it appears that a diminution of pressure is attended with a comparatively small diminution in the penetrating power of the siren.

In regard to this unexpected result of great practical importance, the following appears to be the explanation. It is a well-known principle in aerial mechanics that the velocity of the efflux of air from an orifice in a reservoir does not increase with an increase of condensation, when the spouting is into a vacuum. This is evident when we reflect that the weight of density of the air moving out is increased in proportion to the elasticity or pressure; that is, the increase in the propelling force is proportional to the increase in the weight to be moved, hence the velocity must remain the same.

In the foregoing experiments with high pressures large in proportion to the resistance of the air, the velocity of efflux should therefore be but little increased with the increase of pressure, and inasmuch as the velocity is the most important factor in the expression mv^2, which indicates the effect on the tympanum, the penetrating power of the sound should be in accordance with the above experimental results.

A similar result cannot be expected with the use of the whistle or the trumpet, since in the former the stiffness of the aerial reed depends upon its density, which will be in proportion to the pressure in the boiler, and in the case of the latter no sound can be produced on the one hand unless the pressure be sufficient to overcome the resistance of the reed, and on the other the sound must cease when the pressure is so great as to prevent the recoil of the reed.

5. An experiment was made to determine the effect of a small whistle inserted into the side of a trumpet near the small end. The whistle being sounded before and after it was placed in the trumpet, the result was as follows: The penetrating powers were in the ratio of 40: 51, while the tone was considerably modified. From this experiment it appears that a whistle may be used to actuate a trumpet or to exercise the functions of a reed. In order however to get the best results, it would be necessary that the trumpet and whistle should be in unison, but it may be doubted however whether an increase of effect, with a given amount of power, would result from using such an arrangement; it might nevertheless be of advantage in certain cases to direct the sound of a locomotive in a definite direction, and to use a smaller whistle, especially in cities, in which the locomotive passes through long streets; perhaps in this case the sound might be less disagreeable than that of the naked whistle, which sends its sound-waves laterally with as much force as in the direction of the motion of the engine.

6. General Poe called attention to the sound produced by the paddle-wheels of a steamer in the offing at a distance estimated at four and a half miles. The sound was quite distinct when the ears were brought near the surface of the beach.

In this connection he stated that he had heard the approach of a small steamer on the northern lakes when its hull was still below the horizon, and was even enabled to designate the particular vessel from among others by the peculiarity of the sound.

The sound in the case of the steamer is made at the surface of the water, and it might be worth the trouble to try experiments as to the transmission of sound under this condition, and the collection of it by means of ear-trumpets, the mouths of which are near the water, the sound being conveyed through tubes to the ears of the pilot. In order however to determine in this case the direction of the source of sound, two trumpets would be necessary, one connected with each ear, since we judge of the direction of a sound by its simultaneous effects on the two auditory nerves. This suggestion, as well as many others which have occurred in the course of these researches, is worthy of special investigation.

7. A series of experiments was made to compare trumpets of different materials and forms having the same length and transverse areas, all blown at a pressure of 9½ pounds.

The following table gives the results:

No.	Material of trumpet.	Cross-section.	Relative distances at which the sand ceased to move.
1	Wood.	Square.	13
2	Brass.	Circular.	23
3	Cast iron.	Circular.	24
4	Wood.	Circular.	30

From these experiments it would appear that the material or elasticity of the trumpet had little or no effect on the penetrating power of the sound, although the shape appeared to have some effect, the pyrimidal trumpet, or one with square cross-section (No. 1), giving a less result than the conical ones of the same sectional area. A comparison was made between a long straight trumpet and one of the same length curved at its upper end, which gave the same penetrating power with the same pressure. It is probable that a thin metallic trumpet would give greater lateral divergency to the sound, and also a slightly different tone.

8. The effect of a hopper-formed reflector was next tried with the whistle, the axis of which was about 5 feet in length, the mouth 6 feet square, and the small end about 18 inches. When the whistle was sounded at the small end of this reflector, the distance at which the sand ceased to move was 51; the sound of the same whistle without the reflector ceased to move the sand at 40. The ratio of these distances would have been less with a more sensitive instrument at a greater distance on account of the divergency of the rays.

9. In order to determine the diminution of sound by departing from the axis of the trumpet, a series of experiments was made with a rotating trumpet, the axis of which was at first directed along the graduated line of observation, and subsequently deflected from that line a given number of degrees. The following were the results:

Direction of the trumpet.	Relative distance at which sand moved.
Along the line	26
Deflected 30°	23
Deflected 60°	21
Deflected 90°	18
Deflected 120°	13

These results illustrate very strikingly the tendency of sound to spread on either side of the axis of the trumpet; had the experiments been made with a more sensitive instrument, and at a greater distance, the effect would have shown a much greater divergency. It should be observed however that the mouth of the trumpet in this case was 36 inches, which is unusually large.

From the experiments made near New Haven, and also from those at this station, it appears that the actual amount of power to produce sound of a given penetration is absolutely less with a reed trumpet than with a locomotive whistle. This fact probably finds its explanation in the circumstance that in each of these instruments the loudness of the sound is due to the vibration of the air in the interior of the trumpet and in the bell of the whistle, each of these being a resounding cavity; and furthermore that in these cavities the air is put in a state of sustained vibration by the undulations of a tongue, in the one case of metal, in the other of air; and furthermore it requires much more steam to set the air in motion by the tongue of air than by the solid tongue of steel, the former requiring a considerable portion of the motive power to give the current of which it consists the proper degree of stiffness, if I may use the word, to produce the necessary rapidity of oscillation. But whatever may be said in regard to this supposition, it is evident, in case reliable hot-air engines cannot be obtained, that the Daboll trumpet may be operated by a steam-engine, although at an increased cost of maintenance, but this increase we think will still not be in proportion to the sound obtained in comparison with the whistle.

Another question which naturally arises, but which has not yet been definitely settled by experment, is whether both the siren and the whistle would not, equally with the trumpet, give more efficient results when worked by condensed air than by steam.

From hypothetical considerations this would appear to be the case, since the intensity of sound depends upon the density of the medium in which it is produced; and as the steam is considerably lighter than air, and as the cavities of all of these instruments are largely filled with steam, the intensity of sound would, on this account, seem to be less than if filled with air.

At the conclusion of the experiments at Sandy Hook, the siren was adopted as a fog-signal, in addition to the reed-trumpet and the locomotive-whistle, to be applied to the more important stations, while large bells were retained for points at which fog-signals were required to be heard at but comparatively small distances. These instruments of the first class being adopted, it became of importance to determine, in actual practice, the cost of maintenance, the best method of working them, and any other facts which might have a bearing on their use.

But as investigations of this kind would require much time and peculiar advantages as to location and mechanical appliances, this matter was referred to General Duane, the engineer in charge of the 1st and 2d light-house districts, who had peculiar facilities near his residence, at Portland, Me., in the way of workshops and other conveniences, and who, from his established reputation for ingenuity and practical skill in mechanism, was well qualified for the work. The assignment of this duty to General Duane by the Light-House Board was made during my absence in Europe, in 1870, and as my vacation in 1871 was devoted to light-house duty in California, I had no opportunity of conferring with him on the subject until after his experiments were completed. His results are therefore entirely independent of those obtained under my direction, and I give them herewith in his own words, with such comments as they may suggest and as are necessary to a proper elucidation of the subject.

EXPERIMENTS AT PORTLAND, ME. 1871, BY GENERAL DUANE.

The apparatus employed consisted of the first-class siren, first-class Daboll trumpet and steam-whistles of various sizes.

The points to be decided were:

1st. The relative power of these machines; *i. e.*, the distances at which they could be heard under various conditions of the atmosphere.

2d. The amount of fuel and water consumed by each.

3d. The attention and skill required in operating them.

4th. Their endurance.

5th. Whether they are sufficiently simple in construction to permit of their being managed and kept in running order by the class of men usually appointed light-house keepers.

In conducting these experiments the following method was pursued:

The signals were sounded at alternate minutes, and their sound compared at distances of two, three, and four miles, and from different directions. On every occasion the quantity of fuel and water consumed per hour by each was carefully noted, and the condition of each machine examined, both before and after the trial, to ascertain whether any of its parts had sustained injury.

Before giving the results of these experiments some facts should be stated, which will explain the difficulty of determining the power of a fog-signal.

There are six steam fog-whistles on the coast of Maine; these have been frequently heard at a distance of twenty miles, and as frequently cannot be heard at the distance of two miles, and this with no perceptible difference in the state of the atmosphere.

The signal is often heard at a great distance in one direction, while in another it will be scarcely audible at the distance of a mile. This is not the effect of wind, as the signal is frequently heard much farther against the wind than with it. For example, the whistle on Cape Elizabeth can always be distinctly heard in Portland, a distance of nine miles, during a heavy northeast snow-storm, the wind blowing a gale directly from Portland toward the whistle.

[In this sentence, General Duane certainly does not intend to convey the idea that a signal is frequently heard "at a much greater distance against the wind than with it," since this assertion would be at variance with the general experience of mankind; but the word "frequently" applies to the whistle on Cape Elizabeth, which has been already mentioned as a remarkably exceptional case, in which the sound is heard best against the wind during a northeast snow-storm.]

The most perplexing difficulty, however, arises from the fact that the signal often appears to be surrounded by a belt, varying in radius from one to one and a half miles, from which the sound appears to be entirely absent. Thus, in moving directly from a station, the sound is audible for the distance of a mile, is then lost for about the same distance, after which it is again distinctly heard for a long time. This action is common to all ear-signals, and has been at times observed at all the stations, at one of which the signal is situated on a bare rock twenty miles from the main-land, with no surrounding objects to affect the sound.

All attempts to re-enforce the sound by means of reflectors have hitherto been unsuccessful. Upon a large scale, sound does not appear, on striking a surface, to be reflected after the manner of light and heat, but to roll along it like a cloud of smoke.

[This statement is in a measure in accordance with results which I have previously found in connection with investigations at the lighthouse near New Haven, in which the conclusion was arrived at, that although rays of feeble sounds, and for a short distance, observe the law that the angle of reflection is equal to the angle of incidence after the manner of light, yet powerful sounds tend to diverge laterally to such a degree as to render reflectors of comparatively little use.]

In view of these circumstances, it will be obvious that it was extremely difficult to determine the extent of the power of the various signals under examination.

It should be remembered that while the sound from the whistle is equally distributed in all directions,* that from the two other signals, both of which are provided with trumpets, is not so distributed.

[The difference is apparent near by, but, as we have seen before, on account of the tendency of sound to spread it is imperceptible at a distance.]

In the siren the sound is most distinct in the axis of the trumpet.

In the Daboll trumpet it is usually strongest in a plane perpendicular to this axis.

[This is at variance directly with any observation I have myself made.]

Relative power.—From the average of a great number of experiments the following result was obtained:

The power of the first-class siren, 12″ whistle, and first-class Daboll trumpet, may be expressed by the numbers 9, 7, 4.

The extreme limit of sound of the siren was not ascertained. That of the 12″ whistle is about twenty miles, and of the trumpet twelve.

Consumption of fuel and water.—The siren, when working with a pressure of 72 pounds of steam, consumes about 180 pounds of coal and 126 gallons of water per hour.

The 12″ whistle, with 55 pounds pressure of steam, consumes 60 pounds of coal and 40 gallons of water per hour.

The Daboll trumpet, with 10 pounds pressure of air in the tank, consumes about 20 pounds of coal per hour.

The relative expenditure of fuel would be: siren, 9; whistle, 3; trumpet, 1.

The siren.—Of the three machines this is the most complicated. It uses steam at a high pressure, and some of its parts move with very great velocity, the siren spindle making from 1,800 to 2,400 revolutions per minute. The boiler must be driven to its full capacity in order to furnish sufficient steam. A large quantity of steam is, at intervals, suddenly drawn from the boiler, causing a tendency to foam, and to eject a considerable amount of water through the trumpet.

The constant attention of the keeper is required to regulate the fire, the supply of water to the boiler, of oil to the journals, &c.

In general terms, it may be stated that the siren requires more skill and attention in its management than either of the other signals.

The Daboll trumpet.—As the caloric engine, which has been hitherto employed to operate this signal, requires little fuel, no water, and is perfectly safe as regards danger from explosion, it would, at the first glance, appear to be the most suitable power that could be applied to fog-signals, and was accordingly at first exclusively adopted for this purpose. It was however found to be so liable to accident and so difficult to repair that of late years it has been almost entirely rejected. In the steam-boiler the furnace is surrounded by water, and it is impossible, under ordinary circumstances, to heat the metal much above the temperature of the water. The furnace of the caloric engine is surrounded by air, and is therefore liable to be burned out if the fire is not properly regulated.

The working-piston is packed with leather, and as it moves horizontally, with its whole weight resting on the lower side of the cylinder, the packing at its lower edge is soon worn out.

If the engine is allowed to stop with the piston at the furnace-end of the cylinder,

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* The sound of the whistle is equally distributed horizontally. It is, however, much stronger in the plane containing the lower edge of the bell than on either side of this plane. Thus, if the whistle is standing upright, in the ordinary position, its sound is more distinct in a horizontal plane passing through the whistle than above or below it.

the leather is destroyed by the heat. The repacking of a piston is a difficult and expensive operation, requiring more skill than can be expected among the class of men from whom light-house keepers are appointed.

Another accident to which these engines are subject arises from a sudden check in the velocity of the piston, caused either by the jamming of the leather packing or the introduction of dirt into the open end of the cylinder, in which case the momentum of the heavy, eccentrically-loaded fly-wheel is almost sure to break the main rocker-shaft.

The expense of repairs is considerably increased by the fact that these engines are not now in general use, and when important repairs are required it is usually necessary to send to the manufacturer.

This signal requires much attention. The fires must be carefully regulated to avoid burning out the furnace, the journals thoroughly oiled, and the cylinders well supplied with tallow.

The steam-whistle.—This machine requiring much less steam than the siren in proportion to the size of its boiler, there is not the same necessity for forcing the fire; the pressure of steam required is less, and the point from which it is drawn much higher above the water-level in the boiler, and there is consequently no tendency to foam.

The machinery is simple; the piston pressure very light, producing but little strain on the different parts of the engine, which is therefore not liable to get out of order and requires no more attention than a common stationary engine.

One marked advantage possessed by this signal is that should the engine become disabled, the whistle may still be sounded by working the valve by hand. This is not the case with the two others, where an accident to any part of the machinery renders the signal for the time useless.

It will thus be seen that the siren is the most expensive of the fog-signals as regards maintenance, and that it is adapted only to such stations as are abundantly supplied with water and situated in the vicinity of machine-shops where the necessary repairs can be promptly made.

On the other hand, as it is the most powerful signal. there are certain stations where it should have the preference; as, for example, Sandy Hook, which from its importance demands the best signal that can be procured, regardless of cost. Such stations should be provided with duplicate apparatus, well supplied with spare parts, to guard against any possibility of accident.

There should be a keeper whose sole business must be to attend the signal, and who should have sufficient mechanical skill to make the ordinary repairs. He should moreover be a licensed engineer.

There will also be required an assistant, who may be one of the light-keepers, to relieve him during the continuance of foggy weather.

The steam-whistle is the simplest in construction, most easily managed and kept in repair, and requires the least attention of all the fog-signals. It is sufficiently powerful for most localities, while its consumption of fuel and water is moderate.

It has been found on this coast that a sufficient quantity of rain-water can be collected to supply the 12″ whistle at nearly every station. This has been the case for the last two years at Martinicus.

The Daboll trumpet, operated by a caloric engine, should only be employed in exceptional cases, such as at stations where no water can be procured, and where, from the proximity of other signals, it may be necessary to vary the nature of the sound.

The trumpet however may undoubtedly be very much improved by employing steam power for condensing the air. The amount of work required, which is that of compressing 70 cubic feet of air to an average pressure of 8 pounds per inch, would be less than two-horse power. For this purpose the expenditure of fuel and water would be moderate; indeed, the exhaust steam could be condensed and returned to the cistern, should the supply of water be limited.

The siren also is susceptible of improvement, especially as regards simplification.

[In the foregoing remarks we think the general has expressed a somewhat undue partiality for the whistle, and somewhat overestimated the defects of the other instruments. The trumpets, with Ericsson engine, have not been abandoned, except partially in the two districts under the direction of General Duane, to which he probably intended to confine his statement. They are still in use in the third district, where they are preferred by General Woodruff, who finds no difficulty in keeping them in repair, having employed a skilled machinist who has made these instruments his special study, and who, visiting them from time to time, makes repairs and supplies new parts.]

The intermittent action of fog-signals makes it necessary to employ a peculiar form of boiler. The steam used is at a high pressure, and drawn off at intervals; consequently there is a tendency to foam and throw out water with the steam. To obviate this difficulty the form of boiler found by experience to be best adapted to this service is a horizontal tubular boiler (locomotive), with rather more than one-half of the interior space allowed for steam-room. The steam-dome is very large, and is surmounted by a steam pipe 12″ in diameter. Both the dome and pipe were formerly made much smaller, but were gradually enlarged as long as any difficulty with regard to foaming was noticed. The steam is drawn off at a point 10″ above the water-level in the boiler. The main points to be observed are to have plenty of steam-room, and to draw the steam from a point high above the water-level. It will be readily perceived that a vertical tubular boiler is entirely unsuited to this work.

It is essential, both as regards economy of fuel and the efficient working of the signal, that the boiler, including the dome and stand-pipe, should be well covered with some good non-conductor of heat. A material, called salamander felting, manufactured in Troy, N. Y., was used on the fog-whistle boiler at House Island during the winter of 1870. There resulted a saving of more than 20 per cent. of fuel over that consumed in the same boiler when uncovered. Where this material cannot be procured, a thick layer of hair felting, covered with canvas, will be found to answer a good purpose.

Various expedients have been proposed with the view of keeping the water in the boilers hot when the signals are not in operation, that the signal may always be ready to sound at a very short notice, and that the water in the boiler and pipes may be prevented from freezing in extremely cold weather. One of these contrivances is "Sutton's circulating water-heater." It consists essentially of a small, vertical, tubular boiler, entirely filled with water, and connected with the boiler or tank which contains the water to be heated, by two pipes on different levels. As soon as the water in the heater is warmed, a circulation commences, the hot water flowing through the upper pipe into the boiler, and the cold through the lower pipe from the boiler to the heater. As the furnace in the heater is very small but little fuel is consumed, and nearly the entire heat produced by the combustion is utilized.

The apparatus has been extensively employed in heating the water in tanks designed for filling the steam fire-engine boilers, when the alarm of fire is first given, and appears admirably adapted to this purpose. If used in connection with a steam-boiler, it should be disconnected before steam is raised in the latter, as, from its construction, it is not calculated to withstand any considerable pressure.

An arrangement, similar in principle, has been used in the first light-house district, consisting of a small cylinder coal-stove, of the ordinary pattern, around the interior of which, and above the grate, is introduced a single coil of ¾″ pipe. This coil is connected with the boiler by two pipes, one entering near the bottom, the other about 2 feet higher. It has been found that in consequence of the rapid circulation of the water through this coil, and the great capacity of water for heat, that nearly all the heat from the fire in the stove is transferred to the water in the boiler. This arrangement possesses the advantage of the ¾″ pipe, being strong enough to stand any pressure that can be used in the boiler, rendering it unnecessary to disconnect it at any time.

Experience has, however, proved that none of these contrivances are essential. It is seldom that an attentive keeper cannot foresee the approach of fog or snow in time to have the apparatus in operation as soon as required, even when obliged to start his fire with cold water in the boiler.

Keepers should be directed to watch the state of the weather carefully, and to light their fires at the first indication of fog or snow-storm. As soon as the water in the boiler is near the boiling point, should the necessity for sounding the signal have not yet arisen, the fire may be banked, and in this state the water may be kept hot for any length of time at a moderate expenditure of fuel. With proper care, no more fuel is required to keep the water at the requisite temperature by means of a banked fire than by any other method, and it is a matter of great importance to avoid complicating fog-signal apparatus by unnecessary appendages.

The same plan should be adopted in extremely cold weather to prevent the water in the boiler from freezing. There should be a small air-cock in the draught-pipe near its junction with the feed-pump, and in cold weather this should be opened when the pump is not in use, in order to allow the pipe to empty itself.

When the draught-pipe cannot be protected from the cold, and the well is at a considerable distance from the engine, the following expedient has been employed with success: The pipe is inclosed in an India-rubber hose of about double its diameter, and from time to time steam is forced through the space between the hose and draught-pipe by means of a small pipe from the boiler.

Although the laws governing the reflection of light and heat are undoubtedly, in a great measure, applicable to sound, there are yet so many disturbing influences, such as inflection, refraction, caused by the varying density of the atmosphere, &c., interfering with the reflection of the latter, that but little use can be made of this property in directing and condensing the waves of sound issuing from a fog-signal. This fact may be illustrated by an account of some experiments made during the last year.

A whistle being sounded in the focus of a large parabolic reflector, it was very perceptible to an observer in the immediate vicinity that the sound was louder in the front than in the rear of the reflector. As the distance of the observer from the whistle was increased this disparity rapidly diminished, and at the distance of a few hundred yards entirely disappeared. The *beam* of sound had been dissipated and the *shadow* had vanished. The effect of a horizontal sounding-board 10 feet square, suspended over the whistle to prevent the escape of sound in a vertical direction, was inappreciable at the distance of a quarter of a mile.

The employment of a trumpet with the whistle was rather more successful. The trumpet was constructed of wood, in the form of a square pyramid; the lower base being 10′ by 10′, the upper base 2′ by 2′, and the height 20′. The axis was horizontal and the whistle placed at the smaller end. By this arrangement the increased power of the sound could be perceived at the distance of a mile, the action being similar to that of a speaking-trumpet.

It is probable that some modification of this form of whistle may be advantageously employed in certain localities, but there is however a disadvantage attending the use of a trumpet with fog-signals.

The sound from a trumpet not being uniformly distributed, it is difficult to estimate the distance of the signal, or, as the pilots term it, "to locate the sound." This has been observed in the siren and Daboll trumpet. The sound from these signals being stronger on one course than any other, may be distinctly heard from a vessel when crossing the axis of the beam of sound, but as its distance from this line increases, the sound appears fainter and more remote, although the vessel may be approaching the signal.

From an attentive observation, during three years, of the fog-signals on this coast, and from the reports received from captains and pilots of coasting vessels, I am convinced that in some conditions of the atmosphere the most powerful signals will be at times unreliable.

Now it frequently occurs that a signal, which under ordinary circumstances would be audible at the distance of fifteen miles, cannot be heard from a vessel at the distance of a single mile. This is probably due to the reflection mentioned by Humboldt.

The temperature of the air over the land where the fog-signal is located, being very different from that over the sea, the sound, in passing from the former to the latter, undergoes reflection at their surface of contact. The correctness of this view is rendered more probable by the fact that when the sound is thus impeded in the direction of the sea, it has been observed to be much stronger inland.

When a vessel approaches a signal in a fog, a difficulty is sometimes experienced in determining the position of the signal by the direction from which the sound appears to proceed, the apparent and true direction being entirely different. This is undoubtedly due to the refraction of sound passing through media of different density.

Experiments and observation lead to the conclusion that these anomalies in the penetration and direction of sound from fog-signals are to be attributed mainly to the want of uniformity in the surrounding atmosphere, and that snow, rain, fog, and the force and direction of the wind, have much less influence than has generally been supposed.

[In the foregoing I differ entirely in opinion from General Duane as to the cause of extinction of powerful sounds being due to the unequal density of the atmosphere. The velocity of sound is not at all affected by barometric pressure, but if the difference in pressure is caused by a difference in heat, or by the expansive power of vapor mingled with the air, a slight degree of obstruction of sounds may be observed. But this effect we think is entirely too minute to produce the results noted by General Duane, while we shall find in the action of the currents of wind above and below, a true and sufficient cause.]

The experimental whistles were of the following dimensions, viz: 2½″, 3″, 4″, 5″, 6″, 10″, 12″, and 18″ in diameter. Those of 2½″, 3″, 5″, and 10″ were fitted, instead of the ordinary bell, with long cylinders, provided with movable pistons, so that the effective length of the bell could be altered at pleasure. The pitch of the blast was found to vary with the length of the bell, and the power of the whistle with its diameter. The ratio of the power to the diameter was not accurately obtained, but it is probable that the extreme range of sound of a whistle is proportional to the square root of its diameter.

[This result, that the pitch varies with the length of the bell, is in conformity with well-established principles of resounding cavities; and that the power should increase with the extent of the aerial reed, the vibrations of which give motion to the resounding air within the cavity, is also, as we have seen, in accordance with hypothetical considerations; but as the density of this stream of steam, and consequently the rapidity of its vibrations, depends upon the pressure of the steam in the boiler, a perfect whistle should have the capability of changing its dimensions, not only in relation to the width of its throat, but also in regard to the pressure of the steam in the reservoir.]

The pitch giving the greatest range appears to be at the middle of the scale of sound. It is certain that a good result cannot be obtained from either a very shrill or a bass note. This remark is applicable to all varieties of signal.

The 10″ and 12″ whistles are recommended for ordinary use. The 18″ whistle is more powerful, but the increase of power bears too small a proportion to that of the expenditure of fuel to render its employment generally advisable. The best results were obtained by giving the whistle the following proportions: The diameter of the bell equaling two-thirds of its length, and the set of the bell, *i. e.*, the vertical distance of the lower edge above the cup, the one-third to one-fourth of the diameter for a pressure of 50 to 60 pounds of steam

A bell, whether operated by hand or by machinery, cannot be considered an efficient fog-signal on the sea-coast. In calm weather it cannot be heard half the time at a greater distance than one mile, while in rough weather the noise of the surf will drown its sound to seaward altogether.

On approaching a station I have frequently seen the bell rung violently by the keeper, without being able to hear the sound until I had landed.

Nevertheless, all important stations should be provided with bells, as there are occasions when they may serve a useful purpose, but it should be well understood by mariners that they must not expect always to hear the bells as a matter of course.

Bells should not be omitted at stations furnished with steam fog-signals, especially when the latter are not in duplicate, and mariners should be warned that the bell will be sounded when the regular signal is disabled.

It has been observed that a bell rung by hand can be heard further than when sounded by machinery, and many of the steamboat companies on this coast pay the keepers of bells rung by clock-work to ring them by hand when the boats of their line are expected to pass.

[We think the difference in the effect of ringing of bells by hand or by machinery is so slight as to be inappreciable except at a short distance. It is true, as I have before observed, that the sound is louder when the mouth of the bell is directed toward the hearer than when the edge is so directed, but on account of the spreading of this sound the effect is lost in a small distance, and indeed in one light-house the bell is permanently placed with the axis of its mouth directed horizontally, and in this position, if the bell were struck interiorly with a hammer, which would give it a larger vibration than when struck exteriorly, I doubt whether any difference would be observed between the two methods of ringing; and if any existed it would probably be in favor of the fixed bell rung by machinery.]

On rivers, narrow channels, and lakes, where the difficulty from the noise of the surf does not exist, this species of signal may be used to advantage, as its maintenance requires but a small expenditure of either money or labor, and by a proper arrangement of the machinery the intervals between the strokes of the bell may be so regulated as to avoid the danger of confounding the signals, however near together.

Although a bell may be heard better when sounded by hand than by clock-work, yet in thoroughfares where the signal must be kept in constant operation during the entire continuance of a fog, it would be impracticable to make use of the former method, and recourse must be had to machinery.

In arranging the signal the bell and machinery must be placed as low as possible, as the sound is heard much more plainly on the water when the bell is near its surface, and also as the machinery, when thus situated, is steadier and more readily accessible.

Particulars as to the siren.—The boiler of a second-class apparatus is 12 feet long, 42 inches in diameter, and has 300 feet heating-surface. The dome is 2 feet in diameter and 3 feet high.

The cylinder of the engine is 4 inches in diameter and 6 inches stroke. The prolongation of the piston-rod forms the plunger of the feed-pump. The main shaft carries three pulleys, the larger driving the siren-spindle; the second, the worm and screw gear; and the third, the governor.

In the worm-gear the wheel makes two revolutions per minute, and is provided with a cam, which, acting on a lever, opens the valve, admitting steam through the siren-disks. The cam has such a length as to hold the valve open for about seven seconds. A counter-weight closes the valve as soon as the lever is released by the cam.

The siren itself consists of a cylindrical steam-chest, closed at one end by a perforated brass plate. The perforations are twelve in number, equidistant from each other, and arranged on the circumference of a circle, whose center is in the axis of the cylinder. The other end is closed by a cast-iron head. The heads are connected by a brass pipe, through which the spindle passes.

The perforated head is covered on the exterior by a brass disk, attached to the spindle, having twelve rectangular notches corresponding to the apertures on the former, and so arranged that by its revolution these apertures are simultaneously opened and closed. The spindle is driven by a belt from the large pulley on the main shaft. This shaft makes 180 revolutions per minute; the spindle, 1,620; and as there are 12 apertures in the disks, from each there will issue jets of steam at the rate of 19,440 per minute. The sound produced by these impulses may be rendered more or less acute by increasing or diminishing the velocity of revolution.

The valve and valve-seat are disks similar to those already described, having however four openings instead of twelve. The valve revolves on the brass tube inclosing the siren-spindle, and is worked by a bevel gear. The trumpet is of cast-iron.

The Daboll trumpet.—The apparatus used in the foregoing experiments is a second-class trumpet, operated by an Ericsson caloric-engine. The air-pump is single-acting. Its cylinder is 12″ in diameter by 12″ stroke. The engine makes forty strokes per minute. There is a screw-thread raised on the main shaft, which, acting on a wheel, drives a bevel gear, giving motion to a cam-wheel. The latter makes one revolution in two minutes, and is furnished with three equidistant cams. These cams, pressing on the valve-lever, throw the valve open once in forty seconds, admitting the compressed air through the reed-chest into the trumpet.

The quantity of air forced into the tank should be in excess of that needed for the trumpet, the surplus being allowed to escape through a delicate safety-valve. This is necessary to provide against a deficiency in case of leakage, and also to allow the pressure of air to be regulated to accommodate the reed. Each reed requiring a different pressure, it is necessary to alter the pressure of the valve-spring whenever a reed is changed.

The first-class trumpet differs only in size from that described.

The caloric-engine for the first class has a 30″ cylinder. The air-pump is 16½″ by 15″ stroke.

The steam-whistle.—The boiler of this machine is that of the siren. On the forward part of the boiler the bed-plate of a small engine is secured by two cast-iron brackets. The cylinder of this engine is 4″ by 9″. The fly-wheel shaft carries an eccentric, which, acting through a rod and pawl on a ratchet-wheel, gives the required motion to the cam-wheel shaft.

The cam-wheel, which makes one revolution per minute, is provided with one or more cams, depending on the number of blasts to be given in a minute; the length of the blast being regulated by that of the cams.

The valve for admitting the steam into the whistle is a balance-valve, the diameters of the two disks being respectively 3¼″ and 2¾″, which difference is sufficient to cause the pressure of steam to close the valve tight without requiring too great a force to open it. The valve is worked by a stem attached to the rocker-shaft at the lower part of the steam-pipe. This shaft passes through a stuffing-box in the steam-pipe, and is provided with a collar which the pressure of the steam forces against the interior boss on the pipe, thus making the joint steam-tight. The exterior arm on this rocker-shaft, as well as that on the engine, is perforated in such a manner as to allow the throw of the valve to be adjusted.

In the comments we have made on the report of General Duane, the intention was not in the least to disparage the value of his results, which can scarcely be too highly appreciated; but inasmuch as the true explanation of the phenomena he has observed has an important bearing on the location of fog-signals and on their general application as aids to navigation, and are as well of great interest to the physicist, who values every addition to theoretical as well as practical knowledge, we have not only thought the remarks we have offered necessary, but also that special investigations should be made to ascertain more definitely the conditions under which the abnormal phenomena the general has described occur, and to assign, if possible, a more definite and efficient cause than those to which he has attributed them.

We have, therefore, given much thought to the subject, and since the date of General Duane's report, have embraced every opportunity which occurred for making observations in regard to them. The first step we made toward obtaining a clew to the explanation of the phenomena in question resulted from observations at New Haven, namely: 1st, the tendency of sound to spread laterally into its shadow; 2d, the fact that a sound is frequently borne in an opposite direction to the wind at the surface by an upper current; and 3d, that a sound moving against a wind is heard better at a higher elevation. The first point to consider is in what manner the wind affects sound. That it is in some way connected with the distance to which sound can be heard is incontestably settled by general observation. At first sight, the explanation of this might seem to be very simple, namely, that the sound is borne on in the one direction and retarded in the other by the motion of the wind. But this explanation, satisfactory as it might appear, cannot be true. Sound moves at the rate of about 780 miles an hour, and therefore, on the above supposition, a wind of 7.8 miles per hour could neither retard nor accelerate its velocity more than one per cent., an amount inappreciable to ordinary observation; whereas we know that a wind of the velocity we have mentioned is frequently accompanied with a reduction of the penetrating power of sound of more than 50 per cent.

The explanation of this phenomenon, as suggested by the hypothesis of Professor Stokes, is founded on the fact that in the case of a deep current of air the lower stratum, or that next the earth, is more retarded by friction than the one immediately above, and this again than the one above it, and so on. The effect of this diminution of velocity as we descend toward the earth is, in the case of sound moving with the current, to carry the upper part of the sound-waves more rapidly forward than the lower parts, thus causing them to incline toward the earth, or, in other words, to be thrown down upon the ear of the observer. When the sound is in a contrary direction to the current, an opposite effect is produced,—the upper portion of the sound-waves is more retarded than the lower, which advancing more rapidly, in consequence inclines the waves upward and directs them above the head of the observer. To render this more clear, let us recall the nature of a beam of sound, in still air, projected in a horizontal direction. It consists of a series of concentric waves perpendicular to the direction of the beam, like the palings of a fence. Now, if the upper part of the waves has a slightly greater velocity than the lower, the beam will be bent downward in a manner somewhat analogous to that of a ray of light in proceeding from a rarer to a denser medium. The effect of this deformation of the wave will be cumulative from the sound-center onward, and hence, although the velocity of the wind may have no perceptible effect on the velocity of sound, yet this bending of the wave being continuous throughout its entire course, a marked effect must be produced.

A precisely similar effect will be the result, but perhaps in a considerably greater degree, in case an upper current is moving in an opposite direction to the lower, when the latter is adverse to the sound, and in this we have a logical explanation of the phenomenon observed by General Duane, in which a fog-signal is only heard during the occurrence of a northeast snow-storm. Certainly this phenomenon cannot be explained by any peculiarity of the atmosphere as to variability of density, or of the amount of vapor which it may contain.

The first phenomenon of the class mentioned by General Duane, which I had the good fortune to witness was in company with Sir Frederick Arrow and Captain Webb, of the Trinity House, London, in their visit to this country in 1872. At the distance of two or three miles from an island in the harbor of Portland, Maine, on which a fog-signal was placed, the sound, which had been distinctly heard, was lost on approaching the island for nearly a mile, and slightly regained at a less distance. On examining the position of the fog-signal, which was situated on the farther side of the island from the steamer, we found it placed immediately in front of a large house with rising ground in the rear, which caused a sound-shadow, into which, on account of the lateral divergence of the rays, the sound was projected at a distance, but not in the immediate vicinity of the island. In the same year I made an excursion in one of the light-house steamers, with Captain Selfridge, to an island on the coast of Maine, at which abnormal phenomena were said to have been observed, but on this occasion no variation of the sound was noted, except that which was directly attributable to the wind, the signal being heard much farther in one direction than in the opposite.

PART II.—REMARKS ON SOME ABNORMAL PHENOMENA OF SOUND.*

The communication which I propose to make this evening is brought forward at this time especially on account of the presence of Dr. Tyndall, he being connected with the light-house system of Great Britain, while the facts I have to state are connected with the light-house service of the United States, and must therefore be of interest to our distinguished visitor. The facts I have to present form part of a general report to be published by the United States Light-House Board.

The Light-House Board of the United States has from its first establishment aimed not only to furnish our sea-coast with all the aids to navigation that have been suggested by the experience of other countries and to adopt the latest improvements, but also to enrich the light-house service with the results of new investigations and new devices for the improvement of its efficiency, or, in other words, to add its share to the advance of a system which pertains to the wants of the highest civilization.

Among the obstructions to navigation none are more serious, especially on the American coast, than those caused by fogs.

Fog, as it is well known, is due to the mingling of warmer air surcharged with moisture with colder air, and nowhere on the surface of the earth do more favorable conditions exist for producing fogs than on both our Atlantic and Pacific coasts. On the Atlantic the cold stream of water from the polar regions in its passage southward, on account of the rotation of the earth, passes close along our eastern coast from one extremity to the other, and parallel to this but opposite in direction, for a considerable distance is the great current of warm water known as the Gulf Stream. Above the latter the air is constantly surcharged with moisture, and consequently whenever light winds blow from the latter across the former, the vapor is condensed into fog, and since in summer along our eastern coast the southerly wind prevails, we have during July, August, and September, especially on the coast of Maine, an almost continuous prevalence of fogs so dense that distant vision is entirely obstructed.

On the western coast the great current of the Pacific, after having been cooled in the northern regions, in its passage southward gives rise to cold and warm water in juxtaposition, or, in other words, a current of the former through the latter, and hence whenever a wind blows across the current of cold water, a fog is produced.

From the foregoing statement it is evident that among the aids to navigation fog-signals are almost as important as light-houses. The application however of the science of acoustics to the former is far less advanced than is that of optics to the latter. Indeed, attempts have been made to apply lights of superior penetrating power, as the electric

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* Made before the "Philosophical Society of Washington," December 11, 1872.

and calcium lights, to supersede the imperfect fog-signals in use. When however we consider the fact that the absorptive power of a stratum of cloud, which is but a lighter fog, of not more than two or three miles in thickness, is sufficient to obscure the image of the sun, the intensity of the light of which is greater than that of any artificial light, it must be evident that optical means are insufficient for obviating the difficulty in question.

The great extent of the portions of the coast of the United States which are subject to fogs renders the investigation of the subject of fog-signals one of the most important duties of the Light-House Board.

In studying this subject it becomes a question of importance to ascertain whether waves of sound, like those of light, are absorbed or stifled by fog; on this point however, observers disagree. At first sight, from the very striking analogy which exists in many respects between light and sound, the opinion has largely prevailed that sound is impeded by fog. But those who have not been influenced by this analogy have in some instances adopted the opposite opinion—that sound is better heard during a fog than in clear weather. To settle this question definitely the Light-House Board have directed that at two light-houses on the route from Boston to Saint John the fog-signals shall be sounded every day on which the steamboats from these ports pass the station, both in clear and foggy weather, the pilots on board these vessels having, for a small gratuity, engaged to note the actual distance of the boat when the sound is first heard on approaching the signal and is last heard on receding from it. The boats above mentioned estimate their distance with considerable precision by the number of revolutions of the paddle-wheel as recorded by the indicator of the engine, and it is hoped by this means to definitely decide the point in question. We think it probable that fog does somewhat diminish the penetrating power of sound, or in other words, produce an effect analogous to that on the propagation of light. But when we consider the extreme minuteness of the particles of water constituting the fog as compared with the magnitude of the waves of sound, the analogy does not hold except in so small a degree as to be of no practical importance, or, in other words, the existence of a fog is a true, but, we think, a wholly insufficient cause of diminution of sound, which view is borne out by the great distance at which our signals are heard during a dense fog.

Another cause, which without doubt is a true one, of the diminution of the penetrating power of sound is the varying density of the atmosphere, from heat and moisture, in long distances. The effect of this, however, would apparently be to slightly distort the wave of sound rather than to obliterate it. However this may be, we think, from all the observations we have made, the effect is small in comparison with another cause, viz, that of the influence of wind. During a residence of several weeks at the sea-shore, the variation in intensity of the sound of the breakers at a distance of about a mile in no case appeared to be coincident with the variations of an aneroid barometer or a thermometer, but in every instance it was affected by the direction of the wind.

The variation in the distinctness of the sound of a distant instrument as depending on the direction of the wind is so marked that we are warranted in considering it the principal cause of the inefficiency in certain cases of the most powerful fog-signals. The effect of the wind is usually attributed, without due consideration, to the motion of the body of air between the hearer and the sounding instrument; in the case of its coming towards him it is supposed that the velocity of the sound is reinforced by the motion of the air, and when in the opposite direction that it is retarded in an equal degree. A little reflection, however, will show that this cannot be the cause of the phenomenon in question, since the velocity of sound is so vastly greater than that of any ordinary wind that the latter can only impede the progress of the former by a very small percentage of the whole. Professor Stokes, of Cambridge University, England, has offered a very ingenious hypothetical explanation of wind on sound, which we think has an important practical bearing, especially in directing the line of research and subsequent application of principles.

His explanation rests upon the fact that during the passage of a wind between the observer and the sounding instrument the velocity of this will be more retarded at the surface of the earth on account of friction and other obstacles, and that the velocity of the stratum immediately above will be retarded by that below, and so on, the obstruction being lessened as we ascend through the strata. From this it follows that the sound wave will be deformed and the direction of its *normal* changed. Suppose, for example, that the wind is blowing directly from the observer. In this case the retardation of the sound wave will be greater above than below, and the upper part of the wave-front will be thrown backwards so that the axis of the phonic ray will be deflected upwards, and over the head of the observer. If, on the other hand, a deep river of wind (so to speak) is blowing directly towards the observer, the upper part of the front of the wave will be inclined down and towards him, concentrating the sound along the surface of the earth.

The science of acoustics in regard to the phenomena of sound as exhibited in limited spaces has been developed with signal success. The laws of its production, propagation, reflection, and refraction have been determined with much precision, so that we are enabled in most cases to explain, predict, and control the phenomena exhibited under given conditions. But in case of loud sounds and those which are propagated to a great distance, such as are to be employed as fog-signals, considerable obscurity still exists. As an illustration of this I may mention the frequent occurrence of apparently abnormal phenomena. General Warren informs me that at the battle of Seven Pines, in June, 1862, near Richmond,—General Johnston, of the Confederate army, was within three miles of the scene of action with a force intended to attack the flank of the Northern forces, and although listening attentively for the sound of the commencement of the engagement, the battle, which was a severe one, and lasting about three hours, ended without his having heard a single gun. (See Johnston's report.) Another case of a similar kind occurred to General McClellan at the battle of Gaines' Mills, June 27, 1862, also near Richmond. Although a sharp engagement was progressing within three or four miles for four or five hours, the general and his staff were unaware of its occurrence, and when their attention was called to some feeble sound they had no idea that it was from anything more than a skirmish of little importance. (See Report of the Committee on the Conduct of the War.) A third and perhaps still more remarkable instance is given in a skirmish between a part of the Second Corps under General Warren and a force of the enemy. In this case the sound of the firing was heard more distinctly at General Meade's headquarters than it was at the headquarters of the Second Corps itself, although the latter was about midway between the former and the point of conflict. Indeed the sound appeared so near General Meade's camp that the impression was made that the enemy had gotten between it and General Warren's command. In fact so many instances occurred of wrong impressions as to direction and distance derived from the sound of guns that little reliance came to be placed on these indications.

In the report of a series of experiments made under the direction of the Light-House Board by General Duane of the Engineer Corps is the following remark: "The most perplexing difficulty arises from the fact that the fog-signal often appears to be surrounded by a belt varying in radius from one to one and a half miles. Thus in moving directly from a station the sound is audible for the distance of a mile, is then lost for about the same distance, after which it is again distinctly heard for a long time."

Again, in a series of experiments at which Sir Frederick Arrow and Captain Webb, of the Trinity Board, assisted, it was found that in passing in the rear of the opposite side of an island in front of which a fog-signal was placed, the sound entirely disappeared, but by going further off to the distance of two or three miles it reappeared in full force, even with a large island intervening. Again, from the experiments made under the immediate direction of the present chairman of the Light-House Board, with the assistance of Admiral Powell and Mr. Lederle, the light-house engineer, and also from separate experiments made by General Duane, it appears that while a reflector, in the focus of which a steam whistle or ordinary bell is placed, reinforces the sound for a short distance, it produces little or no effect at the distance of two or three miles, and, indeed, the instrument can be as well heard in still air at the distance of four or five miles in the line of the axis of the reflector, whether the ear be placed before or behind it. From these results we would infer that the lateral divergency of sound, or its tendency to spread laterally as it passes from its source, is much greater than has been supposed from experiments on a small scale. The idea we wish to convey by this is that a beam of sound issuing through an orifice, although at first proceeding like a beam of light in paralled rays, soon begins to diverge and spread out into a cone, and at a sufficient distance may include even the entire horizon.

We may mention also in this connection that from the general fact expressed by the divergence of the rays of sound, the application of reflection as a means of reinforcing sound must in a considerable degree of necessity be a failure.

By the application of the principle we have stated and the effect of the wind in connection with the peculiarities of the topography of a region and the position of the sounding body, we think that not only may most of the phenomena we have just mentioned be accounted for, but also that other abnormal effects may be anticipated.

In critically examining the position of the sounding body in the experiment we have mentioned, in which Sir Frederick Arrow and Captain Webb assisted, it was found that the signal was placed on the side of a bank with a large house directly in the rear, the roof of which tended to deflect the sound upwards so as to produce in the rear a shadow, but on account of the divergency of the beam this shadow vanished at the distance of a mile and a half or two miles, and at the distance of, say, three miles the sound of the instrument was distinctly heard. I doubt not that, on examination, all the cases mentioned by General Duane, with one exception, might be referred to the same principle, the exception being expressed in the following remarkable statement in his report to the Light-House Board: "The fog-signals have frequently been heard at a distance of *twenty* miles and as frequently cannot be heard at the distance of *two* miles, and with no perceptible difference in the state of the atmosphere. The signal is often heard at a greater distance in one direction, while in another it will be scarcely audible at the distance of a mile. For example, the whistle at Cape Elizabeth can always be distinctly heard in Portland—a distance of nine miles—during a heavy northeast snowstorm, the wind blowing a gale nearly from Portland towards the whistle."

This is so abnormal a case, and so contrary to generally received opinion, that I hesitated to have it published under the authority of the board until it could be verified and more thoroughly examined. In all the observations that have been made under my immediate supervision, the sound has always been heard farther *with* the wind than against it. It would appear, therefore, from all the observations that the normal effect of the wind is to diminish the sound in blowing directly against it.

There is however a meteorological condition of the atmosphere during a northeast storm on our coast which appears to me to have a direct bearing on the phenomenon in question. It is this: that while a violent wind is blowing from the northeast into the interior of the country, a wind of equal intensity is blowing in an opposite direction at an elevation of a mile or two. This is shown by the rapid eastwardly motion of the upper clouds as occasionally seen through breaks in the lower.

As a further illustration of this principle I may mention that on one occasion (in 1855) I started, on my way to Boston from Albany, in the morning of a clear day, with a westerly wind. The weather continued clear and pleasant until after passing the Connecticut River, and until within fifty miles of Boston. We then encountered a storm of wind and rain which continued until we reached the city. On inquiry I learned that the storm had commenced in Boston the evening before, and, although the wind had been blowing violently towards Albany for *twenty* hours, it had not reached inwardly more than fifty miles. At this point it met the *west* wind and was turned back above in almost a parallel current. This is the general character of northeast storms along our coast, as shown by Mr. Espy, and is directly applicable to the phenomenon mentioned by General Duane, and which, from the frequency with which he has witnessed the occurrence, we must accept as a fact, though by no means a general one applicable to all stations. While a violent wind was blowing towards his place of observation from Cape Elizabeth, at the surface of the earth, a parallel current of air was flowing above with equal or greater velocity in the opposite direction. The effect of the latter would be to increase the velocity of the upper part of the wave of sound, and of the former to diminish it; the result of the two being to incline the front of the wave of sound towards the observer, or to throw it down towards the earth, thus rendering the distant signal audible under these conditions when otherwise it could not be heard. I think it is probable that the same principle applies in other cases to the abnormal propagation of sound.

For the production of a sound of sufficient power to serve as a fog-signal, bells, gongs, &c., are too feeble except in special cases where the warning required is to be heard only at a small distance. After much experience, the Light-House Board has adopted, for first-class signals, instruments actuated by steam or hot-air engines, and such only as depend upon the principle of resonance, or the enforcement of sound by a series of recurring echoes in resounding cavities.

Of these there are three varieties. First, the steam-whistle, of which the part called the bell is a resounding cavity, the sound it emits having no relation to the material of which it is composed; one of the same form and of equal size of wood producing an effect identical with that from one of metal. Another variety is the fog-trumpet, which consists of a trumpet of wood or metal actuated by a reed like that of a clarionet. The third variety is called the siren trumpet, which consists of a hollow drum, into one head of which is inserted a pipe from a steam-boiler, while in the other head a number of holes are pierced, which are alternately opened and shut by a revolving plate having an equal number of holes through it. This drum is placed at the mouth of a large trumpet. The sound is produced by the series of impulses given to the air by the opening and shutting of the orifices and consequent rushing out at intervals with explosive violence of the steam or condensed air. The instrument, as originally invented by Cagniard de Latour, of France, was used simply in experiments in physics to determine the pitch of sound; but Mr. Brown, of New York, after adding a trumpet to it, and modifying the openings in the head of the drum and the revolving plate, offered it to the Light-House Board as a fog-signal, and as such it has been found the most powerful ever employed.

In ascertaining the penetrating power of different fog-signals, I have used with entire success an instrument of which the following is a description: A trumpet of ordinary tinned iron of about 3 feet in length, and 9 inches in diameter at the larger end, and about 1 inch at the smaller, is gradually bent so that the axis of the smaller part is at right angles to the axis of the larger end; on the smaller end is soldered a cone, of which the larger end is about 2 inches in diameter. Across the mouth of this cone is stretched a piece of gold-beater's skin. When the instrument is used, the opening on the larger end is held before the instrment to be tested, the membrane being horizontal, and the mouth of the trumpet vertical; over the membrane is strewed a small quantity of fine sand, which is defended from the agitation of the air by a cylinder of glass, the upper end of which is closed by a lens. When the instrument under examination is sounded, being sufficiently near the sand, is agitated; it is then moved further off, step by step, until the agitation just ceases; this distance, being measured, is taken as the relative penetrating power of the sounding instrument. The same process is repeated with another sounding instrument, and the distance at which the sound ceases to produce an effect on the sand is taken as the measure of the penetrating power of this instrument, and so on. On comparing the results given by this instrument with those obtained by the ear on going out a sufficient distance, the two are found to agree precisely in their indications. The great advantage in using this contrivance is that the relative penetrating power of two instruments may be obtained within a distance of a few hundred yards, while to compare the relative power of two fog-signals by the ear requires the aid of a steamer and a departure from the origin of sound in some cases of 15 or 20 miles.

PART III.—INVESTIGATIONS DURING 1873 AND 1874.*

OBSERVATIONS ON SOUND AND FOG-SIGNALS, IN AUGUST, 1873.

Professor Henry, chairman, and Commander Walker, naval secretary of the Light-House Board, left Portland August 12th, 1873, at 3 o'clock P. M. in the steam-tender Myrtle, Captain Foster, for Whitehead light-station, at which place abnormal phenomena of sound had been observed.

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* From the Report of the Light-House Board, for 1874.

Whitehead light-station is on a small island about a mile and a half from the coast of Maine, on the western side of the entrance to Penobscot Bay, and in the direct line of the coasting-steamers and other vessels from the westward bound into the Penobscot Bay and River. The light-house and fog-signal are situated on the southeast slope of the island, the surface of which consists almost entirely of rock, the middle being at an elevation of 75 feet above the mean tide-level.

The phenomena which had been observed at this and other stations along the coast consisted of great variation of intensity of sound while approaching and receding from the station. As an example of this we may state the experience of the observers on board the steamer City of Richmond on one occasion, during a thick fog in the night in 1872. The vessel was approaching Whitehead from the southwestward, when, at a distance of about six miles from the station, the fog-signal, which is a 10-inch steam-whistle, was distinctly perceived and continued to be heard with increasing intensity of sound until within about three miles, when the sound suddenly ceased to be heard, and was not perceived again until the vessel approached within a quarter of a mile of the station, although from conclusive evidence furnished by the keeper it was shown that the signal had been sounding during the whole time. The wind during this time was from the south, or approximately in an opposite direction to the sound. Another fact connected with this occurrence was that the keeper on the island distinctly heard the sound of the whistle of the steamer, which was commenced to be blown as soon as the whistle at the station ceased to be heard, in order to call the attention of the keeper to what was supposed to be a neglect of his duty in intermitting the operations of his signal. It should be observed in this case that the sound from the steamer was produced by a 6-inch whistle, while that of the station was from an instrument of the same kind of 10 inches in diameter; or, in other words, a lesser sound was heard from the steamer, while a sound of greater volume was unheard in an opposite direction from the station. It is evident that this result could not be due to any mottled condition or want of acoustic transparency of the atmosphere, since this would absorb the sound equally in both directions. The only plausible explanation of this phenomenon is that which refers it to the action of the wind. In the case of the sound from the steamer, the wind was favorable for its transmission, and hence it is not strange that its sound should be heard on the island when the sound from the other instrument could not be be heard on the steamer. To explain on the same principle the fact of the hearing of the sound at the distance of six miles, and afterward of losing it at the distance of three miles, we have only to suppose that in the first instance the retarding effect of the wind was small, and that in the second it became much greater on account of a sudden increase in the relative velocity of the current in the upper and lower portions.

After making a critical examination of the island and the position of the machinery, and also in regard to any obstacle which might interfere with the propagation of the sound, the keeper was directed to put the instrument in operation and to continue to sound it for at least two hours, or until the steamer was lost sight of, which direction was complied with. In passing from the island, almost directly against a light wind, the intensity of the sound gradually diminished as a whole, with the increase of distance, but varied in loudness from blast to blast, now louder, then again more feeble, until it finally ceased at a distance of about fifteen miles, as estimated by the intervals between the blasts and the sight of the steam as seen through a spy-glass, and also from points on the Coast-Survey charts.

The result of this investigation clearly showed the power of the apparatus in propagating sound under conditions not entirely favorable, since the wind, though light, was in opposition to the sound.

Cape Elizabeth Light-Station, Maine, August 29, 1873.—The fog-signal at this place is on a prominent headland to which the course of all vessels is directed when bound from the southward into Portland Harbor. It is furnished with two light houses 919 feet apart and 143 feet above sea-level. The easterly tower is connected with the keeper's dwelling by a wooden-covered way 200 feet long and about 12 feet high; the station is furnished with a 10-inch steam fog-whistle, placed to the southward of the easterly tower, at a distance of about 625 feet and about at right angles with the covered way; it therefore has a background, including the covered way, of about 65 feet above the height of the whistle, which was found to reflect a perceptible echo. The whistle was actuated by steam at 55 pounds pressure, consuming from 60 to 65 pounds of anthracite coal per hour. The whistle itself differs from the ordinary locomotive-whistle by having a projecting ledge or rim around the lower part through which the sheet of steam issues to strike against the lower edge of the bell. What effect this projecting ledge or rim may have is not known to the observers. This whistle is provided, (for the purpose of concentrating the sound in a given direction,) with a hollow truncated pyramid 20 feet long, 10 feet square at the large end, and 2½ feet square at the small end, the axis of the pyramid being placed parallel to the horizon, with the whistle at the smaller end. In order to ascertain the effect of this appendage to the whistle the simplest plan would have been to have noted the intensity of sound at various points on a circle of which the whistle would have been the center. This being impracticable on account of the intervention of the land, the observations were confined to points on the three arcs of a circle of about 120°, of which the axis divided the space into 80° and 40° and a radius of one, two, and three miles. The result of these observations was that, starting from the axis of the trumpet on the east side, the sound grew slightly less loud until the prolongation of the side of the trumpet was reached, when it became comparatively faint and continued so until the line between the whistle and observer was entirely unobstructed by the side of the trumpet, when the sound was apparently as loud as in the prolongation of the axis itself. On the west side of the axis of the trumpet the sound in a like manner diminished from the axis until the prolongation of the side of the trumpet was reached, when it became feeble again, slightly increased, and then gradually diminished until the line of direction made an angle of about 80° with the axis of the trumpet, when it ceased to be heard at a distance of about one and a half miles. It should be observed, however, that at this point the line of sight of the observers was obstructed by the side of the trumpet and the smoke-stack of the boiler. The wind was light, at south-southwest, approximately in direct opposition to the direction of the sound when it ceased to be heard. We are informed that complaints had previously been made by officers of steamers passing near this point that the sound was here inaudible previous to the introduction of this trumpet; it would therefore follow that it is of no use in increasing the effect on the western side of the axis and is of injury to the sound on the lines of prolongation of its sides. If the sound ceased to be heard at the point mentioned, when the trumpet is removed the only apparent cause of the phenomenon will be the prevailing direction of the wind, which, coming from the southwest, will be in opposition to the sound of the whistle; but in the case of the present investigation the force of the wind was so small that it scarcely appeared adequate to produce the effect, and this question, therefore, must be left for further investigation. It may be important to state that in the case where the sound ceased to be heard it was regained by sailing directly toward the station about one mile, or at half a mile from the station. After making the foregoing observations as to the intensity of sound in different directions from the station, the observations were closed by sailing directly along the axis of the trumpet until the sound, which gradually grew fainter as the distance increased, finally ceased to be heard at a distance of about nine miles. In comparing this last result with an instrument of about the same power at Whitehead, which gave a perceptible sound at a distance of fifteen miles, the only apparently variable circumstance was the velocity of the wind, in both cases adverse to the direction of the sound; but in that of Cape Elizabeth it was of considerable more intensity.

During the foregoing experiments, when the vessel was about a mile from the station, steaming directly outward, in the prolongation of the axis of the instrument, there was heard after each sound of the whistle a distinct echo from the broad, unobstructed ocean, which was attributed at the time, as in other cases, to reflections from the crests and hollows of the waves, a similar phenomenon having since been referred to a reflection from air of a different density. This observation becomes important in regard to the solution of the question as to the abnormal phenomena of sound.

Cape Ann Light-Station, Massachusetts, August 31, 1873.—This is one of the most important stations on the New England coast. It is furnished with two first-order lights, and a 12-inch steam-whistle, actuated by 60 pounds pressure of steam. The present is the fourth engine which has been erected at this station, in consequence of the complaints either as to the inefficiency of the sound or its failure to be heard in certain directions. It was at first proposed to sail entirely around the island in order to test the intensity of the sound in different directions, but this was found impracticable on account of want of depth of water on the inland side; the observations were therefore confined to the direction in which complaints had been made as to the deficiency of the signal, namely, in a southerly direction. The result of these observations, the points of which included an arc of 120°, was that the sound was heard with equal intensity except when the direction of the station was to the northward and eastward of the observers; then, in one instance, the sound became very indistinct, and in another was entirely lost, both at a distance of about two miles. In these cases the line of sight between the observers and the signal was interrupted, in the first by a small building, the gable-end of which was within 10 feet of the whistle, and in the second by the south light-tower, which is within 30 feet of the whistle. In this series of experiments, as with the last, the wind was against the sound; the effect was noted by passing over the arc several times at different distances. The wind was from the southward and westward and very light, and the sound was finally lost at about six miles, and in the direction of the obstructions.

Boston Light-Station, August 31, 1873.—The light-house is situated on a low, rocky island, on the north side of the main outer entrance to Boston Harbor, nine miles from the city. It is furnished with three caloric engines; two of the second class and one of the first. The two second-class engines are so arranged as to act separately or together, and in the latter arrangement serve to duplicate the larger engine. At the time the observations were made, the larger engine was about being repaired, and one of the smaller engines with the double air-reservoir was used. The larger engine is used with 12 pounds pressure of air, which falls to 8 pounds in producing the sound. The smaller engine, with the double reservoir, is started with 9 pounds pressure, which falls to 8 pounds. This difference in the pressure of air in the two engines is caused by the larger ratio of the reservoir to the size of the reed. With a greater pressure than 12 pounds to the square inch in the larger engine and 9 pounds in the smaller no sound is produced; the reed is unable to act against the pressure, and, consequently, the orifice remains closed. The trumpet of the larger of the engines is reported to have been heard eighteen miles at sea, which, in consideration of the results obtained at Whitehead, we thought very probable. The time required, from starting fires, to get a good working-pressure, is about half an hour. The amount of coal consumed per hour is 17 pounds.

There is moreover at this station a bell, operated by a Stevens clock, not at present used. It is placed on a high, wooden frame-structure, on which one of the ancient bell-striking machines was originally erected. The most proper position for the fog-signal is on the ground occupied by this bell-tower, but as this was not removed at the time of the erection of the trumpets, they were placed in such positions as to have the line of sound interrupted to the northeastward by the bell and light towers. It was therefore thought probable that this was the cause of the deficiency of sound in this direction. To test this the vessel was caused to traverse the arcs of several concentric circles, in the portion of the horizon where the sound was most required as a signal. The first arc traversed was about one and one-half miles from the signal. The vessel on this crossed the axis where the sound was quite loud, and proceeded northward until the sight of the trumpet was obscured by the before-mentioned towers, when the sound became almost inaudible. The vessel next returned across the axis, on a circle of about three miles radius, with similar results; but after crossing the axis the sound on the southern side continued to be but little diminished in intensity along an arc of two and a half miles, or as far as the land would allow the vessel to go. The vessel was next put upon an arc, of which the radius was one and a half miles, and on the south side of the axis, and sailed to the northward until the axis was reached, it was then turned and ran for the entrance of the harbor, hugging the southern shore, keeping as far from the signal as possible. Throughout this passage the sound was clear and loud, showing very little, if any, diminution of power as the several positions deviated more and more from the direction of the axis, until the vessel was at right angles with the axis, the land not permitting any greater distance. The vessel approached to within three-quarters of a mile of the signal and then continued still farther around, until nearly in the rear of it, the sound still continuing clear and loud. The vessel next proceeded up the harbor, nearly in the line of the axis of the trumpet prolonged in the rear, still continuing to hear the signal distinctly until the keeper, losing sight of the vessel, stopped sounding the instrument. These observations were made under very favorable circumstances, it being nearly calm. What wind did exist was about equally favorable to points on either side of the axis. The inference from these observations is, first, that small objects placed near the source of sound tend to diminish its intensity in the direction of its interruption, and should, therefore, if possible, be removed, or the instrument so placed as to obviate such obstructions; and, second, that, even with the trumpet, the sound so diverges from the axis as to be efficient even in the rear of the instrument.

OBSERVATIONS ON FOG-SIGNALS, AUGUST 25, 1874.

The first of these was on board the steamer Putnam, at Little Gull Island, with Admiral Trenchard, inspector of lights of the third district, accompanied by Governor Ingersoll, of Connecticut, and Captain Upshur, U. S. N.

At this place are two sirens, the one to replace the other in case of an accident. One of the sirens was sounded with the pressure of 50 pounds per square inch. The wind was across the axis of the trumpet, and almost precisely at right angles to it.

The steamer was headed against the wind, on a line at right angles to the axis of the trumpet. The sound in this case also travelled against the wind, which was at an estimated velocity of from 4 to 5 miles per hour. The distance travelled before the sound became inaudible was estimated, by the speed of the steamer, at 3½ miles.

The steamer was next headed in an opposite direction and returned along its previous path, across the mouth of the trumpet of the siren, the sound gradually increasing in strength without any marked irregularity, until the siren was reached, and on leaving this, the course remaining the same, the sound gradually diminished in intensity, but with less rapidity than before, until it was finally lost at a distance of 7½ miles. In the latter instance the movement of the sound was with the wind. The result of these observations was conformable to that generally obtained from previous observations, namely, that the sound is seldom or never heard at the same distance in different directions, and, moreover, that it is generally heard farther with the wind than against it.

The observations of this day also illustrate the spread of the sound-wave on either side of the axis of the trumpet, a fact which has frequently been observed in other investigations. It may be well to mention that the siren trumpet at this locality is directed horizontally with its prolonged axis passing over, immediately in front of the mouth of the trumpet, a space of very rough ground, the surface of which is principally composed of bowlders, one of which, of very large size, is directly in front of the trumpet, and the idea occurred to me that this rough surface might produce some effect on the transmission of sound to a distance. I observed by strewing sand upon a paper that the former was violently agitated when held near the surface of the large bowlder just mentioned, during the blast of the siren trumpet.

At this station, during the visit of Sir Frederick Arrow, the sound was lost in the direction of the axis of the trumpet at a distance of two miles, and then again regained with distinctness at the light-vessel, a distance of four and one-half miles; this was what we have denominated as an abnormal phenomenon, which we think was due to a slight variation in the velocity of the lower or upper part of the current of air, but, unfortunately, the demand for the use of the vessel as a light-house tender prevented the attempt to ascertain whether the same phenomenon would be observed a second time and to further investigate its cause.

The second investigations this season were September 1, 1874, with General Barnard, of the Light-House Board, and General Woodruff, engineer of the third district. We proceeded on this occasion in the steamer Mistletoe to Block Island, one of the outer stations of the Light-House Board, fully exposed, without intervention of land, to the waves and storms of the ocean.

On the southerly side of this island a light-house is about being erected, and a siren station at this locality had been established and was in full operation.

There are here two sirens attached to one boiler, one to be used in case of an accident to the other. For the sake of experiment they are of slightly different qualities, one with a larger trumpet with a revolving disk of the old pattern, giving a lower tone; the other a smaller trumpet, having a revolving disk with openings allowing a much more sudden full blast of steam, and revolving with greater velocity so as to give a higher pitch. The latter is far the superior instrument, as was evident to us by the sound which it produced, and as had been established by the use of the artificial ear in the manufactory of Mr. Brown. The effect on the unguarded ear was scarcely endurable, and the very earth around appeared to tremble during the blast. The keeper (an intelligent man who has been promoted from the station of assistant keeper at Beaver Tail light to this station) informed us that a fleet of fishing-vessels coming in distinctly heard it at a distance estimated by their rate of sailing at scarcely less than thirty miles; this was on two separate occasions. The keeper had been directed to note and record the date at which he heard the sound from other signals; he reported that he had frequently heard the fog-signal at Point Judith, a distance of seventeen miles, and that the observer at the latter place frequently heard his signal; but on comparing records the two sounds had not been heard simultaneously by the two keepers; when it was heard from one station it was not heard from the other, illustrating again the general rule that sound is not transmitted simultaneously with equal intensity in opposite directions.

This occasion also furnished very favorable conditions for observing the remarkable phenomenon of the ocean-echo. At the cessation of each blast of the trumpet, after a slight interval, a distinct and prolonged echo was returned from the unobstructed ocean. It is important to observe, in regard to this phenomenon, that the siren is placed near the edge of a perpendicular cliff, at an elevation of from 75 to 100 feet above the ocean, and, furthermore, that the direction of the wind formed an angle of about 35° with the axis of the trumpet. Now, the loudness of this echo was not the greatest at the siren-house, but increased in intensity until a point was reached several hundred yards from the trumpet, approximately more in accordance with a reflection from the waves. The wind was blowing from the shore with the direction of the sound as it went off from the trumpet, and nearly against it on the return of the echo. I have attributed this phenomenon, which was first observed in 1866 at East Quoddy Head on the coast of Maine, and since at various stations, at which the trumpet or siren has been used, to the reflection of the sound from the crests and slopes of the waves, and the observation we have mentioned would appear to favor this hypothesis. In connection with this explanation, I may mention that my attention has been called by General Meigs, of the United States Army, to an echo from the palings of a fence, and also from a series of indentations across the under side of the arch of one of the aqueduct bridges of the Washington water-works. The fact that the sound was much louder at a point considerably distant from the trumpet was noted by one of the party entirely unacquainted with the hypothesis.

The keeper at this station confirmed without a leading question the statement of Captain Keeney, that it frequently happens that a feeble sound of a distant object, as the roar of the surf, can be heard against the direction of the wind, and that in this case it always betokens a change in the weather, and is, in fact, used generally by the fishermen as a prognostic of a change in the direction of the wind, which will, in the course of a few hours, invariably spring up from an opposite quarter. In such case, it is highly probable, as has been stated, that a change has already taken place in the direction of the upper strata of the air, although, from theoretical considerations, we might infer that the same result would be produced if the wind were stationary above and moving with a considerable velocity in a direction opposite to the sound at the surface of the earth, the velocity gradually diminishing as we ascend, for in this case, also, the inclination of the sound waves would be downward.

The third series of investigations, September 23, 24, 1874, was made in company with Captain John Davis and Major Hains, both of the Light-House Board, and General Woodruff, engineer of the third district, and Mr. Brown, patentee of the siren. For the purpose three light-house tenders were employed, viz: Mistletoe, Captain Keeney; Putnam, Captain Field; Cactus, Captain Latham.

The place of operation chosen for the first day's series was about 1½ miles from the northern point of Sandy Hook.

From the experience gained by the accumulated observations which had been made, it was concluded that the phenomena of sound in regard to perturbing influences could not be properly studied without simultaneously observing the transmission of sound in opposite directions. It was therefore concluded to employ at least two steamers in making the investigations.

In regard to this point the commission was fortunate in being able to command the use, for a limited period, of the three tenders mentioned above, which happened to be at the time assembled at the light-house depot, Staten Island, and could be spared from their ordinary operations for a few days without detriment to the service. It was also fortunate in selecting for the scene of the investigations an unobstructed position in the lower bay of New York, and perhaps still more fortunate in the season of the year when, on account of the heat of the sun, a land and sea breeze, which changed its direction at a particular hour of the day, enabled results to be obtained bearing especially on the phenomena to be investigated.

Attention was first given to the character of the several steam-whistles which were intended to be used as the sources of the sound during the series of investigations.

These whistles, which were sounded during the whole of the observations with 20 pounds of steam on each boiler, gave at first discordant sounds, and were found by their effect upon an artificial ear to be considerably different in penetrating power; they were then adjusted by increasing or diminishing the space between the bell and the lower cylinder by turning a screw on the axis of the bell intended for that purpose, until they produced the same effect upon the sand in the membrane of the artificial ear; but in order to further be insured of the equality of the penetrating power of the several whistles, the three steamers abreast, forming as it were a platoon, were directed to proceed against the wind, sounding all the time in regular succession—the Cactus first, then, after an interval of a few seconds, the Mistletoe, and then the Putnam—until the stationary observers lost the sound of each. They became inaudible all very nearly at the same moment. The sound of the Putnam was thought to be slightly less distinct; it was therefore chosen as a stationary vessel, from which the observations of the sound of the other two were to be made.

The Putnam being anchored at the point before mentioned, arrangements were made for sending off the other two vessels in opposite directions, one with and the other against the wind, with instructions to return when the sound became inaudible to those on the stationary vessel, this to be indicated by a flag-signal. It should be mentioned that the velocity of the wind was measured from time to time during the subsequent experiments with one of Robinson's hemispherical cup anemometers, made by Casella, of London. The velocity of the wind first observed by this instrument, just before the starting of the vessels, was 6 miles per hour, the instrument being freely exposed on the paddle-boxes of the steamer. A sensitive aneroid barometer marked 30.395 in. and continued to rise gradually during the day to 30.43 in. the temperature was 71° F.

The vessels left at 11:18 A. M. the wind being from the west, Captain Davis taking charge of the sounding of the whistle on the Cactus, which proceeded east with the wind, the sound coming to the ear of the observer against the wind; while the sounding on the Mistletoe was in charge of General Woodruff, and, as the vessel steamed against the wind, the sound came to the observers on the stationary vessel with the wind; the other members of the party remained on the Putnam, at anchor at the point before mentioned, off the Hook, Major Hains having charge of the signals. The sound of the first of the vessels was heard faintly at 14 minutes after leaving, but not heard at 16 minutes; we may therefore assume that it became inaudible at 15 minutes. And within a minute of the same time, by a mistake of the signal, the other ceased to advance, and commenced to come back; the sound from it, however, was very distinct, while at the same moment the sound from the other was inaudible. On account of the mistake mentioned, the relative distance at which the sounds from the two vessels might have become inaudible cannot be accurately given; but the fact observed, that the sound which came with the wind was much more audible than the other, is in conformity with the generally observed fact that sound is heard farther with the wind than against it. In the mean time the velocity of the wind had sunk to 1½ miles per hour.

Next, the vessels, leaving at 11:55 A. M. changed positions; the Cactus, under Captain Davis, steamed west, directly in the direction from which the wind came, while the Mistletoe, under General Woodruff, steamed east, directly before the wind. The result of this trial was well marked in all respects; the sound of the Mistletoe was lost in 9 minutes, which, from the speed of the steamer, was estimated at about 1½ miles, while the sound of the Cactus was heard distinctly for 30 minutes, or at an estimated distance of 5 miles. The wind at the middle of this trial had sunk to 0.42 mile per hour, or nearly to a calm. The result of this trial was somewhat abnormal, for though the wind had sunk nearly to a calm, the sound was still heard three times as far in the direction of the slight wind as against it.

After a lapse of an hour and a half a third trial was made; in the mean time the wind had changed within two points of an exactly opposite direction, blowing, from the indications of the anemometer, at the rate of ten and one-half miles per hour.

The Cactus again steamed in the eye of the wind, which was now however from nearly an opposite point of the compass, while the other vessel steamed in an opposite direction. The sound of the Cactus was lost at the end of twenty-seven minutes, with the wind, or at a distance of four and a half miles.

The sound of the Mistletoe was lost at the end of thirty minutes, or at a distance of five miles, moving against a brisk wind then blowing.

This result was entirely unexpected and much surprised every member of the party, since it was confidently expected that an increase in the intensity of the wind of more than ten miles per hour, and a change to the opposite direction, would materially affect the audibility of the sound, and give a large result in favor of the sound, which moved in the same direction with the wind, but this was not the case. In the course of all the observations in several years in which investigations have been carried on under the direction of the chairman of the board, this is the only instance in which he had heard a sound at a greater distance against the wind than with it, although, as before stated, a number of cases have been reported by other observers in which, under peculiar conditions of the weather, this phenomenon has been observed.

To briefly recapitulate the results, we have in this case three instances, in succession, in which a sound was heard farther from the west than from the east, although in the mean time the wind had changed to nearly an opposite direction. Had these results been deduced from the first observations made on the influence of wind on sound, or, in other words, without previous experience, the conclusion would have been definitely reached that something else than wind affected the conveyance of sound, and this conclusion would have been correct, if the suggestion had been confined to the wind at the surface; but from previous observations and theoretical conclusions, the observed phenomena are readily accounted for by supposing that during the whole time of observation the wind was blowing from the west in the higher part of the aerial current, and that the calm and opposing wind observed were confined to the region near the surface. To test this hypothesis, Major Hains constructed a balloon of tissue-paper, which, after being completed, was unfortunately burned in the attempt to inflate it with heated air.

The remainder of this day was devoted to observations on the sound of the siren at the light-house at Sandy Hook. For this purpose the Cactus, under Captain Davis, was directed to steam in the eye of the wind, while the Mistletoe, under General Woodruff, steamed before the wind, and the Putnam steamed at right angles to the wind. Unfortunately, on account of the diminution of light at the closing in of the day, nothing could be observed. The only result obtained was that one of the duplicate sirens was heard more distinctly than the other, namely, the one with the higher note.

Experiments September 24, 1874.—The place chosen for the observations of this day was still farther out in the ocean, at the Sandy Hook light-vessel, 6 miles from the nearest point of land. The pressure of the atmosphere was a little greater than the day before, being 30.52; the temperature about the same, 72° Fahr. wind light, from a westerly direction, as on the previous day, with a force, as indicated by the anemometer, of 1.2 miles per hour. Having been provided with a number of India-rubber toy balloons, the two vessels were sent off in opposite directions—the Mistletoe toward the west, against the wind, the Cactus toward the east, with the wind, leaving at 10:40 A. M. A change was also made in observing the sound. In these observations the sound was noted at each vessel from the other, the speed of the steamers being the same; the distance between them when the Mistletoe lost the sound of the Cactus was two miles, while the Cactus continued to hear the Mistletoe's sound coming with the wind until they were four miles apart. Simultaneously with this observation a balloon was let off from the Putnam at the light-vessel, which, in its ascent, moved continuously obliquely upward in a line slightly curving toward the horizon, in the direction of the wind at the surface, as far as it could be followed with the eye, indicating a wind in the same direction in the several strata through which it passed, but of a greater velocity in the upper strata.

The vessels now changed places, the Cactus steaming west, the Mistletoe east, the wind having entirely ceased at the surface of the earth. In this case the Cactus lost the sound of the Mistletoe when the vessels were two miles apart, while the Mistletoe continued to hear the sound of the Cactus until they were three miles apart. A balloon let off ascended vertically until it attained an elevation of about one thousand feet, when, turning east, it followed the direction of the previous one. The sound in this case from the east was heard three miles, while that from the west was heard two miles, while in the preceding observations the distances were as 2 to 1; the only changing element, as far as could be observed, was that of the wind at the surface, which became less.

Third trial, 12:45 P. M.—The wind previous to this trial had changed its direction 10 points or about 112½° round through the south, and as indicated by the anemometer at a velocity of 4.8 miles per hour. In this case the Cactus, going against the wind, lost the Mistletoe's sound coming to her against the wind when the vessels were 1 mile apart, while the Mistletoe heard the Cactus, the sound coming to her with the wind when the vessels were 1⅞ miles apart. The several balloons set off at this time were carried by the surface wind westwardly until nearly lost to sight, when they were observed to turn east, following the direction of the wind observed in the earlier observations. The results of the whole series of observations are extremely interesting. In all the experiments the difference in the audibility of the sound in different directions was very marked, and indeed it rarely happens that the sound is equal in two directions, although from the hypothesis adopted this may be possible, since, according to this hypothesis, both the upper and lower currents have an influence upon the audibility of sound in certain directions. From the first trial, the motion of the air being in the same direction both below and above, but probably more rapid above than below on account of resistance, the upper part of the sound-wave would move more rapidly than the lower, and the wave would be deflected downward, and therefore the sound, as usual, heard farther with the wind than against it. In the third experiment of the same day, in which the wind changed to an almost opposite direction, if the wind remained the same above, as we have reason to suppose it did from the observations on the balloons on the second day, the sound should be heard still farther in the same direction or against the wind at the surface, since, in this case, the sound-wave being more retarded near the surface would be tipped over more above and the sound thus be thrown down.

The observations of the second day are also in conformity with the same hypothesis, the change in the wind being probably due to the heating of the land, as the day advanced, beyond the temperature of the water, and thus producing a current from the latter to the former, while the wind observed in the morning from the west was the land-wind due to the cooling of the latter.

In the morning the wind was blowing from the west both in the higher strata and at the surface of the earth, and in this condition the sound was heard farther with the wind than against it.

The wind at the surface about midday gradually ceased, and shortly afterward sprang up from an east direction; in this condition the sound, with the wind at the surface, was heard at a greater distance. This is also in strict conformity with the theory of a change in the form of the sound-wave, as in the latter case the lower portion would be retarded, while the upper portion of the wave would be carried forward with the same velocity, and hence the sound would be thrown down on the ear of the observer. To explain the result of the third trial of the second day, we have only to suppose that the influence of the upper current was less than that of the lower. The conditions for these observations were unusually favorable, the weather continuing the same during the two days, and the change of the wind also taking place at nearly the same hour.

The fact thus established is entirely incompatible with the supposition that the diminution in the sound is principally caused by a want of homogeneity in the constitution of the atmosphere, since this would operate to absorb sound equally in both directions.

In May, 1873, Professor Tyndall commenced a series of investigations on the subject of the transmission of sound, under the auspices of the Trinity House, of England, in which whistles, trumpets, guns, and a siren were used, the last-named instrument having been lent by the Light-House Board of the United States to the Trinity House for the purpose of the experiments in question. The results of these investigations were, in most respects, similar to those which we had previously obtained. In regard to the efficiency of the instruments, the same order was determined which has been given in this report, namely, the siren, the trumpet, and the whistle. Professor Tyndall's opinion as to the efficiency of the siren may be gathered from the following remarks. Speaking of the obstruction of sound in its application as a fog-signal, he says, "There is but one solution of this difficulty, which is to make the source of sound so powerful as to be able to endure loss and still retain sufficient residue for transmission. Of all the instruments hitherto examined by us the siren comes nearest to the fulfillment of this condition, and its establishment upon our coasts will, in my opinion, prove an incalculable boon to the mariner." Professor Tyndall arrived at the conclusions which the information we had collected tended to establish, that the existence of fog, however dense, does not materially interfere with the propagation of sound; and also that sound is generally heard farther with the wind than against it, although the variation of the intensity of the sound is not in all cases in proportion to the velocity of the wind. The result of his investigations in regard to the pitch of sound was also similar to those we have given; and, indeed, all the facts which he has stated are, with a single exception as to the direction of the echo, in strict accordance with what we have repeatedly observed. We regret to say, however, that we cannot subscribe to the conclusions which he draws from his experiments as to the cause of the retardation of sound that it is due to a flocculent condition of the atmosphere, caused by the intermingling with it of invisible aqueous vapor.

That a flocculent condition of the atmosphere, due to the varying density produced by the mingling of aqueous vapor, is a true cause of obstruction in the transmission of sound is a fact borne out by deduction from the principles of wave-motion, as well as by the experiments of the distinguished physicist of the Royal Institution of Great Britain; but from all the observations we have made on this subject we are far from thinking that this is the efficient cause of the phenomena under consideration. A fatal objection, we think, to the truth of the hypothesis Professor Tyndall has advanced is that the obstruction to the sound, whatever may be its nature, is not the same in different directions. We think we are warranted in asserting that in the cases of acoustic opacity which he has described, if he had simultaneously made observations in an opposite direction, he would have come to a different conclusion. That a flocculent condition of the atmosphere should slightly obstruct the sound is not difficult to conceive; but that it should obstruct the ray in one direction and not in an opposite, or in a greater degree in one direction than in another, the stratum of air being the same in both cases, is at variance with any fact in nature with which we are acquainted. We would hesitate to speak so decidedly against the conclusions of Professor Tyndall, for whose clearness of conception of physical principles, skill in manipulation, and power of logical deduction we entertain the highest appreciation, were the facts which were obtained in our investigations of a less explicit character.

While the phenomena in question are incompatible with the assumption of a flocculent atmosphere as a cause, they are in strict accordance with the hypothesis of the refraction of the waves of sound due to a difference in velocity in the upper and lower portions of the currents of air. We do not say, however, that the transmission of sound in the atmosphere is fully investigated, or that the abnormal phenomena which are said to have been observed in connection with fog-signal stations have been fully explained. So far from this, we freely admit we are as yet in ignorance as to how the hypothesis we have adopted is applicable to the critical explanation of the obstruction to sound in the abnormal cases mentioned by General Duane. We feel, however, considerable confidence in its power to afford a rational explanation of these phenomena when the conditions under which they exist shall have been accurately determined.

We are farther confirmed in our conclusion by the publication of an interesting paper in the proceedings of the Royal Society by Professor Osborne Reynolds, of Owens College, Manchester, intended to show that sound is not absorbed by the condition of the atmosphere, but refracted in a manner analogous to the hypothesis which has been adopted in the preceding report.

Much further investigation is required to enable us to fully understand the effects of winds on the obstruction of sound, and to determine the measure of the effect of variations of density in the air due to inequality of heat and moisture. But such investigations can only be made under peculiar conditions of weather and favorable localities, with the aid of a number of steamers, and a series of observers, by whom the transmissibility of the air may be simultaneously observed in different directions. The position which we were so fortunate to obtain in our experiments in the lower bay of New York at the season of the prevalence of land and sea breezes was exceptionally favorable for the study of the action of wind upon sound. It is the intention of the Light-House Board to continue observations in regard to this matter, and to embrace every favorable opportunity for their prosecution under new and varied conditions.

LIGHT-HOUSE BOARD, *October*, 1874.

PART IV.—INVESTIGATIONS IN 1875.*

PRELIMINARY REMARKS.

In the Appendix to the Light-House Report of 1874 I gave an account of a series of investigations relative to fog-signals, which had been made at different times under the direction of the chairman of the committee on experiments.

These investigations were not confined to the instruments for producing sound, but included a series of observations on sound itself, in its application to the uses of the mariner. In the course of these investigations the following conclusions were early arrived at:

1st. That the rays of a beam of loud sound do not, like those of light, move parallel to each other from the surface of a concave reflector, but constantly diverge laterally on all sides; and, although at first they are more intense in the axis of the reflector, they finally spread out so as to encompass the whole horizon, thus rendering the use of reflectors to enforce sound for fog-signals of little value.

2d. That the effect of wind in increasing or diminishing sound is not confined to currents of air at the surface of the earth, but that those of higher strata are also active in varying its transmission.

3d. That although sound is generally heard farther with the wind than against it, yet in some instances the reverse is remarkably the case, espec-

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* From the Report of the Light-House Board, for 1875.

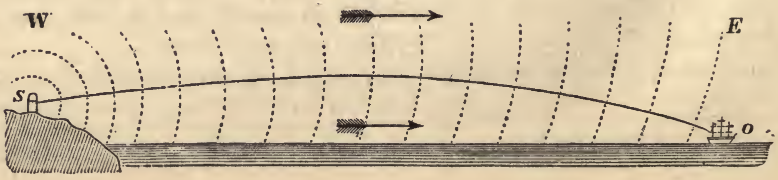
ially in one locality, in which the sound is heard against a northeast snow-storm more distinctly than when the wind is in an opposite direction. This anomaly was referred to the action of an upper current in an opposite direction to that at the earth, such a current being known to exist in the case of northeast storms on our coast. But in what manner the action of the wind increased or diminished the audibility of sound was a problem not solved. It could not be due, as might be thought at first sight, to the acceleration of the sonorous impulse by the addition of the velocity of the wind to that of sound, on the one hand, nor to the retardation of the latter by the motion of the wind, on the other. The inadequacy of this explanation must be evident when we reflect that sound moves at the rate of 750 miles an hour, and therefore a wind of 7½ miles an hour would only increase its velocity one per cent.; whereas the actual increase in audibility produced by a wind of this intensity is in some instances several hundred per cent.

In this state of our knowledge, a suggestion of Professor Stokes, of Cambridge, England, which offered a plausible explanation of the action of the wind, became known to us, and was immediately adopted as a working hypothesis to direct investigations.

This suggestion, the importance of which appears to have escaped general recognition, is founded on the fact that the several strata into which a current of air may be divided do not move with the same velocity. The lower stratum is retarded by friction against the earth and by the various obstacles it meets with, the one immediately above by friction against the lower, and so on; hence the velocity increases from the ground upward—a conclusion established by abundant observation. Now, in perfectly still air, a sounding instrument, such as a bell, produces a series of concentric waves perfectly spherical; but in air in motion the difference of velocity above and below disturbs the spherical form of the sound-wave, giving it somewhat the character of an oblique ellipsoid, by tending to flatten it above—to the windward, and to increase its convexity above—to the leward; and since the direction of the sound is perpendicular to the sound-wave, against the wind it will be thrown upward above the head of the observer, and in the opposite direction downward toward the earth. A similar effect will be produced, but with some variations and perhaps greater intensity, by a wind above, opposite to that at the surface of the earth.

These propositions will be rendered plain by the following illustrations (Figures 1, 2, and 3), for which I am indebted to an article in the American Journal of Science, by William B. Taylor.

Fig. 1.



In these, Figure 1 represents the effect of a favorable wind in depressing the waves of sound, S being the signal-station and O the point of observation. The wind blowing from W to E, as the spheroidal faces of the sonorous waves become more pressed forward by the greater velocity of the wind above, assuming it to be retarded at the surface by friction, and the direction of the acoustic beam being constantly normal to the wave-surfaces, the lines of direction of the sound will gradually be bent downward and reach the ear of the observer with an accumulated effect at the point O.

Fig. 2.

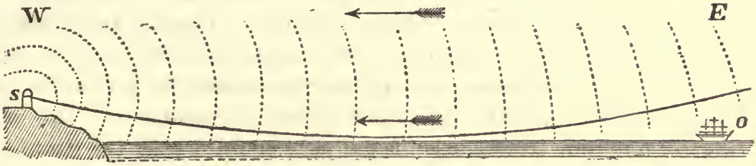


Figure 2 represents the ordinary effect of an opposing wind blowing from E to W against the sound; the wave-faces being more resisted above than below, assuming as before a retardation at the surface, the sound-beams are curved upward, and the lowest ray that would reach, in still air, the distant observer at O, is gradually so tilted up that it passes above the ear of the listener, leaving him in an acoustic shadow.

Fig. 3.

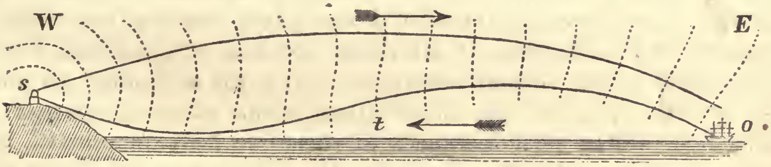


Figure 3 represents the disturbing effect of two winds, the lower in opposition to the sound at the surface, and the upper with it. In this case the principal effect will be a depression of the sound-beam, similar to that shown in Figure 1, but more strongly marked, as the difference of motion will be greater as we ascend. Attending this action, says Mr. Taylor, there will probably be some lagging of the lower stratum by reason of the surface-friction, the tendency of which will be to distort the lower part of the sound-waves, giving them a reverse or serpentine curvature. In this case the upper ray of sound would only have a single curvature, similar to that shown in Figure 1, while the lower rays would be represented by the lower line S O, rendering the sound less audible at an intermediate point, *t*, than at the more distant station O. This hypothetical case of compound refraction offers a plausible explanation of the paradox of a nearer sound being diminished in power by the wind which increases the effect of a more distant one.

In these figures and all the succeeding ones the direction of the wind is indicated by arrows.

The hypothesis we have adopted in connection with the fact of the lateral spread of sound gives a simple explanation of various abnormal phenomena of sound such as has been observed in the previous investigations, and of which the following are examples: First, the audibility of a sound at a distance, and its inaudibility nearer the source of sound; second, the inaudibility of a sound at a given distance in one direction, while a lesser sound is heard at the same distance in an opposite direction; third, the audibility of the sound of an instrument at one time at the distance of several miles, while at another time the sound of the same instrument cannot be heard at more than a fifth of the same distance; fourth, while the sound is heard generally farther with the wind than against it, in some instances the reverse is the case; fifth, the sudden loss of sound in passing from one locality to another in the same vicinity, the distance from the source of the sound being the same.

The first four of these phenomena find a ready explanation in the hypothesis adopted by supposing an increase or diminution in the relative velocity of the currents of wind in the upper or lower strata of air. The fifth is explained by the interposition of an obstacle which casts, as it were, a sound-shadow, disappearing at a given distance by the divergence of the rays on each side of the obstacle into what would be an optical shadow.

Accounts of these investigations were presented from time to time to the Light-House Board, and to the Philosophical Society of Washington in 1872. Subsequently a series of investigations on the same subject was instituted in England by the Elder Brethren of the Trinity House, under the direction of their scientific adviser, the celebrated physicist, Dr. Tyndall. While in the latter investigations various abnormal phenomena, similar in most instances to those we have mentioned, were observed, they were referred by Dr. Tyndall to an entirely different cause, viz, to the existence of acoustic clouds, consisting of portions of the atmosphere in a flocculent or mottled condition, due to the unequal distribution of heat and moisture, which, absorbing and reflecting the sound, produce an atmosphere of acoustic opacity. While we do not deny the possible existence of such a condition of the atmosphere, we think it insufficient to account for all the phenomena in question, and believe that a more general and efficient cause is that of the *wind*, in accordance with the hypothesis of Professor Stokes.

We regret to differ in opinion from Dr. Tyndall, and have published our dissent from his views in no spirit of captious criticism or desire to undervalue the results he has obtained, some of which are highly important. Our only object in our remarks and in our investigations is the establishment of truth.

The determination of the question as to the cause of the abnormal phenomena of sound we have mentioned, and the discovery of new phenomena, are not mere matters of abstract scientific interest, but are of great practical importance, involving the security of life and property, since they include the knowledge necessary to the proper placing of fog-signals, and the instruction of mariners in the manner of using them.

The hypothesis we have adopted, that of the change of direction of sound by the unequal action of the wind upon the sound-waves, is founded on well-established mechanical principles, and offers a ready explanation of facts otherwise inexplicable. It is also a fruitful source from which to deduce new consequences to be verified or disproved by direct experiment. It would however ill become the spirit of true science to assert that this hypothesis is sufficient to explain all the facts which may be discovered in regard to sound in its application to fog-signals, or to rest satisfied with the idea that no other expression of a general principle is necessary. An investigation however to be fruitful in results, as a general rule, must be guided by *a priori* conceptions. Hap-hazard experiments and observations may lead to the discovery of isolated facts, but rarely to the establishment of scientific principles. There is danger however in the use of hypotheses, particularly by those inexperienced in scientific investigations, that the value of certain results may be overestimated, while to others is assigned less weight than really belongs to them. This tendency must be guarded against. The condition of the experiment must be faithfully narrated, and a scrupulously truthful account of the results given. While we have used the hypothesis above mentioned in the following investigations as something more than an antecedent probability, we have not excluded observations which may militate against it, and we hold ourselves ready to admit the application of other principles, or to modify our conception of those we have adopted, when new facts are discovered which warrant such changes. But we require positive evidence, and cannot adopt any conclusions which we think are not based upon a logical correlation of facts.

The investigations described in the following account, though simple in their conception, have been difficult and laborious in their execution. To be of the greatest practical value they were required to be made on the ocean, under the conditions in which the results are to be applied to the use of the mariner, and therefore they could only be conducted by means of steam-vessels of sufficient power to withstand the force of rough seas, and at times when these vessels could be spared from other duty. They also required a number of intelligent assistants skilled in observation and faithful in recording results.

OBSERVATIONS IN AUGUST, 1875, AT BLOCK ISLAND.

The party engaged in these investigations consisted of the chairman of the Light-House Board; General Woodruff, U. S. A., engineer third light-house district; Dr. James C. Welling, president of Columbian University, Washington, D. C.; Mr. T. Brown, of New York, patentee of the siren; Mr. Edw. Woodruff, assistant superintendent of construction; and Captain Keeney, commander of the light-house steamer Mistletoe.

They arrived at Block Island on the afternoon of the 4th of August, 1875. This place was chosen as the site of the experiments, first, on account of its insular position, being as it were in the prolongation of the axis of Long Island, distant fifteen miles from the most easterly part of the latter, and entirely exposed to the winds and waves of the Atlantic Ocean; and, secondly, because there are on Block Island two light-houses, one of which is of the first order, and connected with it are two fog-signals, one of them with the latest improvements. (See Fig. 4.)

OBSERVATIONS IN REGARD TO THE AERIAL ECHO.

This phenomenon has been frequently observed in the researches of the Light-House Board, in case of powerful sounds from the siren and from the fog-trumpet.* It consists of a distinct reflection of sound as if from a point near the horizon in the prolongation of the axis of the trumpet. The question of the origin of this echo has an important bearing, according to Dr. Tyndall, on the explanation of the abnormal phenomena of sound we have mentioned. He refers it to the non-homogeneous condition of portions of the air, which reflect back the waves of sound in accordance with the analogy of the reflection of light at the common surface of two media of different densities. We have adopted, as a provisional hypothesis, that it is due to the reflection from the waves and the larger undulations of the surface of the ocean, in connection with the divergency of beams of powerful sounds. To bring these hypotheses to the test of a crucial experiment, arrangements were made, under the direction of Mr. Brown, to change the direction of the axis of one of the sirens from the horizontal to the vertical position.

The first observations were made August 5, with the siren in its usual horizontal position, while the air was so charged with fog as to render the sound of the instrument necessary for the guidance of the mariner, the image of the sun being obscured and the land invisible from the sea. Under these conditions an echo was heard when the pressure of the steam reached 50 pounds per square inch. The reflection in this case, as usual, was from a point in the sea-horizon in the prolongation of the axis of the trumpet. It was not, however, heard more distinctly when standing near the origin of the sound than at several hundred feet on either side of it. The interval between the cessation of the original sound and the commencement of the echo was not as marked as in some previous observations, not being more than four or five seconds. The

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* The same phenomenon is mentioned by Froissart in his account of the embarkation of the expedition of the French and English to the coast of Africa to assist the Genoese against the pirates in 1390. "It was a beautiful sight," says the chronicler, "to view this fleet, with the emblazoned banners of the different lords fluttering in the wind, and to hear the minstrels and other musicians sounding their pipes, clarions, and trumpets, whose sounds were re-echoed back by the sea." (See Illustrations of Froissart by H. N. Humphrey, Plate IV.)

duration of the echo was on the average about eight seconds, beginning with the time of its first perception, and not with the cessation of the sound of the trumpet. General Woodruff and Doctor Welling both noted the peculiar character of the echo, which was that of a series of reflections varying in intensity from a maximum, near the beginning, and gradually dying away. The wind was nearly at right angles to the axis of the trumpet and also to that of the crests of the swell of the ocean, which was rolling in from the effects of a commotion without. The barometer at 12 M. indicated 30.2 inches; the dry-bulb thermometer 73° F. the wet-bulb 70° F. indicating a remarkable degree of aqueous saturation. During the whole day the air in all the region around Block Island was undoubtedly in a homogeneous condition.

August 6.—On this day the weather was nearly the same. The fog-signal on the 5th instant was kept in operation for the use of the mariner nineteen hours, and on this day it was blown twenty hours continuously. The barometer marked 30.20 inches; the thermometer 70° F.; the fog not as equally distributed as on the preceding day; the north end of the island, distant four miles, being distinctly visible. The wind was S. W. to S., making an angle of about 60° with the axis of the fog-trumpet. The echo continued to be heard distinctly with a sound varying in intensity, but was not as loud as we have heard it on certain occasions in previous years.

During this and the preceding day, workmen were employed under Mr. Brown in inserting a flexible India-rubber tube, two inches in diameter, between the revolving plate of the siren and the smaller end of the trumpet, so that it might be brought into a vertical position. This work, though apparently simple, was difficult in execution, since it involved the necessity of strong supports for the cast-iron trumpet, which in itself weighed eight hundred pounds, and also of a union of the parts of sufficient strength to resist the pressure of the steam at fifty pounds to the square inch.

August 7.—Wind from the S. S. W. Fog continued; the workmen had not as yet completed the attachment.

August 9.—Barometer 30.30 inches at 12 M. Dry-bulb thermometer 74° F.; wet bulb 71°.5. Wind S. S. W. Fog dense along the south coast, but light over all the northern portion of the island. The echo was heard all day, not very loudly, but distinctly. Siren still horizontal, the arrangement for elevating it not having been, at 10 a. m., completed. Experiments were made on the reciprocal sounds of the whistles from two steamers, the results to be given hereafter. At 5 P. M. the adjustment of the flexible tube to the smaller end of the trumpet was finished, which, giving an additional length to the instrument of about 5 feet, threw it out of unison with the siren proper. To restore this unison the speed of revolution of the perforated plate was diminished, and after this the trumpet, still being horizontal, was sounded. An echo similar in character to those which had been observed on the preceding day, and the earlier part of the same day, was produced.

August 10.—Barometer 30.10 inches. Dry bulb 74°; wet bulb 69° F. Wind W. S. W.; atmosphere hazy. Observations first made with the trumpet horizontal. Echo as that of preceding days, distinct but not very loud, and coming principally from the portion of the horizon in the direction of the axis of the trumpet. The position of the trumpet was then changed, its axis being turned to the zenith in order to make what was thought might be a crucial experiment. When the trumpet was now sounded a much louder echo was produced than that which was heard with the axis of the trumpet horizontal, and it appeared to encircle the whole horizon; but though special attention was directed to the point by all the party present, no reverberation was heard from the zenith. The echo appeared however to be more regular and prolonged from the ocean portion of the horizon than from that of the land.

In this experiment, while there was no reflection from the zenith in which the sonorous impulse was strongest, there must have been reverberations from the surface of the land and the ocean. This will be evident when we consider the great divergency of sound by which sonorous waves from a vertical trumpet are thrown down to the plane of the horizon on every side, some of which, meeting oblique surfaces, must be reflected back to the ear of the observer near the source of the sound. This inference will be more evident when it is recollected that the reflected rays of sound diverge as well as those of the original impulse. Hence reflection from the surface of the sea is a true cause of the echo, but whether it be a sufficient one may require further investigation. For this explanation it is not necessary that the sea should be covered with crested waves; a similar effect would take place were the surface perfectly smooth but in the form of wide swells, which in places exposed to an open sea are scarcely ever absent. Moreover, the increased loudness of the echo is a fact in accordance with the same view.

The observations were repeated with the same effect on succeeding days, until this class of experiments was ended by the bursting of the India-rubber tube. Had a distinct echo been heard from the zenith, the result would have been decidedly in favor of the hypothesis of a reflection from the air; but as this was not the case the question still remained undetermined, especially since the atmosphere during these experiments was evidently in a homogeneous condition. We do not agree however in the position taken in the report of the Trinity Board, that on the origin of this echo depends the whole solution of the problem as to the efficient cause of the abnormal phenomena of sound. The ingenious experimental illustrations of the reflection of sound from a flame or heated air, establish clearly the possibility of such reflection; but it must be remembered they were made under exaggerated conditions, the atmosphere being in a state of extreme rarefaction in a limited space, and the sound of a feeble character, while the phenomena in nature are produced with a comparatively small difference of temperature and with powerful sounds.

EXPERIMENTS AT BLOCK ISLAND

RELATIVE TO THE EFFECT OF ELEVATION ON AUDIBILITY.

For this investigation the first-order light-house at Block Island offered peculiar facilities. It is situated near the edge of a perpendicular bluff, 152 feet above the sea. The tower being 52 feet above the base, gives a total height to the focal plane of the lens of 204 feet, on the level of which the ear of the observer could be placed.

The first and second experiments of this class were made on the 10th of August, with two light-house steamers, the Putnam and the Mistletoe, moving simultaneously in opposite directions. The barometer indicated 30.10 inches of atmospheric pressure; the dry-bulb thermometer indicating 74° F., and the wet-bulb 69°. The wind at the time of the experiments was from the west, and of a velocity of seven miles per hour. The vessels started from the point C, Fig. 4, opposite the light-house, A, about one mile distant, a position as near the shore as it was considered safe to venture. The Putnam steamed with the wind, the Mistletoe steamed against the wind, each blowing its whistle every half minute. The duration of the sound was noted at the top of the tower and at the level of the sea, Mr. Brown being the observer at the latter station, while the chairman of the board, with an assistant, observed at the former. On comparing notes, the watches having been previously set to the same time, it was found—

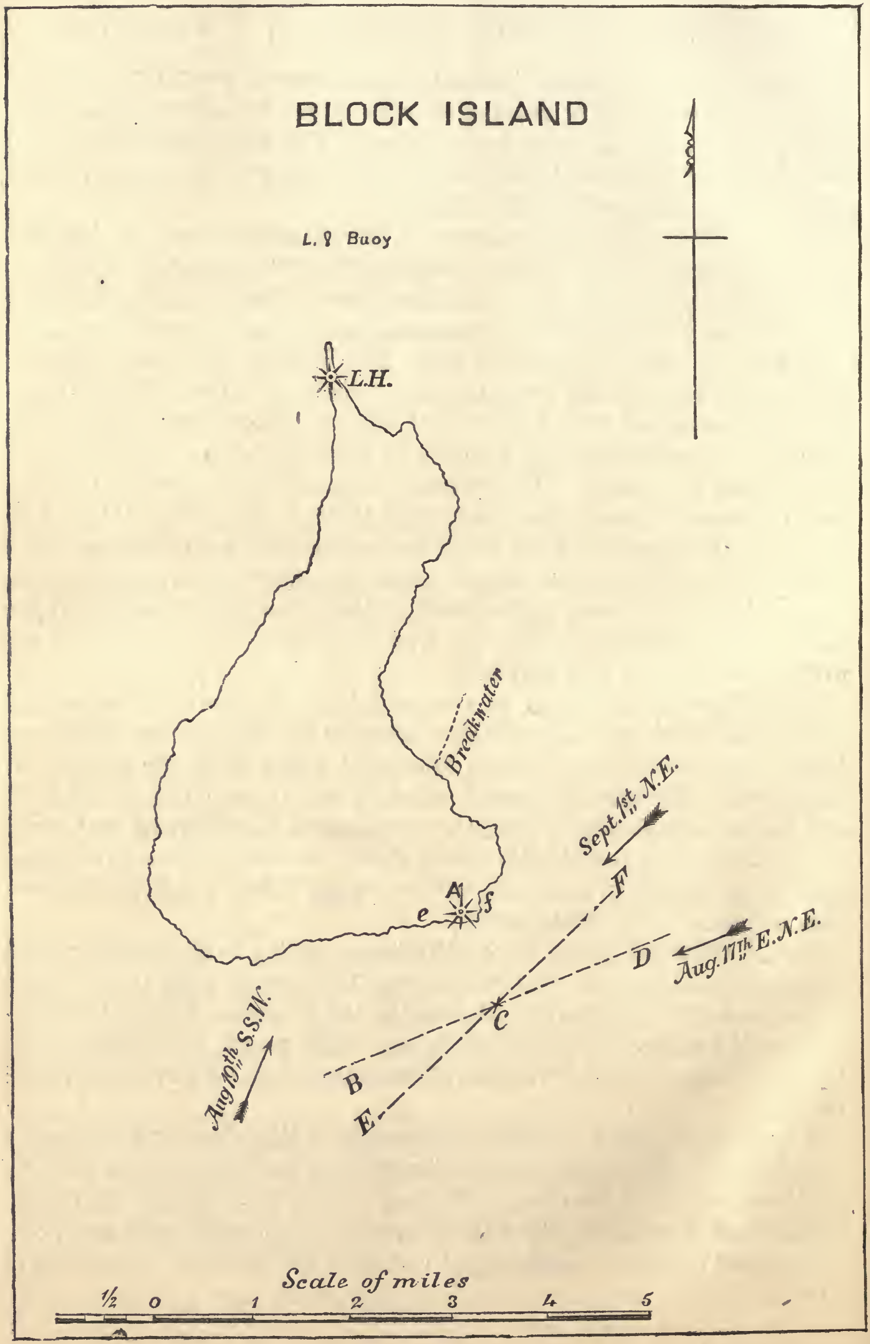
First. That the duration of the sound on the tower, when coming against the wind, was nine minutes, while at the base of the cliff it was heard only one minute. It was afterward found from the records on board of the Putnam, the sound of which came against the wind, that this vessel was moving, during the experiment, at half-speed, and hence the duration of the sound on the tower should be considered as 4½ minutes, and the difference in favor of audition on the tower 4 minutes instead of 8, as given by the first record.

Second. That the sound of the Mistletoe, coming to the observer with the wind, was heard on the tower during 15 minutes, while it was heard at the base of the cliff during 34 minutes, the difference being 19 minutes in favor of hearing at the level of the sea. This result, which differs from that of all the other experiments of the same class, deserves special attention.

After making the foregoing experiments of this class, and others, on the effect of wind on sound, to be described in the next section, the vessels were called off for other duty, and the investigations were not resumed until August 17, when the following experiments were made:

The third experiment.—The wind was from the E. N. E., at the rate of about five miles per hour at the surface, and a greater velocity at the height of the tower. Barometer, 30.25 ins.; thermometer, 72°.

Fig. 4.



In this and the subsequent experiments of the same day but one steamer—the Mistletoe—was employed. It started at 10:30 A. M. from the point C, Fig. 4, at the foot of the cliff, and steamed W. S. W. along C B for about 12 minutes, or a distance of two miles, blowing the whistle every half-minute. To note the duration of the sound, Dr. Welling was stationed at the foot of the cliff, at the level of the sea, while the chairman of the Light-House Board, with an assistant who acted as clerk, was on the upper gallery of the tower, the ears of the latter being almost precisely 200 feet above those of the observer at the foot of the cliff.

The watches having been previously set to the same time, on comparing results it was found that the whistle was heard at the top of the tower for twelve minutes and at the bottom of the cliff for five and one-half minutes, making the difference in favor of audition on the tower six and one-half minutes. In this experiment the sound came to the observers nearly against the wind.

The *fourth experiment* consisted in directing the Mistletoe to proceed in the opposite direction from the same point, along the line C D. It started at 11:5 A. M. the breeze being light at the time, and proceeded about two and one-half miles before the sound was lost to the observers. On comparing notes it was found that the sound was heard at the top of the tower during fifteen minutes, and at the level of the sea for eleven minutes, giving a difference in favor of the hearing on the top of the tower of four minutes.

In the *fifth experiment*, the Mistletoe steamed again in the direction with the wind, the sound from its whistle coming to the ears of the observers against the wind. Starting about 11:45 A. M. and steaming about two miles, the sound was heard on the tower during twelve minutes and at the foot of the cliff during five and one-half minutes, making a difference of six and a half minutes in favor of audition on the tower. Previous to this experiment the wind had veered one point to the west, bringing the direction of the sound to the observers in less direct opposition to the wind than in the last experiment.

The sixth experiment.—In this case the steamer was directed to proceed in the opposite direction, or against the wind, so that the sound of the whistle would reach the ear of the observers in the same direction as that of the wind. It started at 12:19 P. M. and proceeded two and one-sixth miles; the whistle was heard during thirteen minutes on the top of the tower, and at the bottom of the cliff during precisely the same time, the difference between the top of the tower and the bottom of the cliff in this case being nothing.

The vessel having again been called off on other duty the *seventh experiment* was made the 1st of September. On this day the wind was northeast; the velocity at the top of the tower was thirteen and a half miles per hour, and at the bottom of the tower eleven miles per hour. The barometer indicated 30.20 inches pressure, the dry bulb 72°, and the wet bulb 67½°.

The theoretical conditions for exhibiting the effect of height on audition in this experiment were much more favorable than any of the preceding. First, the velocity of the wind was greater; second, the difference between the velocities at top and bottom of the tower was well marked, and the direction of the wind was more favorable for direct opposition to the sound as it came to the ear of the observer. In this case General Woodruff was the observer at the bottom of the cliff, while the chairman of the Light-House Board and his assistant, with several visitors, were at the top of the tower.

The steamer started at 10:58 A. M. and proceeded during eight minutes, or a mile and one-third, when the sound was lost at the top of the tower. In this case, though the sound was heard for eight minutes from the top of the tower, and the first five blasts marked on the notes as quite loud, it was not heard at all at the bottom of the cliff at least a hundred yards nearer the source of the sound.

This result, which interested and surprised a number of intelligent visitors, who were in the tower at the time, strikingly illustrates the effect of elevation on the audibility of sound moving against the wind. The result was so important that it was thought advisable to immediately repeat the experiment under the same conditions.

In the *eighth experiment*, the Mistletoe was again directed to proceed, in the direction of the wind, along the line it had previously traversed. It started at 11:25 A. M., and proceeded during six minutes, or one mile, when the sound was lost at the top of the tower. In this case, the first blast of the whistle was feebly heard at the base of the cliff, but no other, while thirteen blasts were heard at the top of the tower, of which the first six were marked as loud.

That this remarkable effect was not produced by an acoustic cloud or a flocculent atmosphere is evident from the experiment which immediately succeeded.

The ninth experiment.—In this trial, the Mistletoe was directed to proceed against the wind, so that the sound of its whistle should come to the ears of the observers with the wind. It started at 11:48 A. M., and proceeded during sixteen minutes, or two and two-thirds miles, when the sound of its whistle was lost to the observers on the top of the tower. In this case the sound of the whistle became audible at the bottom of the cliff as soon as the position of the vessel became such as to bring the sound to the observers approximately with the wind, and continued to be audible during fifteen minutes, or within one minute as long as the sound was heard at the top of the tower.

It may be mentioned as an interesting fact, that an assistant who was observing the sound with General Woodruff at the foot of the cliff, when the sound could not be heard at the level of the sea, in the sixth experiment perceived it distinctly by ascending the side of the cliff to a height of twenty-five or thirty feet.

All the conditions and results of these experiments are strikingly in conformity with the theory of the refraction of sound which we have previously explained.

The following recapitulation of the results of the foregoing experiments will exhibit their correspondence with the general theory:

Sound heard coming against the wind.

Experiments.	Duration at the top of the tower.	Duration at the base of the cliff.	Difference in favor of audition on the tower.
First	4½ minutes	½ minute	4 minutes.
Third	12 minutes	5½ minutes	6½ minutes.
Fifth	12 minutes	5½ minutes	6½ minutes.
Seventh	8 minutes	Not heard	8 minutes.
Eighth	6 minutes	First blast heard, but no other, ½ minute after starting.	5½ minutes.
	42½ minutes	12 minutes.	30½ minutes.
Average	8½ minutes	2.4 minutes	6.1 minutes.

Sound heard coming with the wind.

Experiments.	Duration at the top of the tower.	Duration at the base of the cliff.	Difference in favor of audition at base of cliff.
Second	15 minutes	34 minutes	19 minutes.
Fourth	15 minutes	11 minutes	— 4 minutes.
Sixth	13 minutes	13 minutes	0 minutes.
Ninth	16 minutes	15 minutes	— 1 minute.
	59 minutes	73 minutes	14 minutes.
Average	14¾ minutes	18¼ minutes	3½ minutes.

From the first of the foregoing tables it appears that the elevation of the observer has a marked effect on the audition of sound moving against the wind while, from the second, with one important exception, it has very little, if any, effect on sound moving with the wind. Another experiment relative to the same class of phenomena was made on the 19th of August (see Fig. 4), the wind being S. S. W. Two observers, General Woodruff and Dr. Welling, starting from the bottom of the cliff immediately below the light-house, went along the beach, the one in the direction A *f*, and the other in direction A *e*. General Woodruff found that the sound of the siren was distinctly heard all the way to the breakwater, and was so loud that it probably could have been heard for several miles in that direction. Dr. Welling, on the contrary, entirely lost the sound within a quarter of a mile of the light-house. This result is readily explained as a case of lateral refraction; the wind was in the direction traversed by General Woodruff, and contrary to that pursued by Dr. Welling. In the one case the wind, retarded by the surface of the cliff, moved with less velocity than it did farther out, and consequently the sound was thrown against the face of the cliff, and on the ear of the observer, and in the other thrown from it, thus leaving, as it were, a vacuum of sound. The effect in the case was very striking, since the siren was pointed toward the zenith, and the sound in still air could have been heard for miles in every direction.

INVESTIGATIONS AT BLOCK ISLAND

IN REGARD TO THE EFFECT OF WIND ON AUDIBILITY.

These were made by the aid of two steamers. Captain Walker, naval secretary of the board, having completed a series of inspections in the Third District, sent the steamer Putnam, under Captain Fields, to aid the Mistletoe in the investigations. They were commenced on the 9th of August, at 12 o'clock. The wind was S. S. W. with a velocity of 7¼ miles per hour. Barometer, 30.3 inches; thermometer, dry bulb, 74° F. wet bulb, 71½° F.

The two steamers started from a buoy near the north end of the island, the one steaming against the wind, and the other with it, each blowing its whistle every minute. The distance travelled by each steamer was estimated by the running time, which, from previous observations, was found to be ten miles per hour. Each vessel was furnished with a whistle of the same size, of 6 inches diameter, actuated by the same pressure of 20 pounds of steam, and which, by previous comparison, had been found to give sound at this pressure of the same penetrating power. The observations on the Mistletoe were made by General Woodruff, and on the Putnam by Dr. Welling, each assisted by the officers of the respective vessels. The two steamers proceeded to buoy off the north end of the island, in which position the wind was unobstructed by the land—a low beach. Indeed, the island being entirely destitute of trees, and consisting of a rolling surface, the wind had full sweep over it in every direction.

First experiment.—The Putnam went against the wind and the Mistletoe in the opposite direction. The Putnam lost the sound of the whistle of the Mistletoe in two minutes and stopped, but continued to blow the whistle. The Mistletoe continued on her course and heard the Putnam's whistle for twenty minutes in all. During the first two minutes both vessels were in motion, and therefore the space through which the sound was heard moving against the wind would be represented by 4, while the space through which the sound was heard moving with the wind would be represented by 20 + 2 = (22), the ratio being 1 : 5½.

Second experiment.—In this the Putnam went with the wind and the Mistletoe in the opposite direction. The Mistletoe lost the sound of the Putnam's whistle in two minutes. The Putnam then stopped and remained at rest, while the Mistletoe continued on her course until the Putnam lost sound of her whistle, twenty-six minutes later. As both steamers were separating during the first two minutes with equal speed, the distance travelled by the sound heard moving against the wind is represented by 4, while the distance of the sound heard with the wind is represented by 26 + 2=28, the ratio being 1 : 7. It should be mentioned, however, that the notes in this experiment are defective and somewhat discrepant.

Third experiment.—The Putnam went against the wind, the Mistletoe in the opposite direction. The Putnam lost the sound of the whistle of the Mistletoe in two minutes, while the Mistletoe continued to hear the whistle of the Putnam ten minutes longer. Owing to a misunderstanding, one of the steamers stopped for two minutes and then resumed its course. As both steamers were separating during the first two minutes with equal speed, the distance of the sound heard moving against the wind is represented by 4, while the sound heard with the wind through a space denoted by 2 × 10 + 4—2=22, the ratio being 1 : 5½.

Fourth experiment.—The vessels again changed directions, the Putnam going with the wind, and the Mistletoe in the opposite direction. The Mistletoe lost the sound in two minutes, and the Putnam nine minutes later. As each steamer was moving from the other at the same rate, the distance of the sound heard moving against the wind would be represented by 4, while the distance of the sound moving with the wind would be represented by 9 × 2 + 4=22, the ratio being again 1 : 5½.

Fifth experiment.—This experiment was made August 10, by the same vessels and same observers, wind W. S. W., of about the same intensity as on previous days; barometer, 30.1 ins.; dry bulb, 74° F. wet bulb, 69°. The Putnam steamed against the wind, and the Mistletoe in the opposite direction. The Putnam lost the sound in two minutes, and the Mistletoe nine minutes later. The two vessels moving apart with equal velocity, the space traversed by the sound moving against the wind was represented by 4, while that in the opposite direction was represented by 22, viz, 9 × 2 + 4=22.

Sixth experiment.—The vessels were next separated in a direction at right angles to the wind, when each reciprocally lost the sound of the other on an average of six minutes, giving a distance travelled by the sound, while audible, of twelve spaces.

Seventh experiment.—The vessels were next directed along an intermediate course between the direction of the wind and a line at right angles to it, with the following results : The Mistletoe, against the wind, lost the sound in about two minutes, while the Putnam heard the sound seven minutes longer. As in the previous case, the two vessels moving apart with equal velocity would in two minutes be separated by a space represented by 4, which would indicate the audibility of the sound moving against the wind, and for the same reason the other vessel, hearing the sound seven minutes longer, would have the additional space represented by 14, and adding to this four spaces, we have 18 to represent the audibility of the sound in the direction approximating that of the wind.

The following table exhibits at one view the results of the foregoing experiments, which relate to sound moving against the wind, and with the wind, reduced to miles.

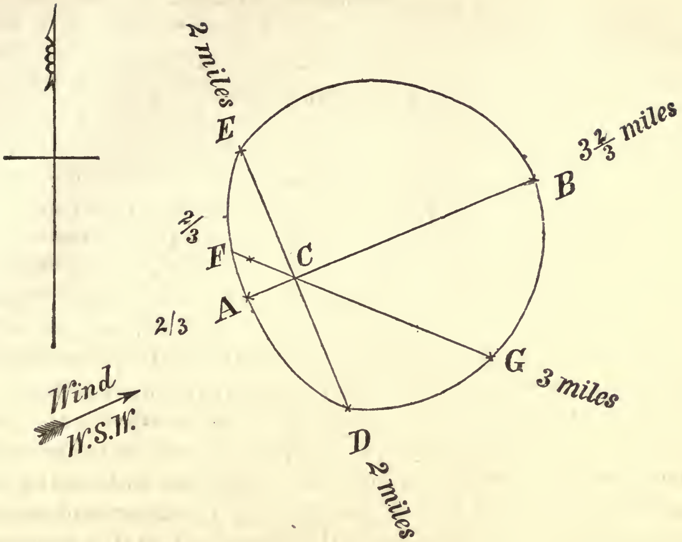
Experiment.	Sound with the wind.	Sound against wind.
	Miles.	*Miles.*
1	3. 66	0.66
2	4. 66	0.66
3	3. 66	0.66
4	3. 66	0.66
5	3. 66	0.66

These results are in accordance with those of all the direct observations which had previously been made on sound in regard to wind by the Light-House Board, with the exception of those at Sandy Hook in September, 1874, as given in the last report, in which the sound was heard from a steamer farther against the wind than in the direction of the wind. This anomaly was explained by the existence of an upper current of air, moving in an opposite direction to that at the surface, in accordance with the hypothesis of the refraction of sound.

It will be observed that four of the experiments give exactly the same distances to represent the audibility of sound with and against the wind. This coincidence was not observed until after the notes were collated for discussion, and, if not accidental, was due to the equal velocity of the wind and the general conditions of the atmosphere on the two days.

To give a definite idea of these relations we have plotted the results obtained on August 10, in Fig. 5, converting the distances into miles and referring them to a common center, and tracing through the several extremities of the lines representing the distances a continuous line, which may be designated as the curve of audibility. C being the center to which the sounds are referred, C A represents the distance at which the sound was heard against the wind, and C B in the direction of the wind, while C E and C D represent the distance at right angles to the wind, and F C and C G the distances respectively with and against the wind on an intermediate course.

FIG. 5.



The curve which is presented in the foregoing figure may be considered as that which represents the normal limit of audibility during the two days in which the experiments were made. The line D E divides the plane of the curve into two unequal portions, D A F E and D G B E, the former representing the audibility of sound moving against the wind, and the other the audibility of sound moving with the wind.

We can scarcely think that any other condition of the air than that of its motion could produce a result of this kind. It exhibits clearly the fact that sound is not heard as a general rule at right angles to the wind farther than with the wind, as has been asserted. In this case the ratio of the latter to the former is as 11 to 6, or nearly double.

The investigation of the relation of wind to the penetration of sound was renewed in a series of subsequent experiments, the results of which are to be given in a succeeding part of this report.

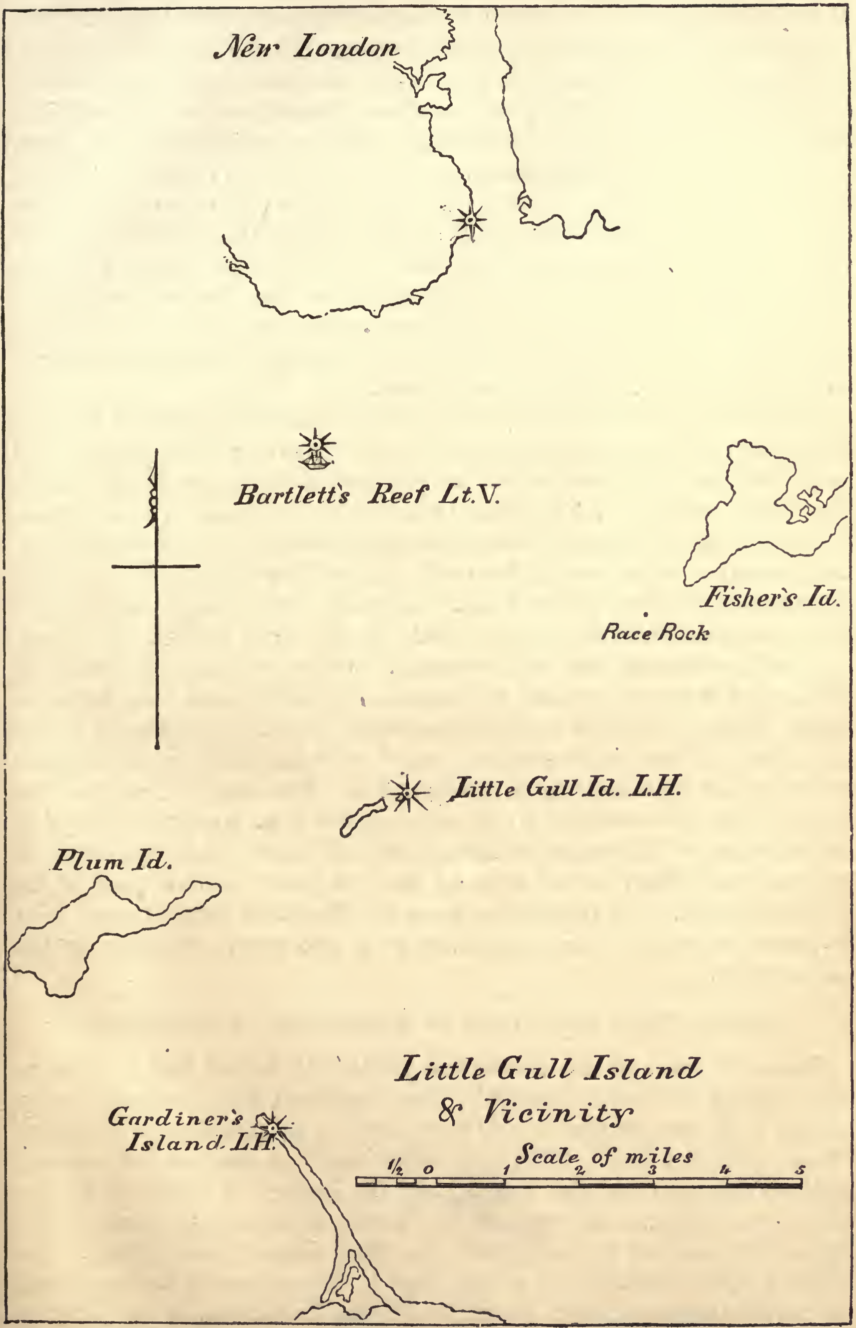
It should be observed, in comparing Fig. 5 with the subsequent figures representing the curve of audibility, that the arrow representing the direction of the wind points in the longest direction to the figure, whereas in other figures the pointing is in the opposite direction. The difference arises from the fact that in Fig. 5 the sound is supposed to radiate from the center, C, while in the others the sound converges to the center as a point of observation. The foregoing diagram and all that follow in this report were plotted by Mr. Edward Woodruff, assistant superintendent of construction of the third light-house district.

EXPERIMENTS AT LITTLE GULL ISLAND, SEPTEMBER, 1875.

The next series of experiments made during this season was at Little Gull Island, at the east end of Lond Island Sound. This location was chosen on account of its convenience of approach from the harbor of New London, seven miles distant, at which the light-house steamers of the third district usually remain when not engaged in active service, and also because there is a light-house on the island furnished with two sirens of the second order, and an extent of water on every side which would allow the vessels used in the experiments to proceed from the island as a center to a considerable distance in every direction. The island itself is a small protuberance above the water, merely sufficient in area to support a raised circular platform of about 100 feet in diameter, on which the light-house and other buildings are erected. The following sketch (Fig 6) will give an idea of the position of Gull Island relative to the main-land and the islands in the vicinity.

From this it will be seen that the position was not the most favorable for a stable condition of the atmosphere. As the heat of the sun increases during the first part of the day, the temperature of the land rises above that of the sea; and this excess of temperature produces upward currents of air, disturbing the general flow of wind both at the surface of the sea and at an elevation above. But although the locality was unfavorable for obtaining results tending to exhibit the effects of broad currents of wind flowing in one direction, it had the advantage of offering more varied phenomena than could otherwise have been exhibited. Before commencing the experiments, directions were given to attach a rotating iron neck to the trumpet of one of the sirens, in order that it might be directed to the zenith; while the other siren remained with its axis in a horizontal direction. The observers in these investigations consisted of the chairman of the board; General Woodruff, engineer third district; Porter Barnard, assistant superintendent of construction; Captain Keeney, and other officers of the Mistletoe; with an assistant who acted as one of the observers and recording clerk. The Mistletoe was daily employed, though on two occasions the Cactus, another of the light-house steamers, rendered assistance.

Fig. 6.


New London
Bartlett's Reef Lt.V.
Fisher's Id.
Race Rock
Little Gull Id. L.H.
Plum Id.
Little Gull Island & Vicinity
Scale of miles
½ 0 1 2 3 4 5
Gardiner's Island L.H.

OBSERVATIONS ON THE ECHO AT LITTLE GULL ISLAND.

The first observations to be mentioned are those relating to the echo; the results, however, in regard to this are not very satisfactory. The sirens were of the second order, and therefore the echoes produced were not as distinct as those from the larger instrument at Block Island. The echo from the horizontal trumpet was distinct, and in the prolongation of its axis; the interval however between the blast of the siren trumpet and the commencement of the echo was very brief; so short, indeed, that the ending of the one and the beginning of the other were generally difficult to distinguish. A slight leak in the apparatus of the siren produced a continuous hum, which interfered somewhat with the distinct appreciation of the sound of the echo. The keeper thought the weather was not favorable for the production of echoes. He thinks they are heard most distinctly during a perfect calm, which did not occur during the course of these investigations.

The axis of the siren with the movable trumpet being directed to the zenith, strict attention was given by all the observers to any echo which might be produced from it; but in this case, as in that at Block Island, the slight echo which was heard came from all points of the horizon. On one occasion General Woodruff called attention to a small cloud passing directly over the zenith, from which a few drops of rain fell upon the platform on which the light-house is erected. Advantage was taken of this occurrence to direct strong blasts of the siren toward the cloud, but no perceptible echo was returned. We have failed, therefore, in this series of investigations, to obtain any positive facts in addition to those already known as to the character of the echo. In regard to the hypothesis offered for its explanation, if we found little in its support, we have met with nothing to invalidate it. But whatever may be the cause of the phenomenon, we do not consider it an important factor in explanation of the results we have obtained, since it was too feeble to produce any effect in the way of absorbing any notable part of the original sound. Its importance from Dr. Tyndall's point of view is its apparent support of the hypothesis of a flocculent condition of the atmosphere.

OBSERVATIONS ON EFFECT OF ELEVATION ON AUDIBILITY.

The next class of experiments at Little Gull Island had relation to the effect of elevation on sound. The conditions here, however, for arriving at definite results on this point were by no means as favorable as those at Block Island. The height which could be commanded was only that of the tower of the light-house, the gallery of which is 74 feet above the platform upon which the buildings are erected, and 92 feet above the level of the sea, much less than that at Block Island. Besides this, the variableness of the wind at the surface of the ocean and at heights above was not favorable for the illustration of the point in question.

The theoretical conditions in order that the sound may be heard with greater distinctness at an elevation than below are, as we have said before, that the wind be moving with a greater velocity in a given direction at an elevation than at the surface of the earth, and that the difference in the velocities may be against the sound-wave, so that its upper part may be more retarded than the lower. In this case the direction of a beam of sound will be curved upward, leaving as it were a vacuum of sound beneath. The distance of the origin of sound, however, must not be too great relatively to the elevation of the observer; otherwise it will pass over his head, as well as over that of the observer at the surface of the earth. In most instances the sound was not continuous, but was interrupted—heard for a time, then lost; again becoming audible, it was heard until it finally became imperceptible. Besides this, it was difficult to determine when the sound ceased to be heard, since this depended on the sensibility of the ear and the greater or less attention of the observer at the time of the observation. To obviate these difficulties as well as the unfavorable condition of too great a distance of the origin of sound from the observer, it was concluded to adopt as the duration of the sound the elapsed time between its beginning and the period when it was first lost.

The observer on the tower was Mr. P. Barnard, while the one below was General Woodruff. From the records of the observations of these gentlemen the following tables are compiled, the first of which indicates the relative duration of sound on the top of the tower and at the bottom, the sound moving against the wind; the second, the same duration, the sound moving with the wind; and the third, the same with the sound at right angles to it.

TABLE 1.—*Sound against the wind.*

Date.	Heard at top of tower.		Heard at bottom.	
1875.	*min.*	*sec.*	*min.*	*sec.*
September 2	5	30	4	00
4	4	30	3	30
4	5	30	3	00
4	5	00	4	00
6	7	00	2	15
6	4	00	3	00
7	5	00	2	15
8	6	00	4	00
8	5	30	3	45
8	3	30	2	15
8	3	00	1	15
Mean	4	57	3	01

It appears from Table 1 that without a single exception the duration of the sound was greater at the top of the tower than at the bottom, although the difference in favor of the top of the tower in the several experiments is very variable. These results are in accordance with what was anticipated.

TABLE 2.—*Sound with the wind.*

Date.	Heard at top of tower.		Heard at foot of tower.	
	min.	*sec.*	*min.*	*sec.*
September 2	30	00	30	00
3	16	30	18	00
4	21	00	20	30
4	18	00	23	30
6	12	30	12	30
7	6	30	5	30
Mean	17	25	18	20

In these observations the duration of the sound at the bottom and top are nearly the same, from which we might infer that the elevation of the observer has little effect on the hearing of sound moving with the wind. Were it not for the result of the first experiment of this class at Block Island, we should not hesitate to adopt this as a general conclusion.

TABLE 3—*Sound heard nearly at right angles to the wind.*

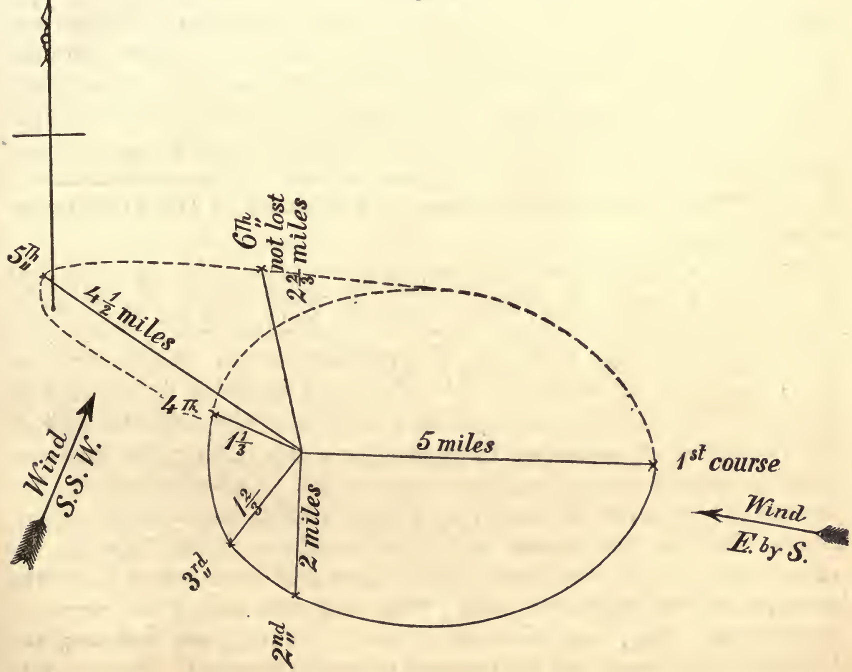
Date.	Heard at top of tower.		Heard at foot of tower.	
	min.	*sec.*	*min.*	*sec.*
September 2	6	00	4	00
2	6	45	10	00
2	25	00	23	00
2	16	30	4	00
3	21	00	19	15
3	16	00	14	30
3	23	30	16	45
4	19	30	17	30
6	6	30	5	30
7	5	00	6	45
7	12	00	12	30
8	4	15	3	15
8	9	30	5	00
Mean	13	12	10	55

From the result of this table it would appear that the sound can be heard moving at right angles to the wind better at an elevation that at the surface—a result not anticipated.

OBSERVATIONS ON THE EFFECT OF WIND ON SOUND.

This series was commenced on the 2d of September. Barometer, 30.3 inches; thermometer, dry-bulb, 70°.5 F. wet-bulb, 67°.5. Wind at the surface of sea was six miles per hour, and variable; at 3 p. m. the velocity was eight miles at the surface. (See Fig. 7.)

Fig. 7.



The experiments were made by means of the steamer Mistletoe, which proceeded from the light-house, as a center, in different directions, blowing the whistle every half-minute, and returning when, from a signal, the sound was lost; the time being noted by different observers, and the distance estimated by the position of the steamer in reference to known objects on the Coast-Survey chart, as well as by angles of azimuth and time of sailing. The steamer was directed to proceed, as indicated in Fig. 7, 1st, against the wind, so that the sound would come to the observers with the wind; 2d, at right angles to the wind; 3d, in an intermediate direction between the last course and the direction of the wind; 4th, approximately with the wind, so that the sound would come to the ears of the observers against the wind; 5th, in an intermediate direction; and, 6th, again at right angles to the wind. It was supposed that by this arrangement a symmetrical curve of sound would be obtained; and we think this would have been the case had the wind remained constant in direction. It did remain nearly the same during the time of describing the first, second, and third courses, and only slightly varied during the fourth; but previous to running the fifth and sixth courses the wind had changed to a direction nearly at right angles to its first course.

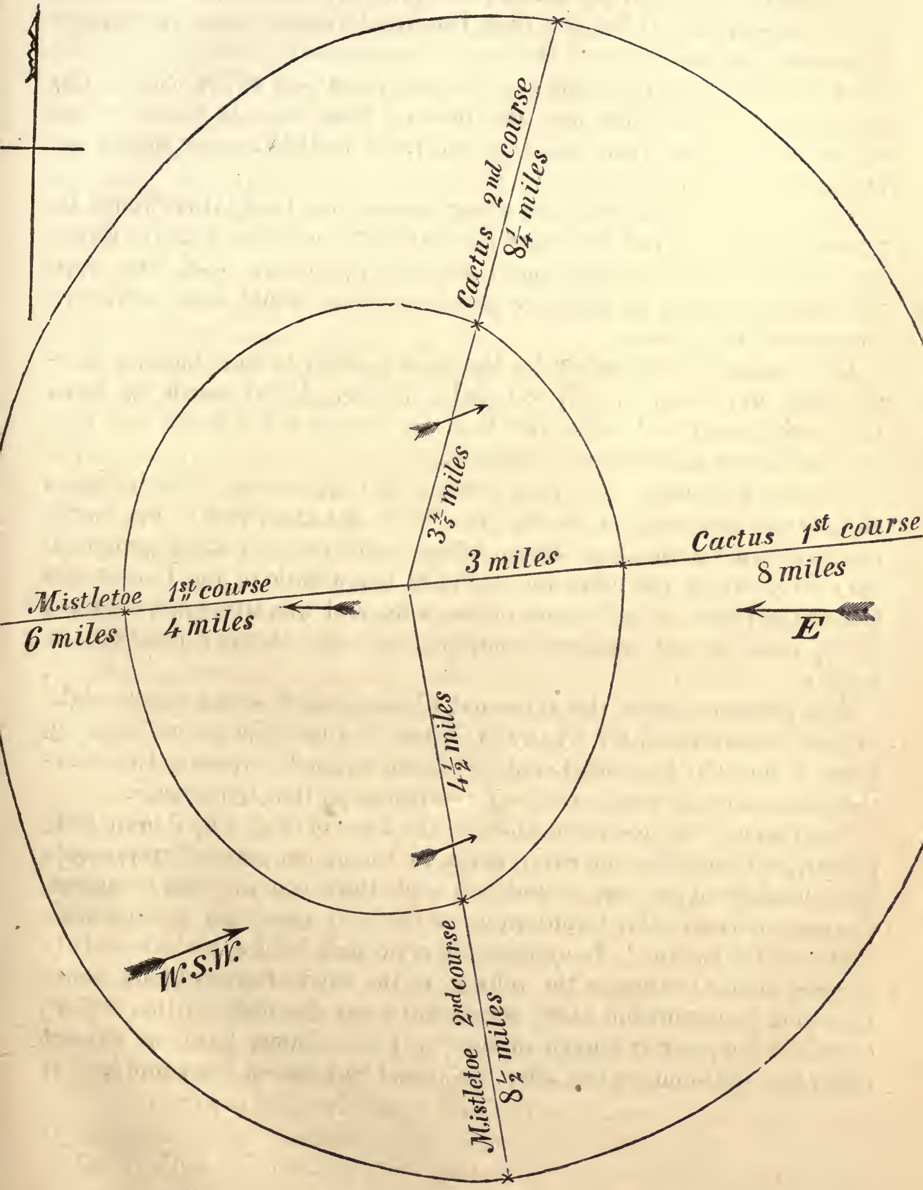
As is shown in Fig. 7, the first, second, third, and fourth courses form a normal curve of audition; the fifth and sixth courses, however, give discordant results, being much longer than a symmetrical curve would indicate, showing a change in the condition of the medium from that which existed during the running of the other courses; this change was evidently that of the wind, which, veering, as we have seen, through an arc of a little more than 90°, brought it nearly at right angles to the fifth course, and approximately in the direction of the sixth course; the wind also increased its velocity. These changes are sufficient, without other considerations, to give a rational account of the phenomena observed. They both tend to increase the distance at which the sound would be heard.

In these experiments, as in subsequent ones, it is to be regretted that for want of balloons the motion of the air above could not be ascertained, as was done at Sandy Hook in September, 1874. Previous to sailing from the depot at Staten Island attempts had been made to secure a supply of toy balloons, but none could be found at that time in the city of New York. Arrangements were therefore made for procuring a reservoir of condensed hydrogen, by which India-rubber balloons could be inflated at the time they were wanted. Unfortunately this apparatus did not arrive in time to be of much avail in this series of experiments. Besides this, on account of the smallness of the balloons, the ascent was too slow compared to the horizontal motion to indicate the direction of the wind at a considerable elevation above the points of observation. They were however of use in pointing out definitely the direction of the wind and the changes it was undergoing. Moreover, at the time of leaving New York we were only able to procure one anemometer, whereas we ought to have had a number, one for the top of the tower, one for the bottom, and one for each vessel.

Experiments of September 3.—Barometer, 30.02 inches; thermometer, dry bulb, 72°.5 F. wet bulb, 70°; wind from the east, but too slight to move the cups of the anemometer; it soon however spang up from the opposite direction, in which it continued during the remainder of the day, attaining a velocity of five and a quarter miles per hour.

In these experiments two light-house steamers were employed, the Mistletoe and Cactus, which enabled us to obtain the results in half the time, and thus to obviate the effect, in some degree, of any change in the direction of the wind. On this occasion the sound was noted at the light-house as it converged to a center from the whistle of each vessel,

Fig. 8.


Cactus 2nd course
8¼ miles
3⅘ miles
Cactus 1st course
8 miles
3 miles
E
Mistletoe 1st course
6 miles
4 miles
4½ miles
W.S.W.
Mistletoe 2nd course
8½ miles

and also simultaneously by each vessel as it diverged from the vertical siren.

We were enabled, in this way, to produce two curves by a reverse process. These are plotted in Fig. 8, and exhibit a remarkable degree of similarity. The corresponding parts of the two curves, being in each case reversed, exhibit the fact that, through the same space in opposite directions, the audibility of the sound was similarly increased with the wind and diminished against it. The effect however of the wind in the experiments of this day was less marked than on any in the whole series, and consequently the two curves of audition more nearly approximate circles.

We can see in this result no other effect than that which would be produced from a wind flowing with a uniform but slow velocity at the surface, but having a slightly increased velocity above. Had there been no wind, according to this view the two curves would have exhibited two concentric circles.

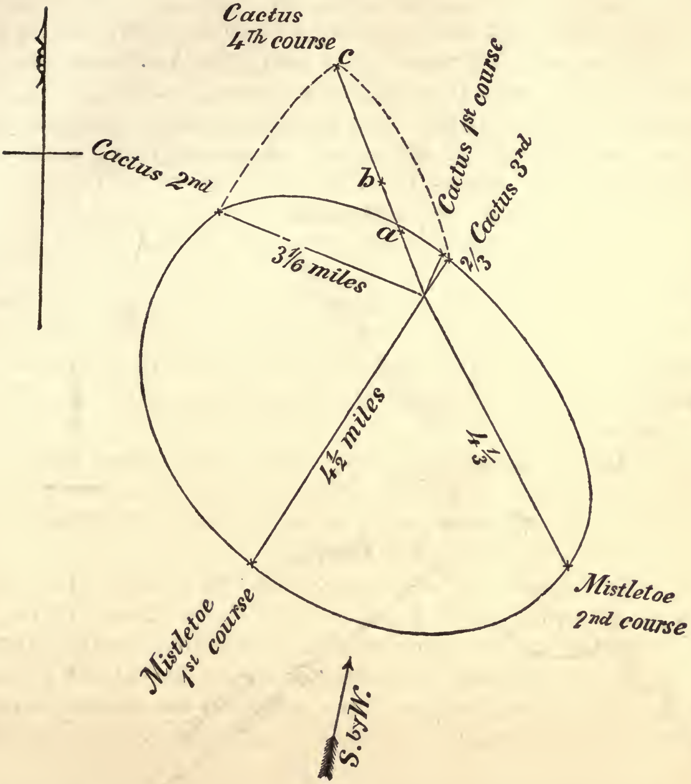
Experiments of September 4.—Barometer, 29.85 inches, falling; thermometer, dry bulb, 77° F. wet bulb, 73°.25. Wind south by west, twelve and one-fourth miles per hour at the top of the tower and nine and one-fourth miles below; variable.

These experiments were also made with two vessels. The distances and directions are given in Fig. 9. With the exception of the fourth course of the Cactus, the other courses would form nearly a symmetrical curve, but in this case the sound of the whistle of the Cactus was lost at the point *a* at a distance of one mile, and was afterward regained at the point *b*, and continued audible until the steamer reached the point *c*.

This presents one of the abnormal phenomena of sound which might in part be accounted for by the existence of a flocculent cloud between *a* and *b*, but why the sound could be heard so much farther in this direction than in the others is not easy to explain on that hypothesis.

The line *b c* was described after all the lines of Fig. 9 had been completed, and therefore the curve given in the figure correctly represents the boundary of the area of audition while these courses were being run, the point *a* being the termination under that condition of the fourth course of the Cactus. To explain the abnormal line *b c*, we have only to suppose that a change in the velocity of the wind afterward took place, by which its opposition to the sound-wave was diminished; this will account for the greater length of the line; the change however did not reach the light-house until after the vessel had passed the point *b*.

Fig. 9.

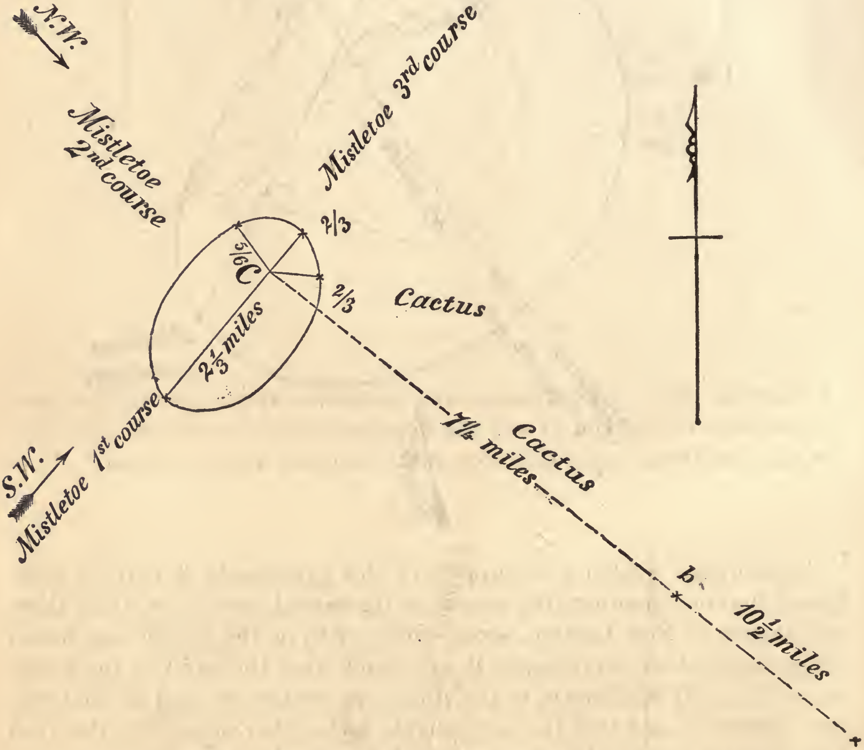


As affording evidence in support of this hypothesis, it may be mentioned that on examining the records of the Signal-Service, of which there is a station at New London, seven miles north of the position at which these observations were made, it was found that the wind in the morning of that day was south, in the afternoon southwest, and in the evening northwest, and that it was probable, as in other cases, that the wind had changed above while the part of the course *b c* was run.

Experiments of September 6.—Barometer, 29.93 inches; thermometer, dry bulb, 74°.5 F. wet bulb, 67°; wind from northwest to southwest, seventeen miles per hour. The wind, though of higher velocity than on any other occasion, was variable. On this day the experiments were principally made with the Mistletoe. The Cactus, being obliged to leave on other duty, ran one course a distance of two-thirds of a mile before the sound of her whistle was lost at the light-house. She afterwards steamed off in the direction C *b* (Fig. 10), noting the sound of the siren, which was lost at the point *b*, afterward regained, and heard distinctly ten and one-half miles distant.

During the passage of the first course of the Mistletoe, the wind at the surface and above was from southwest, the latter being indicated by a cloud passing the zenith. During the second course the wind was variable, changing its direction about 90°, principally from the northwest; while during the third course the wind was again from the southwest. The long course of the Cactus marked on the figure indicates the sound of the siren, from the center outward, as it was heard seven and one-fourth miles, then lost for an interval, and afterward heard again at a distance of three and one-fourth miles farther, making, in all, ten and one-half miles.

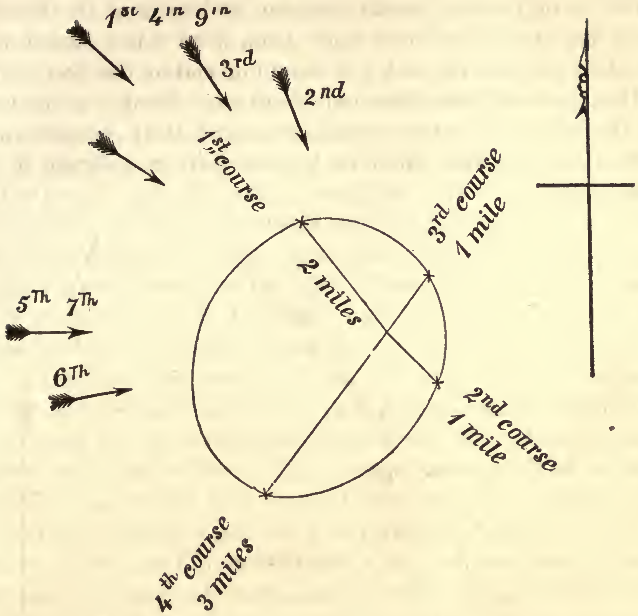
Fig. 10.



Experiments of September 7.—Barometer, 30.1 inches; thermometer, dry-bulb, 73° F. wet-bulb, 62°; wind, eight miles per hour above, and five miles per hour below, tower. The wind was variable, as indicated by the letting-off of balloons, which however did not rise to any great height. The direction of the wind is shown in Fig. 11 by arrows. There is nothing remarkable in the curve of audition of this day. It indicates, as usual, a greater distance toward the side on which the sound was moving with the wind.

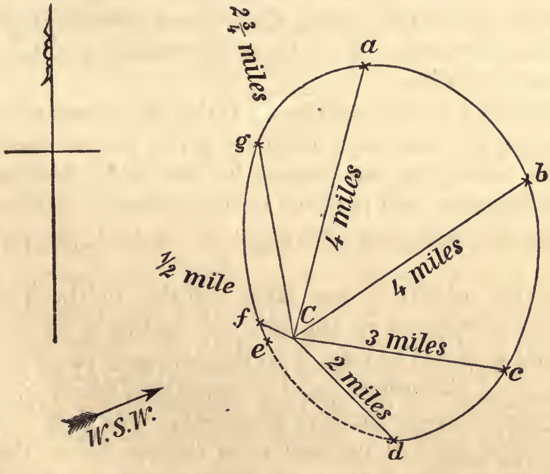
Experiments of September 8.—Barometer, 30.3 inches; thermometer, dry-bulb, 71° F. wet-bulb, 64°.5; wind, west-southwest, fifteen miles per hour at top of tower, nine miles per hour below. Fig. 12 indicates the curve of audition of the vertical siren as compared with that of the

Fig. 11.



horizontal siren. The steamer first proceeded along the line C *a* nearly in the direction of the axis of the horizontal trumpet. For the distance of the first three miles the horizontal trumpet was the louder. At the

Fig. 12.



point *a*, four miles distant, the two were distinct and very nearly equal. At *b* they were distinct, also very nearly equal, the vertical perhaps a little more distinct. At *c* very nearly equally distinct. At *d* the vertical siren was decidedly more distinct just before entering the optical shadow of the light-house tower and the keeper's dwelling. This shadow continued to the point *e*, which was nearly the extent of the acoustic as well as of the optical shadow, since from *d* to *e* the sound was heard from neither instrument, and the origin of sound was too near to cause much difference between these two shadows. From *f* to *a*, through the point *g*, the two instruments continued to be fully heard—the vertical the more distinct. The effect of the wind in this figure is also very distinctly marked, the longer lines indicating the distance the sound was heard with the wind, and the shorter against it. The curve of this figure is not traced through points at which the sound was absolutely lost, but at which it was heard feebly and with nearly equal distinctness.

Thus far all the facts we have observed, if not in strict conformity with our conception of the hypothesis of Professor Stokes, are at least not incompatible with it. We are now however to direct attention to a fact of much interest, which may not have escaped the attention of the reader; namely, the remarkable difference in the area of audition as exhibited in the several figures, all drawn to the same scale. Compare, for example, the curve of Fig. 10 with the inner curve of Fig. 8. It might at first sight be inferred that the smallness of the curve in the former case was due to a mottled condition of the atmosphere, which, by absorbing the sound, diminishes the sphere of audition; but, unfortunately for this explanation, it would appear from the observations made by the Cactus within the hour of obtaining the data for describing the curve, that the air was then in a remarkably favorable condition for the transmission of sound, since it was heard ten and a half miles, the ordinary limit of the maximum penetrating power of the instrument—a siren of the second order; while on the 3d of September, the day on which the large curve, Fig. 8, was described, the greatest distance at which the sound of the same instrument could be heard was eight and a quarter miles.

The only difference in the condition of the air observed during the time of describing the curve of audition given in the figure, and the hearing of the sound by the Cactus for ten and a half miles, was a change in the direction, and perhaps in the intensity, of the wind, in the latter case the direction being the same as that of the course of the Cactus.

Before therefore admitting any other solution of the question as to the cause of the difference in the area of audition, we must inquire whether it is not possible to refer it to the action of the wind itself.

The most marked difference in the conditions which apparently affected the phenomenon on the days in question was that of the greater velocity of the wind, both at the surface of the sea and at the top of the tower, and by comparing the several figures in regard to the wind it will be seen that where the condition of the air was nearest that of a calm the larger was the curve of audition, and the nearer the figures approach to a circle, of which the point of origin of sound or the point of perception is the center. From these facts we are inclined to think that sound is not heard as far during a time of high wind in any direction as it is during a perfect calm, and that it is heard farthest with a gentle wind. This conclusion, which was not anticipated at the beginning of these investigations, is we think in strict conformity with the hypothesis adopted. In the case of sound moving against a strong wind, the sonorous waves being thrown up above the ears of the observer, the sphere of audition in that direction is without question greatly diminished; and that it should be also diminished when sound is moving with a strong wind having a greater velocity above than below is not difficult to conceive. In this case the sound-wave will be so thrown down against the earth, and so much of it absorbed, as to weaken the intensity of that part which reaches the ear, while in the case of a feeble wind, moving faster above than below, the portion of the wave thrown down from above will only be sufficient to compensate for the smaller loss by friction, and thus the sound may be heard at a greater distance than in still air. But on this point, as well as others, further experiments are required.

While we consider the wind as the principal agent in producing the abnormal phenomena of sound, we do not by any means regard it as the sole agent. Prof. Osborn Reynolds, of Owens College, Manchester, without any knowledge of what was doing in America on this subject, instituted a series of experiments on the effect of wind upon sound, and finally adopted precisely the same hypothesis which we have used for generalizing the observed phenomena. He has however in a very ingenious and important paper, presented to the Royal Society in 1874, extended the same principle to the effect of heat in changing the form of the sound-wave, and has shown, both by reasoning and experiment, that the normal direction of the sound-wave in still air, instead of proceeding horizontally should be turned upward, on account of the greater velocity of sound near the earth, due to the greater heat of the strata in that position than of those above. This principle, which indicates the existence of a true refraction of sound independent of the motion of the medium, is undoubtedly applicable as a modifying influence to the phenomena we have recorded. It produces however only a slight effect in the case we have last mentioned, since the observation on board the Cactus shows the condition of the air was that of little acoustic absorption. It would nevertheless favor the hypothesis that sound in perfectly still air of homogeneous density could be heard farther than sound in a moving medium, or in one of unequal temperature. This is also in accordance with the fact repeatedly observed in arctic regions, in which the sound of the human voice is heard at great distances during times of extreme cold. In this case, the air is of a uniform temperature above and below, but of diminished elasticity, and should, on this account, transmit sound with less intensity; and yet the audibility is increased, which is explained by the assumption that its stillness and uniformity of temperature more than compensate for the diminished elasticity. The same may be said with regard to the audibility of sound during a fog, which usually exists during extreme stillness of the air.

Whatever be the cause of the variation in the limit of audition as exhibited in the diagrams, it is less efficient than the ordinary action of the wind in producing the same phenomena. This is evident from the fact that while the ratio of the extreme variation in the limits of audition in the first case is not more than 1:3, in the second it is that of 1:5.

Moreover, when the effect of the wind on the audition of sound in relation to elevation is considered, we think we are fully warranted in asserting, as we did in our last report, that the wind is a more efficient cause of the variability of the penetration of sound than the invisible acoustic clouds adopted by Professor Tyndall for the explanation of the phenomena.

The object of these investigations, as stated at the beginning of this report, was to obtain facts which might serve to establish the true theory of the abnormal phenomena of sound, an object, independent of its scientific interest, of much practical importance in its application to fog-signals. Although the observations were not as perfect as we could wish in many respects, from want of certain appliances, they are yet sufficient we think to establish principles of much practical value. For example, if the mariner in approaching a fog-signal while the wind is blowing against the sound fails to perceive it on deck, he will probably hear it by ascending to the mast-head; or, in case a sound from a given station is constantly obscured in a certain direction, while it is audible in adjacent directions, we may attribute it to a sound-shadow produced by some interposing object. If again, the obscuration of sound in a given direction is only observed during a wind moving against the sound, the cause will probably be found in a lateral refraction, due to the retardation of the current of wind against a perpendicular wall or cliff, as in the case observed at Block Island, August 19. The subject however is one of great complexity, and requires further investigation, but the results thus far obtained may be considered as furnishing the preliminary data on which to found more precise observations. These should be made with the aid of a number of steamers simultaneously employed, each furnished with anemometers and balloons for determining with more accuracy the direction and velocity of the wind.

We hope to renew the investigations during next summer, and in view of this have directed that in the mean time the light-keepers at Block Island and at Point Judith shall continue to sound their sirens a certain length of time every Monday, noting the direction and velocity of the wind, the temperature and pressure of the air, and the audibility of the sound as it comes reciprocally from each instrument.

It is shown, from the results thus far obtained from these reciprocal observations, that sound is occasionally heard more distinctly against the wind than in a contrary direction. We think however that these instances are generally followed by a change in the direction of the wind at the surface of the earth.

LIGHT-HOUSE BOARD, *October*, 1875.

PART V.—INVESTIGATIONS IN 1877.*

On account of the occurrence of the Centennial Exhibition, which absorbed most of the time of the officers of the Light-House Board not devoted to ordinary light-house service, but few observations were made relative to sound in 1876, and an account of what were made is incorporated in the following report.

Agreeably to previous engagement, I visited Portland, Me., to make some investigation in regard to an abnormal phenomenon of sound, which was noticed in a former report. We left Portland on the afternoon of September 3, 1877, in the steamer Iris, which had been fitted up during the year under the direction of the inspector, Commander H. F. Picking, and was in excellent condition, and well adapted to the duty of a light-house tender. The party consisted of General J. C. Duane, engineer of the first district; Commander H. F. Picking, inspector of the first district; Mr. Edward L. Woodruff, assistant engineer of the third district; Mr. Charles Edwards, assistant engineer of the first district, and myself.

We first examined one of the automatic whistling-buoys invented by Mr. Courtenay, of New York. This was in place and emitting sounds at a station called Old Anthony, off Cape Elizabeth, about nine miles from Portland. On approaching it at right angles to the direction of the wind, we heard it at the distance of a mile. But the sound did not appear loud even within a few rods. It was however of considerable quantity, being from a locomotive whistle of ten inches in diameter. The instrument is operated by the oscillation of the waves, which at this time were not of sufficient height to move it vertically through a space of more than one foot. It emitted a sound at each oscillation. This invention consists of a large pear-shaped buoy about twelve feet in diameter at the water-surface, and floats about twelve feet above the same plane. In the interior of this buoy is a large tube or hollow cylinder, three feet in diameter, extending from the top through the bottom to a depth of about thirty feet below the latter. This tube is open at the bottom, but projects air-tight through the upper part of the buoy, and is closed with a plate having three orifices in it, two for letting in the air into the tube, and one between the others for letting it out to operate the whistle. These orifices are connected with three tubes which extend downward to near the level of the water, where they pass through a diaphragm which divides the cylinder into two parts.

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*From the Report of the Light-House Board for 1877.

When the buoy rises, the water in the cylinder by its inertia retains its position, and a partial vacuum is formed between the head of the column and the diaphragm, into which the air is drawn through two of the tubes, and when the buoy descends, the escape through the injection-tube being prevented by valves, it is forced out of the inner tube and actuates the whistle.

The mooring-chain, which is sixty fathoms in length, is attached to the cylinder at a point just below the buoy, and is secured to a large stone weighing about six tons. The apparatus rides perpendicularly.

The sound in this instrument is not produced merely by the difference in hydrostatic pressure of the water in the two positions of the buoy, but by the accumulated effect of impulse generated by the motion of the apparatus.

Plans have been devised, but have not yet been perfected, to condense the air in the buoy by the effect of repeated oscillations, until a valve loaded to a definite pressure would open automatically and allow the air to escape. In this way the sound from the accumulated pressure would be produced at intervals to a greater or less extent, and would serve to diversify the character of the sound so as to enable the mariner to distinguish different locations. The invention, as it is, is considered a valuable addition to the aids to navigation, has received the unqualified approbation of all navigators on this coast who are acquainted with its operation, and will probably be introduced in all countries where its merits are known. Experience has shown that it can be permanently moored in deep water, and that vessels can safely approach it within the nearest distance, and take perfect departure from it.

The Light-House Board has adopted this buoy as one of its permanent aids to navigation, and will in time introduce it at all points where its presence will be of importance to the navigator. In order to obtain reliable data as to the operations of the automatic buoy, Commander Picking has established a series of observations at all the stations in the neighborhood of the buoys, giving the time of hearing it, the direction of the wind, and the state of the sea, from which it appears that in the month of January, 1877, one of these buoys was heard every day at a station one and one-eighth miles distant; every day but two at one two and one-quarter miles distant; fourteen times at one seven and one-half miles distant, and four times at one eight and one-half miles distant. It is heard by the pilots of the New York and Boston steamers at distances of from one-fifth to five miles, and has been frequently heard by the inspector of the first light-house district at a distance of nine miles, and even, under the most favorable circumstances, fifteen miles.

We sailed around the buoy and observed the difference in the intensity of sound in regard to the direction of the wind, which was at the time a fresh breeze of from twelve to fifteen miles per hour, from the westward, the greatest intensity being apparently at points forty-five degrees on either side of the axis of the wind. The effect however was not very definitely marked, though the sound on the whole appeared to be greater on the semi-circumference of the circle to the leeward; but the velocity of the wind was so great that the noise produced by it on the rigging of the vessel prevented the effects from being definitely observed.

Experiments have been made with this buoy carrying whistles of different sizes, the result being that a whistle of less than ten inches diameter does not give a sound which can be heard as far as one of the latter size, although it appears to the ear near by equally loud.

There is a difference between the quantity of sound and the loudness. Two sounds may be equally loud when heard near by, yet differ very much in regard to their being heard at a distance, the loudness depending upon the intensity of sound or on the amplitude of vibration of the sounding body, while the quantity of sound depends on the extent of the vibrating surface.

The size of the whistle must be limited by the quantity of air ejected at each oscillation of the buoy. The fact that the ten-inch whistle gives a sound which can be heard farther than one of eight inches appears to have a bearing on the question (the actuating force being the same) of the united effect of two sounds of the same quantity and pitch, since the sound from several parts of the circumference of the larger whistle may be considered as a union of several sounds of less quantity.

After these observations on the automatic buoy we proceeded along the coast to White Head, at the entrance of Penobscot Bay, a distance of sixty miles, which we reached at about twelve o'clock at night, and cast anchor in Seal Harbor, near the White Head light-house.

Our first operation next morning was the examination of an automatic fog-bell, invented by Mr. Close, and which has been erected by a special appropriation of Congress. It is very simple in conception, and would do good service in southern latitudes, where it would not be affected by the ice. It consists of an upright shaft thirty-two feet long, fastened to the rock beneath the water, and kept in a vertical position by a series of iron rods serving as braces. Around this shaft is a hollow metallic float, having sufficient buoyancy by the motion of the waves to elevate a vertical rod having at the upper end a rack gearing into a ratchet-wheel. By means of projecting pins on the surface of the wheel the hammer of the bell is elevated and the bell sounded at each descent of the float. This arrangement is the most simple and efficient of any of the kind of which we have any knowledge.

The objection to it is its liability to be deranged by the action of ice and the rusting of the parts from exposure to the weather.

Our next operation at this place was the examination of the remarkable abnormal phenomenon, which was the principal object of our excursion. It has been frequently observed by the captains of the steamers plying between Boston and New Brunswick, and has also been noticed on two different occasions by officers of the light-house establishment. The phenomenon, as reported by these authorities, consists in hearing the sound distinctly on approaching the station at the distance of from six to four miles, then losing it through a space of about three miles, and not hearing it again until within about a quarter of a mile of the instrument, when it becomes suddenly audible in almost full power. This phenomenon is always noticed when the vessel is approaching the signal from the southwest, and the wind is in the same or in a southerly direction, and therefore opposed to the direction of the sound from the station, which is the case during a fog. Commander Picking, having frequently received complaints from masters of vessels as to losing the sound at this place, concluded to verify the facts by his own observation. For this purpose he embraced the opportunity of an inspection-tour in July, 1877, to approach the station from the southwest during a fog. In his own words, he heard the sound distinctly through a space of from six to four miles, then lost it and could hear nothing until within a quarter of a mile of the station, when the blast of the whistle burst forth in full sound. The wind at this time was from the southward, or against the sound. This cessation in the hearing of the sound could not have been due to the failure of the instrument to emit sound, since its operation is automatic when once started, and in this case the fog so lifted on nearing the station as to admit the observation of the puffs of steam emitted at each blast of the whistle.

On a previous occasion General Duane and Mr. Edwards on approaching the same signal from the southwest heard the sound at about six miles distance, then lost it, and did not again hear it until within about a quarter of a mile. The wind in this instance was also the same as that in the observation of Commander Picking, namely, from the southwest.

So well established was this phenomenon that General Duane attempted to remedy the evil by elevating the duplicate whistle (with which every station is provided) to a height twenty-two feet above the level of the other whistle, by placing it on the upper end of a tube. But this arrangement produced no beneficial effect.

In the morning of September 4, 1877, on which we commenced our experiments, the weather was clear, the wind west-southwest, the velocity from ten to twelve miles, remaining nearly constant during the day. Our first object was to verify by direct observation the several features of the phenomenon, and for this purpose we steamed to the southward, or directly to the windward, from the station through the region in which the abnormal phenomena had been noticed. The pressure of the atmosphere, as indicated by an aneroid barometer, was 28.9 inches. The temperature of the air was 67° Fahrenheit; that of the water at various points along our course was 58°, except at two points where the thermometer indicated 57°. This difference was too small to have any perceptible effect on the density of the rapidly moving air which was passing over the surface of the water. As we increased our distance from the signal the sound slightly diminished in loudness until the distance was between a quarter and half a mile, when it suddenly ceased to be heard, and continued inaudible through a distance of about a mile, when it was faintly heard and continued to increase in loudness until we reached the distance of four miles; at this point it was heard with such clearness that the position of the station could be located with facility; but on proceeding farther in the same direction it appeared to diminish gradually except at one point, when a blast, as indicated by the steam issuing from the whistle, was inaudible; but on turning the vessel around the next blast was distinctly heard.

As a second experiment we retraced the same line back to the station and observed the same phenomena in a reverse order. The sound was heard the loudest at a point four miles from the station; afterward it diminished and then became inaudible through a space of two miles, and then suddenly burst forth nearly in full intensity at the distance of a quarter of a mile, and continued loud until the station was reached.

As a third experiment the same line was traversed again, the only difference in the condition of the experiment being that the whistle on the steamer was sounded every minute between the blasts of the signal at the station; and while the observers on the vessel noted the sounds from the latter, those at the station observed the sound from the former. The same phenomena as described in the previous experiments were witnessed by those on board the vessel, but on receiving the report of the observers at the station, it was found that no cessation of the sound from the steamer was observed through the whole distance traversed by the vessel. It should be noted that the whistle at the station is ten inches in diameter, actuated by a pressure of sixty pounds of steam, and that on board the vessel six inches in diameter with twenty-five pounds of steam. It appears from this remarkable result that a feeble sound passes freely through what has been called the region of silence when sent in the direction of the motion of the wind, when a louder sound does not pass in the opposite direction.

As a fourth experiment the vessel proceeded northward on the opposite side of the station to that before traversed, but in the prolongation of its previous course. The sound in this case from the signal to the observers on the vessel was with the wind, while that from the vessel to the observers at the station was against the wind. In this experiment no cessation was observed on the vessel in the hearing of the sound from the station; it was heard with varying intensity to the distance of four and a half miles, and could probably have been heard much farther had our progress not been interrupted by land. On returning to the station the observers there reported that after the vessel had left the station and was scarcely more than a hundred yards distant not a single blast of its whistle was heard. In this case the phenomena which had been observed on the southerly side of the station were exhibited in a reverse order on the northerly side.

In what may be considered the fifth experiment, the vessel being at a distance of four miles from the station on the line traversed in the first two experiments, the sound was heard slightly. The vessel then altered its course so as to steam, as it were, around the signal, keeping at the same distance until the direction of the station from the vessel was nearly at right angles to the direction of the wind; at this point no sound was heard from the station, although it had been slightly heard at points along the curved line traversed in reaching the point mentioned. The vessel then proceeded toward the station in a straight line, but no sound was heard until it approached the latter within one-fourth of a mile. The observers at the station however heard the sound from the vessel through the whole distance.

This experiment was made to ascertain the truth of the general impression that at this place the sound was always heard better coming at right angles or across the wind than in the direction in which it was blowing. The experiment however was found in conformity with the general rule previously established, that the sound was usually heard farthest with the wind, less against the wind, and at an intermediate distance across the wind.

The primary object of these investigations is to determine the mechanical causes to which the phenomena may be referred and from which new conclusions may be deduced, to be further tested by experiment, and such definite views obtained as may be of value in the employment of fog-signals for the uses of the mariner.

For this purpose a number of different hypotheses may be provisionally adopted and each compared with the actual facts observed.

The first hypothesis which has been suggested for the explanation of the phenomena in question is that they are due to some configuration of the land; but on inspecting the Coast-Survey chart of this region it will be seen that the nearest land consists of a series of broken surfaces not rising above the ocean enough to reflect sound or in any way to produce sound-shadows in the region through which the phenomena are observed. This hypothesis therefore is inadmissible.

Another hypothesis is that of what have been called invisible acoustic clouds or portions of atmosphere existing over the water at the region of silence, which might absorb or variously refract the sound. That such a condition of a portion of the atmosphere really exists in some cases is a fact which may be inferred from well-established principles of acoustics, as well as from experimental data. They would occur especially in the case of dissolving clouds, which would be accompanied by local diminutions of temperature, and also from portions of air which have been abnormally heated by contact with warm earth. But, if the phenomena in question were produced by a cloud of this kind, its presence ought to be indicated by transmitting through it the usual set of meteorological instruments. This was done in the foregoing experiments, but no change was observed in the indications either of the thermometer or barometer. Unfortunately we had not a hygrometer in our possession, but this observation was less necessary, since from abundant testimony it is established that the same phenomena are exhibited during a dense fog, in which all parts of the atmosphere for miles in extent must be in a homogeneous condition. Furthermore, a local cloud could not continue to exist in a given space for more than an instant while a wind was blowing with a velocity of from ten to twelve miles an hour. Again, this hypothesis fails entirely to explain the fact that this phenomenon is always observed at nearly the same place, especially during a fog, when the wind is in a southerly direction. Finally, it is impossible to conceive of a cloud so arranged as a screen producing a sound-shadow of greater intensity on one side than on the other.

Another hypothesis is that of the refraction of sound due to the action of the wind. It is an inference from well-established theory, as well as from direct observation, that the sound is refracted by the wind, that it tends to be thrown upward when moving against the wind, and downward with the wind. This result is attributed very properly to the different velocities of the strata, that next the surface being retarded, those above being less retarded.

The upper part of the front of the wave is thus thrown backward, and the direction of the wave turned upward. In the case of the experiment south of the station, the wind passing over a long line of rough sea was moving less rapidly in its lower stratum than in the higher, and consequently the sound-wave was thrown backward above, and, as it issued from the instrument, tended to rise above the head of the observer, and at a certain distance from the origin of the sound, depending upon the difference of velocity above and below, was lost entirely to the observer, and a sound-shadow was thus produced by refraction which is closed in again by the lateral spread of the sound at a given distance.

In the experiment on the other side of the signal, the vessel proceeding to the north, the wind coming to the observer on the vessel had to pass over a rougher surface than that of water, and consequently the difference of velocities above and below, and therefore the refraction would be greater, and consequently the sound from the vessel was almost entirely lost to the observer at the station, while the sound from the station was heard uninterruptedly on the vessel, since it was moving with the wind.

On examining the records of experiments of previous years, I find a number of cases recorded where sounds were heard at a greater distance, while inaudible at a less distance, especially one in connection with the fog-signal at Gull Island, in 1874. In this case the sound, in passing from the signal, was heard distinctly at the distance of about two miles against the wind, then lost for a space of about four and a half, and heard again distinctly for a distance of perhaps one mile. At the same station, during the experiments of 1875, the sound of the whistles of the steamers was heard for a certain distance, then ceased to be heard for a considerable interval, and was then heard again. Furthermore, the pilots of the steamboats from New York to Boston report that the automatic buoy is found to intermit its sound, being heard at a distance, then becoming inaudible, and heard again as the steamer approaches the source of sound.

From all the facts which we have gathered on this subject, I think it highly probable that in all cases in which sound moving against the wind is thrown up above the head of the observer it tends to descend by the lateral spread of the sound-wave and to reach the earth at a distance; the conditions however for the actual production of this effect are somewhat special, and will depend upon the amount of the initial refraction and the quantity of the sound-waves. Besides the lateral spread of the sound-wave there are two other causes sufficient, in certain cases, to bring a portion of the sound-waves which have been elevated in the air back again to the earth: the first is when an upper current of wind is moving in an opposite or approximately opposite direction to that at the surface of the earth, in which case an opposite or downward refraction would take place; and the second is the case in which the surface-wind is terminated above by strata of still air; in this case, also, a reverse refraction, but of less amount, would take place, which would tend to bring the sound-wave downward.

We can readily imagine that an isolated island, cooled by the radiation of the heat by night, would send every morning, in all directions, a current of cold air from its center. In this case, the sound from a whistle placed in the center of the island would be inaudible in a space entirely surrounding it, and thus give rise to a condition mentioned by General Duane, in which a fog-signal appeared to be surrounded by a belt of silence.

The next experiment was made on the morning of the 5th, on leaving the station. In this case we proceeded along the direction of the same line in which the first, second, and third experiments were made the day before. The wind had changed about four points to the southward. As in the preceding experiments, the sound was lost again at the distance of about one-fourth of a mile, but was not distinctly regained, though some of the observers thought they heard it at a distance of two and one-half miles.

The only perceptible difference in the wind on the 5th was that it was a little less rapid, and four points more to the southward.

From a subsequent report of the keepers, the whistle of the vessel was heard continuously as far as the puffs of steam could be observed, a distance six or seven miles. In this case the sound was moving with the wind. These results therefore are in accordance with those previously obtained.

The next experiments were made at Monhegan, an island sixteen miles southwest of White Head. On this island there is a Daboll trumpet actuated by a hot-air engine.

We departed from this station in a westerly direction at an angle of

45° to the right of the direction of the wind, and after proceeding about one mile, as estimated by time, we lost the sound of the signal. We then turned at right angles to our former course and proceeded toward the leeward, keeping about the same distance from the signal, when the sound was regained at a point which probably depended upon the direction of the wind and the axis of the trumpet combined. From this point it was heard to a point to the leeward, and thence we retraced our course at about the same distance and proceeded across the axis of the trumpet toward the windward, where the sound was again lost. The only definite result from this experiment was another case of the sound being heard farther to the leeward than to the windward.

After this experiment we returned to Portland.

An interesting fact may be mentioned in connection with this station, having a bearing upon the protection of light-houses from lightning. The fog-signal is placed on a small island separated from the large island by a water-space of about one-eighth of a mile. General Duane, desiring to connect the light-house and fog-signal by an electrical communication, suspended a wire between the two points and attempted to form a ground connection by depositing a plate of metal in the ground on each island, but to his surprise, though the arrangements were made by a skilled telegrapher, no signal would pass. The two islands being composed of rock and the soil limited in thickness, the conduction was imperfect, and it was only by plunging the plate of metal into the water on each side of the space between the two islands that a signal could be transmitted.

No further experiments on sound were made during this excursion, because the vessel could no longer be spared from more pressing light-house duty in the way of inspection and the stated supply of materials to the stations.

On my return to New York, accompanied by Mr. Woodruff, I took the route by the Western Railway to the Hudson River at Troy. This line was chosen in order to make some investigations relative to any peculiarities of sound which might be observed in the Hoosac tunnel, through which the railroad passes. For this purpose we spent a day at East Windsor, a village situated near the west end of the tunnel, and were very cordially received by the engineers in charge.

The tunnel is four and three-quarters miles in length, twenty-four feet wide, and twenty feet high to the crown of the arch. It ascends slightly from either end to a point near the center, where there is a ventilating-shaft 1,028 feet high extending to the outer air above. In winter, when the external temperature is less than that within the tunnel, there is a constant current from each end toward the center, and in the summer, when the temperatures are reversed, there is a current out of the tunnel at either end, except when the external wind is sufficiently strong, especially from the west, to reverse the direction of the current from one half and direct the stream entirely out of the other entrance. At the time of our visit, there was a gentle current flowing out of both ends.

The only peculiarity of sound which had been observed, as stated by the engineers, was that it was greatly stifled at the time by the smoke with which the air was filled immediately after the passage of a locomotive. So great was this in some cases that accidents were imminent to the workmen, who are constantly occupied in the tunnel in lining the crown of the arch with brick, by the sudden appearance of a locomotive, the approach of which had not been heard.

That the audibility of sound should be diminished by smoke was so contrary to previous conceptions on the subject, since sound is not practically interrupted by fog, snow, rain, or hail, that I was induced to attribute the effects which had been observed to another cause, and to regard the phenomenon as due to an exaggerated flocculent condition of the air in the tunnel; adopting in this instance the hypothesis advanced by Dr. Tyndall, and so well illustrated by his ingenious experiments. The effect which would be produced in the condition of the air in the tunnel by the passage of a locomotive is indicated by the appearance of the emitted steam extending behind the smoke-stack of a locomotive in rapid progress before the observer at a distance. This consists of a long stream composed of a series of globular masses produced by the successive puffs of steam which are emitted at equal intervals. Allowing the diameter of the driving-wheels to be five feet, then since four puffs are made at each revolution of the wheels, a puff of hot steam would be given out at every four feet travelled by the engine, and these puffs mingling with the air at the ordinary temperature would produce an exaggerated flocculent condition. On our expressing a desire to witness the effect upon sound of the passage of a locomotive through the tunnel, Mr. A. W. Locke, one of the engineers who had charge of the western section, politely offered us the means of experimenting on this point, and also of passing leisurely through the tunnel on a hand-car.

To observe the effect of a locomotive on the sound we took advantage of the entrance of a freight train, impelled by two engines, the extra one being necessary to drive the load up the inclined plane to the middle of the tunnel, where it was detached and returned along the same line, while the train was drawn the remaining distance along the eastern decline by a single engine. In order to make the experiment with regard to sound the time was accurately noted during which the noise of the entering engines could be distinctly heard, which would give approximately the distance the sound travelled through the flocculent atmosphere produced by the locomotive before becoming inaudible, and again the time was noted from the first hearing of the returning engine until it reached the end of the tunnel. In the mean time the current of air blowing through the tunnel had removed a considerable portion, at least, of the flocculent atmosphere, so that the sound in this case came through an atmosphere of comparative uniformity of temperature, or one much less flocculent than the other; the result was that the duration of sound in the first case was about a minute, while in the second it was upward of two minutes. The darkness in the tunnel, on account of the smoke, was so profound immediately after the passage of a locomotive, that with two large torches, charged with mineral oil, the sides of the tunnel at a distance of six feet could scarcely be observed; while in the other half of the tunnel, where no smoke existed, the eastern opening could be observed like a star in the distance of upward of two miles. It was therefore not surprising that the stifling of the sound which was observed should be referred to the smoke as a palpable cause, and that the more efficient one of the varying density or flocculent condition should be disregarded.

The method of determining by experiment the question as to which of these causes was the efficient one did not occur to me until we had left the tunnel, and then the simple expedient suggested itself to me, for the purpose of repeating the experiment, that instead of locomotives charged with wood, two locomotives charged with charcoal or coke—which emit no smoke, but only transparent gases principally carbonic acid—should be used in an experiment similar to the one just described. This experiment Mr. Locke has kindly promised to perform as soon as a convenient opportunity shall occur.

The opportunity was embraced while at the mouth of the tunnel to make some observations which might have a bearing upon the phenomena of the aërial echo. For this purpose, advantage was taken of a large tool-chest, which happened to be placed about twenty or thirty feet within the western mouth of the tunnel. By slamming down violently the cover of this chest, a loud sound of an explosive character was produced, from which a prolonged echo was returned from the interior of the tunnel. This echo was slightly intermittent, suddenly increasing in loudness at intervals for a moment, and again resuming its uniform intensity. This effect was attributed to projecting pieces of rock in that part of the tunnel which had not been lined with brick. An echo was however evidently returned from that portion of which the sides were not projecting, which I would consider an effect of the same cause which produces the aërial echo.

AËRIAL ECHOES.

During the year 1877, (as also in 1876,) series of experiments were made on the aërial echo, in which I was assisted—in the first series by General Woodruff, engineer of the third light-house district,—and in the second series by Edward Woodruff, assistant engineer of the same district. These experiments were made principally at Block Island, but also at Little Gull Island. Especial attention has been given to this phenomenon, which consists in a distinct echo from the verge of the horizon in the direction of the prolongation of the axis of the trumpet of the siren, because the study of it has been considered to offer the easiest access to the solution of the question as to the cause of all the abnormal phenomena of sound, and also because it is in itself an object of much scientific interest.

In my previous notice of this phenomenon, in the report of the light-house board for 1874, I suggested that it might be due to the reflection from the crests of the waves of the ocean; but as the phenomenon has been observed during all conditions of the surface of the water, this explanation is not tenable.

Another hypothesis has been suggested, that it is due to a flocculent condition of the atmosphere, or to an acoustic invisible cloud, of a density in different parts differing from that of the general atmosphere at the time. To test this hypothesis experimentally, the large trumpet of the siren was gradually elevated from its usual horizontal position to a vertical one. In conception, this experiment appears very simple, but on account of the great weight of the trumpet, it required the labor of several men for two days to complete the arrangements necessary to the desired end. The trumpet, in its vertical position, was sounded at intervals for two days, but in no instance was an echo heard from the zenith, but one was in every case produced from the entire horizon. The echo appeared to be somewhat louder from the land portion of the circle of the horizon than from that of the water. On restoring the trumpet to its horizontal position, the echo gradually increased on the side of the water, until the horizontal position was reached, when the echo, as usual, appeared to proceed from an angle of about twenty degrees of the horizon, the middle of which was in the prolongation of the axis of the trumpet. A similar experiment was made with one of the trumpets of the two sirens at Little Gull Island. In this case the trumpet was sounded in a vertical position every day for a week with the same result. On one occasion it happened that a small cloud passed directly over the island on which the light-house is erected, and threw down on it a few drops of rain. At the moment of the passage of this cloud the trumpet was sounded, but no echo was produced.

From these experiments it is evident that the phenomenon is in some way connected with the plane of the horizon, and that during the continuance of the experiment of sounding the trumpets while directed toward the zenith no acoustic cloud capable of producing reflection of sound existed in the atmosphere above them.

Another method of investigating this phenomenon occurred to me, which consisted in observing the effects produced on the ears of the observer by approaching the origin of the echo. For this purpose, during the sounding of the usual interval of twenty seconds of the large trumpet at Block Island, observations were made from a steamer which proceeded from the station into the region of the echo and in the line of the prolongation of the axis of the trumpet, with the following results:

1. As the steamer advanced, and the distance from the trumpet was

increased, the loudness of the echo diminished, contrary to the effect of an echo from a plane surface, since in the latter case the echo would have increased in loudness as the reflecting surface was approached, because the whole distance travelled by the sound-wave to and from the reflector would have been lessened. The effect however is in accordance with the supposition that the echo is a multiple sound, the several parts of which proceed from different points at different distances of the space in front of the trumpet, and that as the steamer advances toward the verge of the horizon, it leaves behind it a number of the points from which the louder ones proceed, and thus the effect upon the ear is diminished as the distance from the trumpet is increased.

2. The duration of the echo was manifestly increased, in one instance, from five seconds, as heard at the mouth of the trumpet, to twenty seconds.

This would also indicate that the echo is a multiple reaction of varying intensities from different points, and that at the place of the steamer the fainter ones from a greater distance would be heard, which would be inaudible near the trumpet.

3. The arc of the horizon from which the echo appeared to come was also increased in some cases to more than three times that subtended by the echo at the place of the trumpet. This fact again indicates that the echo consists of multiple sounds from various points at or near the surface of the sea, the angle which the aggregate of these points subtend necessarily becoming greater as the steamer advances.

But perhaps the most important facts in regard to the echo are those derived from the series of observations on the subject, made by Mr. Henry W. Clark, the intelligent keeper of the principal light-house station on Block Island, and by Joseph Whaley, keeper of the Point Judith light-house. Mr. Clark was furnished with a time-marker to observe the duration of the echo, and both were directed to sound the trumpets every Monday morning for half an hour, noting the temperature, the height of the barometer, the state of the weather as to clearness or fog, the direction and intensity of the wind, and the surface of the ocean.

From the observations made at these two points, for more than two years at one station and over a year at the other, the echo may be considered as produced constantly under all conditions of weather, even during dense fogs, since at Block Island it was heard 106 times out of 113, and at Point Judith 50 times out of 57, and on the occasions when it was not heard the wind was blowing a gale, making a noise sufficiently intense to drown the sound of the echo. These results appear to be sufficient to disprove the hypothesis that the phenomenon is produced by an acoustic cloud accidentally situated in the prolongation of the axis of the trumpet. It must be due to something more permanent in its effects than that from a portion of air differing from that of the general atmosphere in temperature or density, since such a condition cannot exist in a dense fog embracing all the region of the locality of the phenomenon. Indeed, it is difficult to conceive how the results can be produced, even in a single instance, from a flocculent portion of atmosphere in the prolongation of the axis of the trumpet, since a series of patches of clouds of different temperature and densities would tend to absorb or stifle by repeated reflections a sound coming from their interior rather than to transmit it to the ear of the observer.

The question, therefore, remains to be answered: what is the cause of the aërial echo? As I have stated, it must in some way be connected with the plane of the horizon. The only explanation which suggests itself to me at present is that the spread of the sound which fills the whole atmosphere from the zenith to the horizon with sound-waves may continue their curvilinear direction until they strike the surface of the water at such an angle and direction as to be reflected back to the ear of the observer. In this case the echo would be heard from a perfectly flat surface of water, and as different sound-rays would reach the water at different distances and from different azimuths, they would produce the prolonged character of the echo and its angular extent along the horizon.

While we do not advance this hypothesis as a final solution of the question, we shall provisionally adopt it as a means of suggesting further experiments in regard to this perplexing question at another season.

General Conclusions.

From all the experiments which have been made by the Light-House Board in regard to the transmission of sound in free air and those derived from other observations which can be fully relied upon, the following conclusions may be considered established, subject however to such further modification and extension as subsequent investigation may seem to indicate:

1. The audibility of sound at a distance (the state of the atmosphere being constant) depends upon the character of the sound. The distance through which a sound may be heard is governed by the pitch, the loudness, and the quantity of sound. The pitch or frequency of the impulses in a given time must not be too high, otherwise the amplitude of vibration will be too small to allow a sufficient quantity of air to be put into motion; neither must the pitch be too low, for in this case the motion of the atoms of air in the sound-wave will not be sufficiently rapid to convey the impulse to a great distance. Again, the greater the loudness of the sound, which depends upon the amplitude of the vibrations of the sounding-body, the greater will be the distance at which it will be heard. And finally, the greater the quantity of sound, which depends upon the magnitude of the vibrating surface, the greater will be the distance to which it is audibly transmitted. These results are derived from observations on the siren, the reed-trumpet, and the automatic buoy. The effect of quantity of sound is shown in the fact that in sounding different in-

struments at the same time, it was found that two sounds apparently of the same loudness were heard at very different distances.

2. The audibility of sound depends upon the state of the atmosphere. A condition most favorable to the transmission of sound is that of perfect stillness and uniform density and temperature throughout. This is shown by the observations of Parry and other Arctic explorers; although in this case an efficient and co-operating cause is doubtless the downward refraction of sound due to the greater coldness of the lower strata of air, as first pointed out by Professor Reynolds. Air however is seldom in a state of uniform density, but is pervaded by local currents, due to contact with portions of the earth unequally heated, and from the refractions and reflections to which the sound-wave is subjected in its passage through such a medium it is broken up and lost to the ear at a less distance.

3. But the most efficient cause of the loss of audibility is the direct effect produced by the wind. As a general rule, a sound is heard farther when moving with the wind than when moving against it. This effect, which is in conformity with ordinary observation, is not due to an increase of velocity of the sound-wave in one direction and a diminution in the other by the motion of the wind except in an imperceptible degree; for since sound moves at the rate of about seven hundred and fifty miles an hour, a wind of seven miles and a half an hour could increase or diminish the velocity of the sound-wave only one per cent. while the effect observed is in some cases several hundred per cent. It is however due to a change in its direction. Sound moving with the wind is refracted or thrown down toward the earth; while moving against the wind it is refracted upward and passes over the head of the observer, so as to be heard at a distance at an elevation of several hundred feet when inaudible at the surface of the earth.

4. Although, as a general rule, the sound is heard farther when moving with the wind than when moving against it, yet in some instances the sound is heard farthest against the wind; but this phenomenon is shown to be due to a dominant upper wind, blowing at the time in an opposite direction to that at the surface of the earth. These winds are not imaginary productions invented to explain the phenomena, but actual existences, established by observation, as in the case of the experiments made at Sandy Hook, in 1874, by means of balloons, and from the actual motion of the air in the case of northeast storms, as observed at stations on the coast of Maine.

5. Although sound issuing from the mouth of a trumpet is at first concentrated in a given direction, yet it tends to spread so rapidly that at the distance of three or four miles it fills the whole space of air inclosed within the circuit of the horizon, and is heard behind the trumpet nearly as well as at an equal distance in front of its mouth. This fact precludes the use of concave reflectors as a means of increasing the intensity of sound in a given direction; for although at first they do give an increase

of sound in the direction of the axis, it is only for a comparatively short distance.

6. It has been established, contrary to what has formerly been thought to be the case, that neither fog, snow, hail, nor rain, materially interferes with the transmission of loud sounds. The siren has been heard at a greater distance during the prevalence of a dense and widely-extended fog than during any other condition of the atmosphere. This may however be attributed to the uniform density and stillness of the air at the time.

7. In some cases sound-shadows are produced by projecting portions of land or by buildings situated near the origin of the sound, but these shadows are closed in by the spread of the sound-waves, and thus exhibit the phenomenon of sound being heard at a distance and afterwards lost on a nearer approach to the station.

8. It frequently happens on a vessel leaving a station, that the sound is suddenly lost at a point in its course, and after remaining inaudible some time, is heard again at a greater distance, and is then gradually lost as the distance is farther increased. This phenomenon is only observed when the sound is moving against the wind, and is therefore attributed to the upward refraction of the sound-wave, which passes over the head of the observer and continues an upward course until it nearly reaches the upper surface of the current of wind, when the refraction will be reversed and the sound sent downward to the earth; or the effect may be considered as due to a sound-shadow produced by refraction, which is gradually closed in at a distance by the lateral spread of the sound-wave near the earth, on either side, in a direction which is not affected by the upward refraction. Another explanation may be found in the probable circumstance of the lower sheet of sound-beams being actually refracted into a serpentine or undulating course, as suggested in the Appendix to the Report of the Light-House Board for 1875. (See page 513.) Such a serpentine course would result from successive layers of unequal velocity in an opposing wind; as being retarded at and near the surface of the earth, attaining its maximum velocity at a height of a few hundred feet, and then being again retarded at greater elevations, by the friction of upper counter currents or stationary air. In some cases the phenomenon is due to one or the other of these causes, and in other cases to all combined. That it is not due to the obstructing or screening effects of an abnormal condition of the atmosphere is shown by the fact that a sound transmitted in an opposite direction, through what is called the region of silence, passes without obstruction. It is probable from all the observations, that in all cases of refraction of a sound moving against the wind it tends again to descend to the earth by the natural spread of the sound.

9. The existence of a remarkable phenomenon has been established, which is exhibited in all states of the atmosphere during rain, snow, and dense fog, to which has been given the name of aërial echo. It consists

of a distinct echo, apparently from a space near the horizon of fifteen or twenty degrees in azimuth, directly in the prolongation of the axis of the trumpet. The loudness of this echo depends upon the loudness and quantity of the original sound, and therefore it is produced with the greatest distinctness by the siren. It cannot be due to the accidental position of a flocculent portion of atmosphere, nor to the direct reflection from the crests of the waves, as was at first supposed, since it is always heard except when the wind is blowing a hurricane.

As a provisional explanation, the hypothesis has been adopted that in the natural spread of the waves of sound, some of the rays must take such a curvilinear course as to strike the surface of the water in an opposite direction and thus be reflected back to the station or location of the origin of the sound.

LIGHT-HOUSE BOARD, *October*, 1877.

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