REFRACTION OF SOUND IN THE ATMOSPHERE

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Introduction

It is natural to think that the path sound travels is more or less straight. Certainly sound "leaks" around buildings and reflects from walls but, for the most part, when you hear a sound, you know where to look to find the source.

You may not realize you've made this assumption but it still affects your interpretations. If you watch a cannon being fired and the sound seems unusually weak, then surely it "must" be the result of some extra loss of energy from the sound wave as it traveled. You might develop an entire theory of sound absorption based on such observations.

But, what if the path of sound isn't straight? What if the sound from the cannon actually curved upward and passed over your head? Then the sound would only *appear* to be absorbed when in fact it had simply changed direction. No matter how plausible your theory of absorption might be, it would be wrong.

As the science of sound developed in the 18th and 19th centuries, this is just what happened. As unlikely as the idea of bending of sound paths seems, we now know that this bending—refraction—is commonplace. The speed at which a sound wave travels in air depends primarily on temperature and on the speed and direction of the wind. If the speed changes from one point to another along the "crest" or "front" of a sound wave, then the wave-front bends as it moves forward. For sound in the atmosphere, the effects of refraction are dramatic and nearly always present. But, in spite of a flurry of activity, the failure to recognize refraction slowed progress in understanding sound to a crawl.

The latter half of the 19th century was a watershed for understanding the science of sound in the atmosphere.

"Understanding the behavior of sound was not merely an intellectual pursuit—lives and commerce were at stake…"

Short-sighted focus on absorption and reflection gave way to understanding and acceptance of refraction as the dominant mechanism. But the context for the story of refraction spans about 250 years from the early 1700's to the middle of the 20th century. The story is a reminder that science is a human pursuit. The story started with ignorance, speculation, and misunderstanding but it led eventually to a deeper understanding of sound and of the structure of the atmosphere itself. And, the story started on a dark and stormy night…

Fog

Returning from France in fog late one October evening in 1707, four ships of the British fleet struck the Outer Gilstone Ledges and sank southwest of the Scilly Isles. The loss of the ships and more than one thousand sailors eventually prompted the British Parliament to pass the Longitude Act of 1714 that called for drastic improvement in navigation at sea. The history of the race to determine location at sea is captivating[1]; however, this navigational "solution" did not prevent shipwrecks in coastal fog. The required observations of, for example, the sun required good weather. Sailing between these often infrequent "fixes" still relied on the educated guesswork known as dead reckoning. In the fog, ships still sank.

Even though shipboard navigation was much improved by 1874, John Tyndall still wrote "…it is not surprising that in dense fogs our most powerful coast-lights…should become useless to the mariner…Disastrous shipwrecks are the consequence. During the last ten years no less than two hundred and seventy-three vessels have been reported as totally lost on our own coasts in fog or thick weather. The loss, I believe, has been far greater on the American seaboard, where trade is more eager and fogs more frequent than they are here. No wonder, then, that earnest efforts should have been made to find a substitute for light in sound-signals, powerful enough to give warning and guidance to mariners while still at a safe distance from the shore."

Understanding the behavior of sound was not merely an intellectual pursuit; lives and commerce were at stake: sound was a logical supplement for lighthouses when visibility was poor. However, the prevailing belief was that sound traveled poorly through fog (and rain and snow). If sound was absorbed by fog, what good would it be as a guide to mariners? In fact, sound does penetrate fog, often quite well, but the contrary belief had become the "expert opinion" from the early 1700's well into the 19th century. How did this happen?

Transparency

In 1708, Reverend William Derham published, in Latin, what became the definitive summary regarding the transmission of sound. Many of Derham's observations were accurate and his comments insightful; however, parts of the paper are conjecture with little supporting observation. Regarding fog, Derham wrote, "…as regards thick fogs, it is certain that they are dampers of sound in the highest degree…a fact that very certainly proceeds from the interposed vapors and thick particles that compose fog." He was confident that fog presented a substantial obstacle to the transmission of sound.

But even Derham admitted that the observations were ambiguous: "A like uncertainty obtains with regard to…foggy air. In rainy and damp weather I have often observed that sounds are blunted…but the contrary also often happens." Unaware that a reduced level of sound could be evidence of the sound bending away from the listener instead of being absorbed, weak sounds were always explained by some sort of loss.

Widespread acceptance of the view that fog absorbed sound was damning to the case for acoustic fog signals. However, there was no other promising technology. Tyndall in England and Joseph Henry in the United States were convinced that a warning system for ships based on sound could be made practical and they both carried out extensive programs of experiment and observation to prove it. Tyndall attributed the prevailing views regarding the absorptive power of fog to uncritical acceptance of Derham's work.

Before presenting his own observations as rebuttal, Tyndall collected some of the prevailing views: "Fog is a mixture of air and globules of water, and at each of the innumerable surfaces where these two touch, a portion of the vibration is reflected and lost." "…we must have some measure of fog's power of stopping sound…It seems probable that this will bear some simple relation to its opacity to light…" "Fogs have a remarkable power of deadening sound…" "…fogs and falling rain, but more especially snow, tend powerfully to obstruct the propagation of sound…" "That sound does not readily penetrate fog is a matter of common observation."

As Tyndall, Henry, and others discovered, instances of *excellent* sound transmission through fog, rain, or snow were easy to find. How, then, did the belief in the sound-deadening power of fog become so ingrained? It was simply too easy to believe that fog would dampen sound. The temptation to compare sound to light was irresistible: light seemed to travel more or less straight and heavy rain, snow, and fog blocked its path. Sometimes sound did seem reduced in foggy weather, sometimes it didn't, but it was easier to dismiss the contrary evidence than it was to explain it.

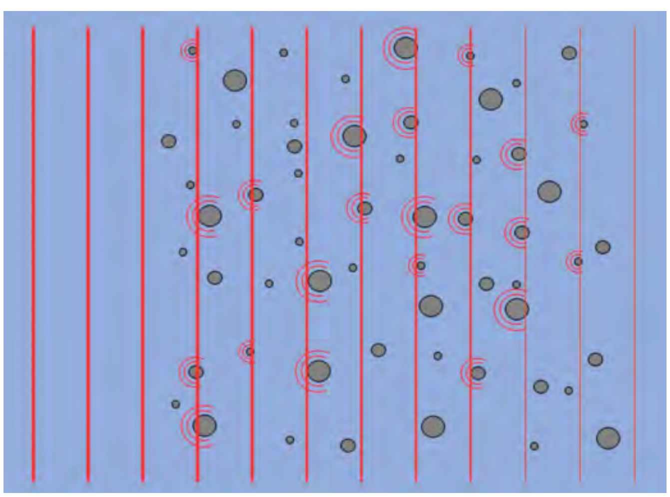

Fig. 1. In 1708, William Derham introduced the concept that suspended particles—whether tiny droplets of water in fog, rain drops, or snow flakes—would absorb and scatter sound perhaps in a manner similar to their effect on light. He might have drawn a figure like this where the sound waves (red) advancing to the right are either scattered from the particles or the friction between the waves and the particles robs the wave of energy. Waves do scatter strongly from particles if the wavelength of the wave is similar in size or smaller than the particles and this is the case for light. However, the wavelengths of audible sound waves are far larger than the particles of fog, rain, or snow so the scattering is much too weak to explain the observations of poor sound reception.

The belief that acoustical transparency was somehow related to optical transparency prevailed for a century and a half. But, in many ways, sound and light were already known to be quite different. Sound traveled better with the wind than against the wind, houses and hills didn't always block sound, and distant sounds seemed clearer and louder at night than during the day.

Curious aberrations in the behavior of sound stimulated further investigation. Sometimes an event was clearly visible but the sounds were not heard. In Tyndall's 1874 paper, he included a letter from R. G. H. Kean who had watched the Battle of Gaines's Mill during the American Civil War[2]. Kean wrote, "I distinctly saw the musket-fire of both lines…I saw batteries of artillery on both sides come into action and fire rapidly. Yet looking for near two hours, from about 5 to 7 P.M. on a midsummer afternoon, at a battle in which at least 50,000 men were actually engaged, and doubtless at least 100 pieces of field-artillery…*not a single sound of the battle* was audible to General Randolph and myself…[However, the] cannonade of that very battle was distinctly heard at Amhurst Court-house, 100 miles west of Richmond, as I have been most credibly informed[3]."

Inaudibility of loud sounds at short distances with good visibility was fatal to arguments based on transparency. Inaudibility could be explained by extreme absorption from some other mechanism. However, the "reappearance" of those sounds at extremely long distances could not be explained by absorption of any kind.

What is, at first, inexplicable stimulates explanation, debate, and experiment. As is common in the history of science, the search for understanding of the nature of sound transmission in the atmosphere started with remarkable observations. Plausible (but often incorrect) explanations followed. More observations raised more questions and stimulated a series of provocative and sometimes daring experiments. These observations and experiments eventually led to a deeper understanding not only of sound propagation but of the nature of the atmosphere itself.

Flocculence

In an attempt to bolster support for acoustic fog signals, Tyndall observed the sounds at sea from on-shore horns, sirens, and cannon fire. On one voyage he recorded that "…the rain at length reached us; but although it was falling heavily all the way between us and the Foreland the sound, instead of being deadened, rose perceptibly in power. Hail was now added to the rain, and the shower reached a tropical violence. …In the midst of this furious squall both the horns and the siren were distinctly heard; and as the shower lightened, thus lessening the local pattering, the sounds so rose in power that we heard…louder than they had been heard through the rainless atmosphere. …This observation is entirely opposed to prevalent notions…"

While Tyndall found many examples of good sound transmission when optical visibility was poor, he also observed poor sound transmission when the air was clear. These latter observations were fatal to the transparency arguments. Regarding his inability to hear a powerful siren on a clear day, Tyndall wrote: "…what…could so destroy [the air's] homogeneity as to enable it to quench in so short a distance so vast a body of sound?…As I stood upon the deck of the 'Irené' pondering it, I became conscious of the exceeding power of the sun beating against my back and heating the objects near me. Beams of equal power were falling on the sea, and must have produced copious evaporation. That the vapour generated should so rise and mingle with the air as to form an absolutely homogeneous medium I considered in the highest degree improbable. It would be sure, I thought, to rise in streams, breaking through the superincumbent air now at one point now at another, thus rendering the air *flocculent* with wreaths and striae…At the limiting surfaces of these spaces, though invisible, we should have the conditions necessary to the production of partial echoes and the consequent waste of sound."

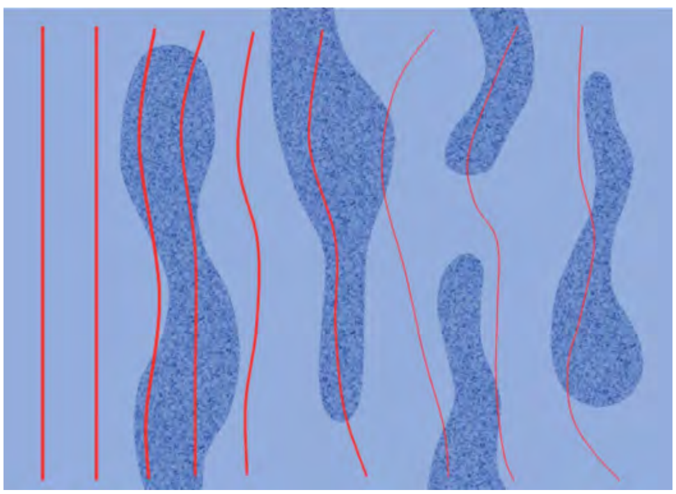

Fig. 2. John Tyndall's concept of flocculence supplanted earlier scattering theories because it seemed to explain poor propagation of sound in optically clear conditions. Tyndall believed that convection currents and streams of vapor would create enough discontinuities in density or sound speed to scatter (and absorb) sound. He might have drawn a figure like this one to illustrate sound waves (red) passing through regions of vapors (shaded). Even though the idea of refraction developed at about the same time as Tyndall's work, Tyndall believed that the loss processes were the primary processes by which sound amplitude was reduced. This sort of scattering and absorption does occur but it is far too weak to explain the large fluctuations in sound level that were often observed.

While such processes in the atmosphere do scatter sound, the effects are not strong enough to explain the dramatic decrease in sound audibility in many conditions. But Tyndall was confident that he had found the answer: "The real enemy to the transmission of sound through the atmosphere…has been proved to be not rain, nor hail, nor haze, nor fog, nor snow…but water in a vaporous form, mingled with the air so as to render it acoustically turbid and flocculent…Thus, I think, has been removed the last of a congeries of errors that for more than a century and a half have been associated with the transmission of sound by the atmosphere." But Tyndall had replaced one error with another[4].

He even went so far as to devise an intricate apparatus in to demonstrate the absorption of sound by flocculence. He arranged a series of tubes that fed carbon dioxide ("carbonic acid") into a duct from above and another series of tubes that fed methane ("coal gas") in from below. This produced alternating layers of heavy and light gas in the duct that successfully attenuated sound passing through the duct. But the "flocculence" was exaggerated far beyond anything that would occur naturally.

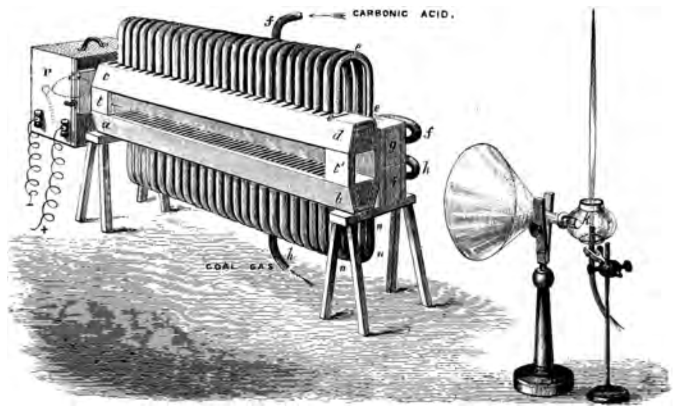

Fig. 3. Since experiments were difficult to perform in the field, Tyndall set out to prove that inhomogeneities in the atmosphere could extinguish sound. He built this intricate apparatus in which carbon dioxide ("carbonic acid") was introduced through many tubes above a duct and methane ("coal gas") was introduced through many tubes beneath. The heavier carbon dioxide flowed downward through the acoustic duct and the lighter methane flowed upward. The tube arrangement created alternating layers of light and heavy gas. The sound detector was a sensitive flame shown at the right. The apparatus produced very high losses in sound level but the inhomogeneity was exaggerated far beyond what would occur in the atmosphere. (From Tyndall's On Sound.)

More observations raised more questions. Sound seemed to travel better at night than during the day. Perhaps the sounds just seemed louder because background noise was lower at night. This was an admirable guess—even today, the loudness of a signal is often confused with the ability to distinguish a signal from surrounding noise. However, Baron von Humboldt provided convincing, contrary evidence. On an expedition to South America, he wrote that the sounds from a waterfall on the Orinoco River were stronger and clearer at night than during the day even though, in the jungle, insect and animal noises were much louder at night than during the day. Humboldt's explanation was similar to Tyndall's, though: Humboldt reasoned that, during the day, uneven heating of the ground caused strong upward and uneven currents of air that scattered the sound.

The Tyndall-Humboldt hypothesis was credible and contains some truth: turbulence in the atmosphere does scatter sound. However, plausibility is no guarantee of accuracy. The effects observed by Humboldt and Tyndall were too strong to be explained by scattering from turbulence; these effects had their roots in another cause entirely.

Refraction by wind gradients

In 1857, George Stokes suggested that the wind passing over the ground—its speed increasing naturally with height—might be the reason that sounds seemed louder downwind than upwind. Sound waves might be "bent" instead of scattered or absorbed. Stokes' view was revolutionary. Some conditions would bend the waves upward over the head of the observer; other conditions would bend the waves down toward the observer. The sound was not absorbed, just redirected. Initially unaware of Stokes's suggestion, Osborne Reynolds had the same idea and he proposed to test the hypothesis.

By the middle of the 19th century, the banks of the river Medlock near Manchester had been replaced by walls. Here, in 1874, Reynolds tried an experiment. He released drops of water into the river near the Oxford Road Bridge: "A pipe sent a succession of drops into the water at a few inches from the wall, that, falling from a considerable height, made very definite waves…Had the water been at rest [the waves] would have been semicircular rings; as it was, the front of the waves up the stream…gradually died out, showing the effect of divergence. The waves proceeding down the stream were, on the other hand, inclined to the wall that they approached."

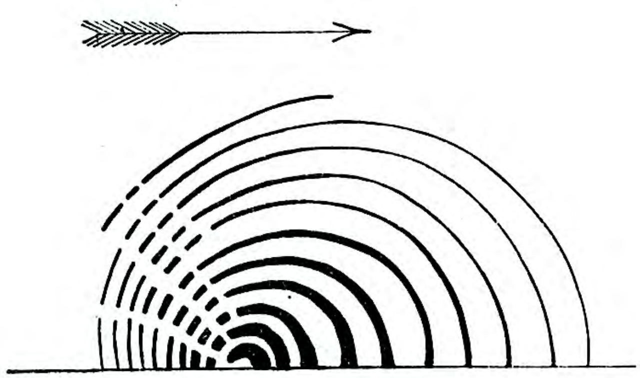

Fig. 4. A reproduction of Osborne Reynolds' sketch of the wave motion on the surface of flowing water. He let drops of water fall into the Medlock River in Manchester where the river flowed past a smooth wall. The flow of the river increases in speed with distance away from the wall and this causes the waves to weaken and lift away from the wall in the upstream (to the left) direction. Reynolds uses the thickness of the lines to indicate the strength of the wave – stronger downstream than upstream along the wall. The curved path would only be clear by watching the waves themselves. The breaks shown to the left of the source Reynolds attributes to interference but this is not fundamental to the process of refraction. (From Reynolds, 1873/4.)

Reynolds proposed that sound waves in the atmosphere behaved in the same way as the water waves on the river's surface. The variation in flow speed of the water—slow at the wall, faster away from the wall—caused the water waves to bend from their normal circular arcs. The waves appeared to be lifting away from the wall as they advanced in the upstream direction while bending toward the wall and strengthening in the downstream direction. This bending of the waves is refraction. Refraction is not caused simply by the flow of the water but by the increase in flow speed with distance from the wall.

Imagine dropping a stick into the river near the wall. The stick would rotate. The end farther from the wall is in faster flow while the end nearer the wall is in slower flow. If the stick was instead a portion of a moving wave front, this rotation would change the wave's direction of travel. If that portion of the wave had been traveling initially upstream, the rotation would cause the wave to veer away from the wall toward the middle of the river. If that portion of the wave had been traveling initially downstream, the rotation would cause it to bend toward the wall. An observer at the wall would see the upstream wave weaken and eventually leave the wall altogether while the downstream wave would seem to strengthen.

In still air, sound waves travel with a speed that depends on the temperature of the air. If the air is also moving, this motion adds to the wave speed if the wind is in the direction of travel and it subtracts from the wave speed if the wind is in the opposite direction. In fact, Reverend Derham had recognized this but he thought that the acceleration or retardation by the wind caused the difference in sound intensity. Stokes understood that a wind that increases in speed with altitude would bend wave fronts traveling in the upwind direction, lifting them away from the ground. This would produce a rapid decrease in audibility. In air, the effect can be so strong that a signal heard clearly at some distance downwind may, at the same distance upwind, be faint or inaudible.

This redirection or refraction of sound caused by variation in wind speed was a new and revolutionary hypothesis. More importantly, Reynolds realized that the hypothesis could be verified with a simple test.

Reynolds wrote: "Thus the effect of wind is not to destroy the sound, but to raise the ends of the wave, that would otherwise move along the ground, to such a height that they pass over our heads…It will at once be perceived that by this action of the wind the distance to which sounds can be heard to windward *must depend on the elevation of the observer* and the sound-producing body…It is difficult to conceive how it can have been overlooked, except that, in nine cases out of ten, sounds are not continuous, and thus do not afford an opportunity of comparing their distinctness at different places…Elevation, however, clearly offered a crucial test whether such an action as that I have described was the cause of the effect of wind upon sound." Reynolds also recognized the value of a continuous sound: "My apparatus consisted of an electrical bell, mounted on a case containing a battery. The bell was placed horizontally on the top of the case, so that it could be heard equally well in all directions…" Furthermore, he arranged to vary the elevation of the observer (or the source of sound).

Upwind of the source, "…at all distances greater than 20 yards from the bell the sound was much less at the ground than a few feet above it; and I was able to recover the sound after it had been lost in every direction by [climbing] a tree, and even more definitely by raising the bell on to a post 4 feet high, that had the effect of doubling the range of the sound…"

Reynolds distinguished himself by his approach to investigation: he proposed a hypothesis that sound traveling into the wind would be refracted upward by the increasing wind speed (the wind speed "gradient") with altitude; he made a critical, testable prediction—that the sound would increase

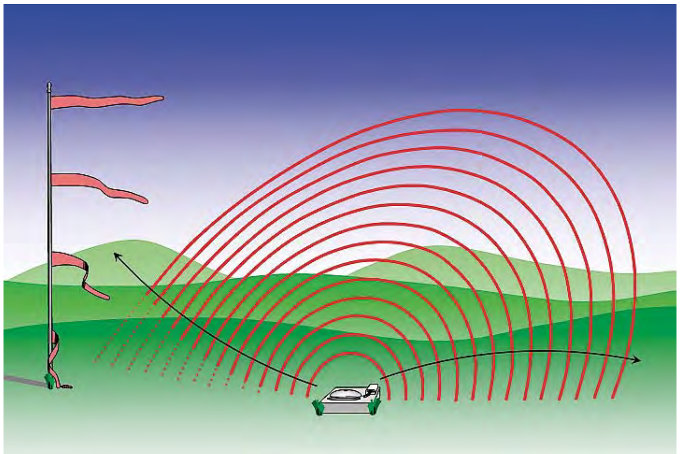

Fig. 5. Wind near the Earth's surface ordinarily increases in strength with altitude. This motion of the air coupled with the natural wave motion causes the waves to tilt downwind. Waves (the red arcs) that start out into the wind (to the left, above), tilt upward and may eventually pass over the head of an observer on that side of the source. Waves that start out with the wind (to the right, above) tilt downward toward the ground. If this happens, then, an observer upwind (to the left) of the source and in the acoustic "shadow" could regain the sound by climbing higher. George Stokes predicted wind-driven refraction in 1857 and in 1873 Osborne Reynolds made a number of experiments with a battery-driven bell to demonstrate what was happening.

with elevation of the observer; and he performed the test—by climbing a tree.

Derham had suggested that optical and acoustical transparency were linked. This hypothesis was testable but it was not tested (at least with published results) until Tyndall's negative results. Tyndall (and others) suggested that inhomogeneity and turbulence in the air caused poor sound transmission. Tyndall attempted to test this hypothesis in the laboratory but his apparatus exaggerated the inhomogeneity so much that the test results had little meaning. Reynolds took Stokes' hypothesis, identified a critical prediction, and tested the prediction under realistic conditions.

Refraction by temperature gradients

The second half of the 19th century saw rapid progress. Reynolds had verified Stokes' theory. Furthermore, Reynolds realized that any change in the effective wave speed could cause refraction. Wind has a strong effect on the speed of sound in the air but sound speed is also a function of temperature. If the temperature of the atmosphere changed with altitude, then so would the sound speed and waves would, again, change direction—bending toward regions of lower sound speed (lower temperature) and away from regions of higher sound speed (higher temperature).

Even in the 1700's reliable and portable thermometers were available and explorers often carried them. Mountain climbers recorded a general decrease in temperature with altitude but these measurements were suspect: the temperatures were influenced by proximity to the ground. So the observed temperature decline may not have been a funda-

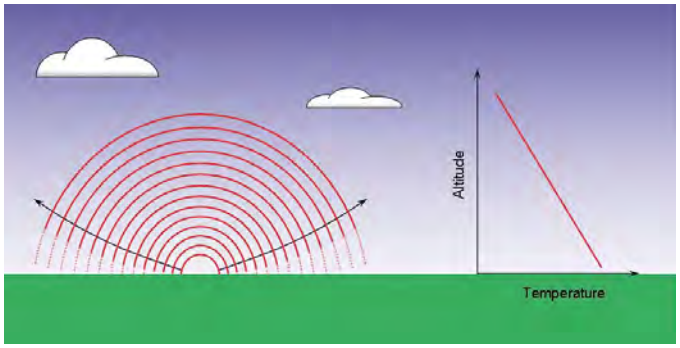

Fig. 6. In the daytime, the temperature normally decreases with altitude. This causes sound to be refracted upward, which reduces the sound level for an observer on the ground. Although the effects of wind often overwhelm those of temperature with respect to refraction, when winds are light, the daytime temperature decrease can cause unexpectedly low sound levels from distant sources.

mental characteristic of the atmosphere.

In 1749, Alexander Wilson, Professor of Practical Astronomy at the University of Glasgow, suggested a direct measurement: "Mr. Wilson proposed…to explore the temperature of the atmosphere in the higher regions, by raising a number of paper kites, one above another, upon the same line with thermometers appended…Upon launching these kites…the uppermost one ascended to an amazing height, disappearing at times among the white summer clouds…To obtain the information they wanted, they contrived that thermometers, properly secured, and having bushy tossels of paper tied to them, should be let fall at stated periods from some of the higher kites; that was accomplished by the gradual singeing of a match-line." Success depended on recovering and reading the thermometers quickly. Considering the difficulty of interpreting the thermometer readings after having fallen back to Earth, it is not surprising that Wilson did not publish the results of these measurements.

A century after Wilson's kite experiments there was a dramatic increase in manned balloon flights for scientific observation. Large fabric balloons filled with "carbureted hydrogen" (methane) lifted scientists and their instruments to tens of thousands of feet altitude. Although the instrumentation was crude by today's standards, the investigators built sun shields to reduce direct solar heating of their thermometers and they forced air past the thermometers to hasten their response to changes in temperature. Temperature measurements from these flights convinced Reynolds that temperature-induced refraction might be possible.

Without oxygen, these aeronauts measured temperature, pressure, and humidity to remarkable altitudes. The British Association for the Advancement of Science funded a series of balloon flights, the first few with John Welsh as the science observer. Then, James Glaisher flew a longer series of more ambitious flights. In fact, "ambitious" hardly does them justice. With Mr. Coxwell as pilot, Glaisher ascended from Wolverhampton on September 5, 1862: "Discharging sand, we… attained the altitude of five miles, and the temperature had passed below zero… we ascended still higher… and I also found a difficulty in seeing clearly… I could not see the column of mercury in the wet-bulb thermometer, nor the hands of the watch, nor the fine divisions on any instrument… In consequence, however, of the rotatory motion of the balloon… the valve-line had become entangled, and [Mr. Coxwell] had to leave the car and mount into the ring to readjust it. I then looked at the barometer, and found its reading to be 9 3/4 in., still decreasing fast, implying a height exceeding 29,000 feet.

"Shortly after I laid my arm upon the table, possessed of its full vigour, but on being desirous of using it I found it powerless…trying to move the other arm, I found it powerless, also…then I fell backwards, my back resting against the side of the car and my head on its edge…I suddenly became unconscious as on going to sleep…Mr. Coxwell told me that while in the ring he felt it piercingly cold, that hoarfrost was all round the neck of the balloon, and that on attempting to leave the ring he found his hands frozen. He had, therefore, to place his arms on the ring, and drop down…when he felt insensibility coming over him too, he became anxious to

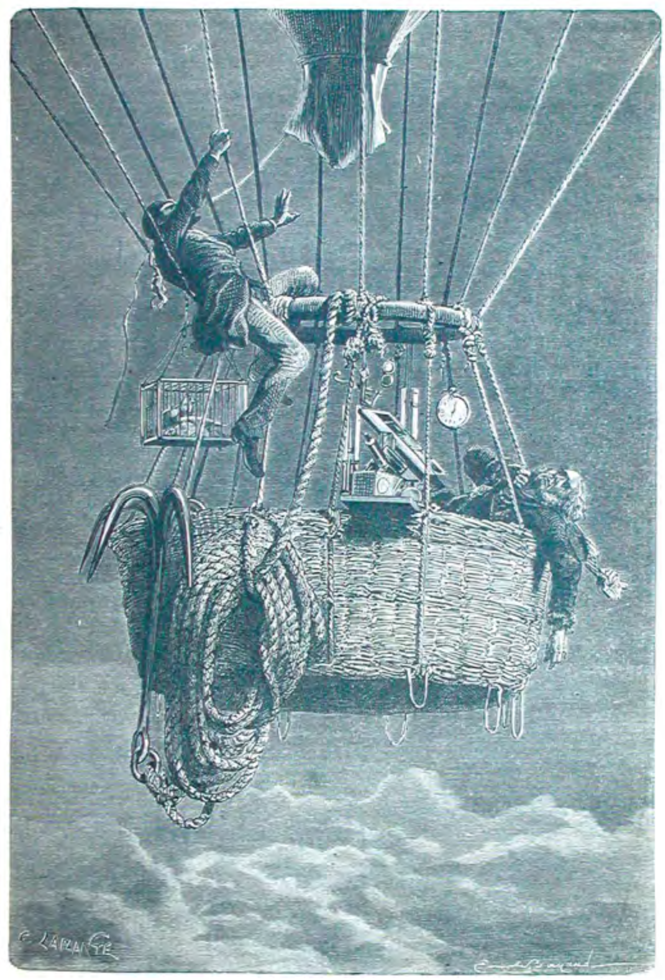

Fig. 7. Before the development of radio telemetry, much of the information about temperature, humidity, and wind speed in the atmosphere came from scientific balloon flights. Some of these expeditions were harrowing. James Glaisher's flight on September 5, 1862 probably exceeded 30 000 feet and nearly killed Glaisher and Coxwell, the pilot. However, data from these 19th century balloon flights came at the right time to support the concept of refraction of sound. In a curious reversal, once atmospheric measurements established refraction as an important effect, sound was later used to probe the upper atmosphere determining both temperature and wind speed at altitudes well in excess of even unmanned balloon flights. (From Glaisher's Travels in the Air.)

open the valve…ultimately he succeeded, by seizing the cord with his teeth and dipping his head two or three times, until the balloon took a decided turn downward." They probably reached at least 30,000 feet on this near-fatal flight.

Less hazardous but even more intriguing were the results from the rare night-time flights. On October 2, 1865, "When the sun had set for nearly three-quarters of an hour…the balloon left Woolwich Arsenal…the temperature at the time being 56° [F]…Within three or four minutes a height of 900 feet was reached…the temperature was 57° and increasing; on reaching 1,200 feet high it had increased to 58.9°. We then descended to 900 feet, and the temperature decreased to 57.8°; on beginning to ascend again the temperature increased to 59.6° at 1,900 feet high…in the several subsequent ascents and descents the temperature increased with elevation, and decreased on approaching the earth…This result was remarkable indeed."

While it was easy for these investigators to believe that the temperature would drop with altitude, they were astonished that, in some circumstances, the temperature increased with altitude. The "normal" drop in temperature produced upward refraction of sound and reduced audibility of sounds near the ground. The night-time temperature "inversion" would produce downward refraction of sound and, consequently, better audibility of distant sounds at night!

Reynolds wanted to prove that temperature gradients could refract sound but he found the experiments frustrating. The effects produced by winds are often larger than the effects produced by temperature gradients: "…Mr. Glaisher's ballon ascents in 1862…found that when cloudy the mean rate of diminution for the first 300 feet was 0.5° [F] for each 100 feet, and that when clear it was 1°…this rate of refraction is very small compared with that caused even by a very moderate wind… This renders the experiment very difficult to carry out…"

But the idea was provocative and it was worth trying to find conditions sufficiently calm. "In the hope of improving the conditions of the experiments, I accepted the invitation of my friend Major Hare, of Docking in West Norfolk, to accompany him in his yacht the 'Feronia' during a cruise on the east coast, taking rockets [as sources of sound] with me. Here I spend three weeks without having a single calm day."

Success often follows persistence and Reynolds finally found a day with little wind and a daytime temperature inversion. He observed excellent sound transmission: "With regard to the cause of the exceptional distances over which we heard the sounds on the 19th of August, 1874…All the morning I had been watching the distant objects to see whether they were lifted or depressed by the refraction of light. They loomed to a remarkable degree that showed that the upward variation of temperature was the reverse of what I wanted…The looming of the distant objects showed that the air was colder below than above. This would tend to bring the sound down and intensify it at the surface of the water—in fact convert the sea into a whispering-gallery."

Reynolds recognized that temperature gradients would refract both light and sound. He had hoped to find a calm day with a normal decrease in temperature with altitude and reduced audibility of sound but the enhanced sound transmission with a temperature inversion was just as convincing.

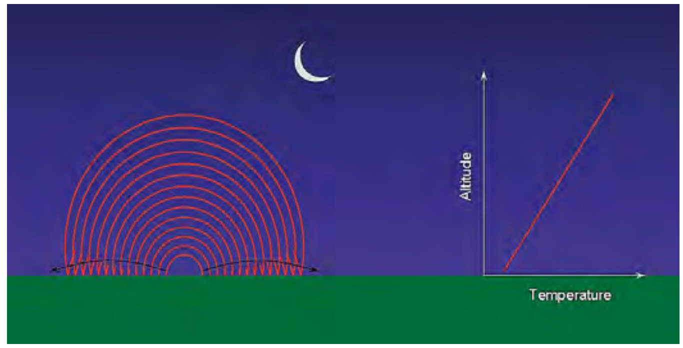

Fig. 8. A temperature increase (an "inversion") with altitude often occurs at night and this causes sound to be refracted downward, which enhances the sounds for an observer on the ground. On an expedition to Venezuela in 1899, Baron von Humboldt observed much better sound transmission from a waterfall on the Orinoco River at night than during the day. Such early observations revealed features of the surface layers of the atmosphere but temperature inversions are also a permanent feature of the stratosphere and account, in part, for long-range transmission of sound to hundreds of kilometers.

The experiments of Reynolds and others eventually led to acceptance of refraction as a principal agent in producing wide variations in audibility of distant sounds. Reynolds acknowledged that there could be other effects including Tyndall's flocculence: "With respect to the stoppage of the sound by the heterogeneity of the atmosphere…it seems to me that it must exist, but that it must at all times be confined to a very small distance above the earth's surface and be over land." Unfortunately, Reynolds' explanation for the weakness of this form of scattering was flawed: "That, as a rule, there are no streams of heated air ascending to any considerable height over land, is definitely proved [!] by the fact that the light smoke from burning weeds never, or very seldom, attains an elevation of any thing like 100 feet." Rising currents of air can, in fact, reach tens of thousands of feet above the Earth's surface; a fact exploited by soaring birds and glider pilots.

Science rarely takes the shortest path from problem to solution. When several effects operate simultaneously, we like to think that we can isolate the major effect, then remove it through a clever experiment and study the next most important effect. In reality, it may not even be obvious what the major effect is. For a century and a half after Derham's paper, scattering by suspended particles (water, snow, hail) was taken to be the primary cause of the peculiarities of sound transmission. Observational evidence did not support this, however, so Humboldt, Tyndall and others postulated that inhomogeneities (flocculence) from mixing processes caused excessive scattering (or absorption) of sound. Plausible, perhaps, but for audible frequencies in the atmosphere, refraction normally dominates; progress in understanding sound propagation was slow until this dominant mechanism was uncovered.

As soon as refraction of sound had reconciled the peculiarities of sound transmission over distances of tens of meters to kilometers, other, more bizarre observations—zones of silence interspersed *between* zones of audibility, for

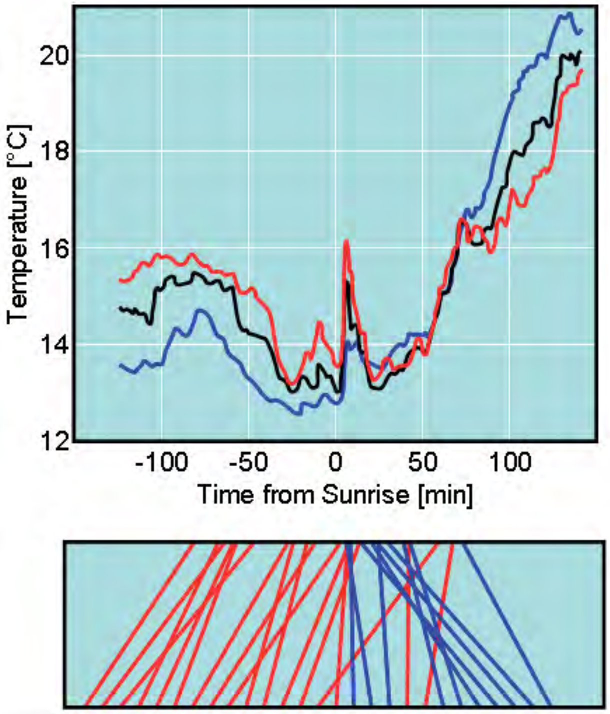

Fig. 9. Near the ground, the air temperature gradient (its change with height) often changes from night to day. The upper graph shows the variation in temperature sampled every ten seconds for three sensors located at 0.2 (blue), 2 (black), and 4 (red) meters above the ground. At night, the ground cools by radiation into the clear sky so the temperature of the air above the ground increases with height. After sunrise, solar heating of the ground reverses the temperature gradient: the temperature at 0.2 meters (blue curve) is higher than that at 4 meters (red curve). The spike after sunrise is probably a small convection current—it was accompanied by a noticeable breeze. The temperature gradient every ten minutes is shown in the lower plot. A line leaning to the right (and colored red) indicates an increase in temperature with altitude (an "inversion") whereas a line leaning to the left (and colored blue) indicates a decrease in temperature with height. (Data taken by the author.)

example—begged for similar resolution. Furthermore, the roles started to reverse. At first, the vagaries of sound propagation prompted investigation of the atmosphere. Gradually, however, sound became a valuable tool for understanding the properties of the atmosphere.

Into the stratosphere

With the recognition of refraction by either wind or temperature gradients, Kean's inability to hear the battle at Gaines's Mill now had a reasonable explanation: little or no wind was reported[5] but the normal temperature decline with altitude produced sufficient upward refraction to prevent Kean from hearing the sounds of rifle and cannon fire. Why, though, were the same sounds heard 100 miles away? If refraction could explain the short-range observations, could it also account for the more distant ones? But what would bring the sound back down at such long ranges?

As common as refraction of sound might be, it took unexpected observations to make people notice. World War I provided a tragically constant source of powerful explosive sounds. Gunfire in France might not be audible within a few kilometers of the source but might be heard hundreds of kilometers away in England.

Isolated large explosions provided additional evidence for long-range effects. Beno Gutenberg wrote: "In 1904, G. von dem Borne investigated a region where an explosion of dynamite had been heard. He found that there were two distinct zones of audibility, one surrounding the source and another, separated from the first by a "zone of silence," at a greater distance. Many subsequent investigations have shown that usually two or more zones of audibility result from explosions." "The data…have led to the conclusion that the sound waves that arrive at the second and succeeding zones have traveled through the stratosphere and that their velocity at the highest point exceeds the velocity of sound near the ground." "The outer boundary of the [second] zone is fixed by the rays that have their highest points between 60 and 70 km above the ground. As Schrödinger has shown no sound can be transmitted at greater heights because the distance between the molecules is too large there."

(Erwin Schrödinger[6], published an account in 1917 of what we now call classical absorption—the absorption of sound from viscosity and thermal conductivity. Schrödinger calculated high levels of absorption at extreme altitudes; so high that refraction of audible sound from heights above 60 km or so would not be observed.)

In order to refract sound back down to earth more than 100 km from the source, the refraction must have been taking place at higher altitudes than could be explained by refraction from surface winds or near-surface temperature gradients. Not only that, the zones of audibility seemed to extend further to the east in the winter and further to the west in the summer. The success of refraction in explaining propagation of sound over shorter distances suggested looking for refraction at higher altitudes. But what was the cause: wind, temperature, or something else?

The road to discovery continued to twist, turn, and even reverse direction. Up to this time, balloon observations of

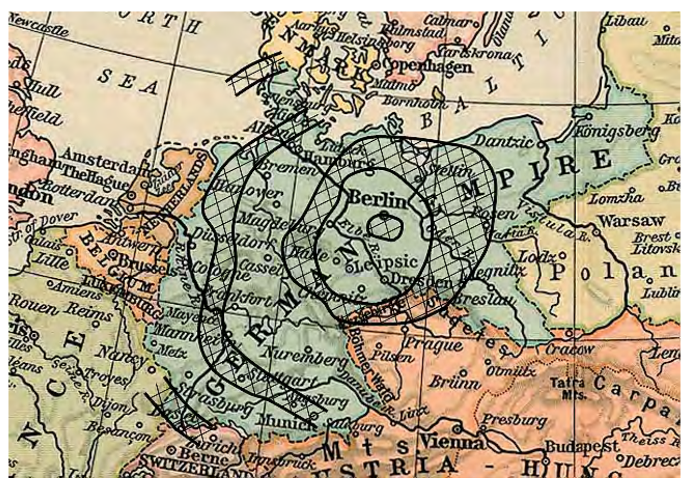

Fig. 10. Observations of unusually long-distance propagation of sound, especially during World War I, led to a series of ambitious experiments after the war. Large explosions were set off and observers reported whether or not they heard the explosion. The results of one such explosion at Kummersdorf (south of Berlin) on December 18, 1925 are shown here. The cross-hatched regions in the figure above are those regions in which the explosion was heard. The ring-like structure with zones of audibility alternating with zones of silence suggested that the sound was reflecting from the ground and then being refracted back down to the ground over and over. The distance between rings suggested that the refraction was taking place in the stratosphere. (Adapted from B. Gutenberg, Handbuch der Geophysik with the base map used by permission from The Historical Atlas by William R. Shephard, 1911.)

temperature had only extended far enough in altitude to show a general temperature decline with hints that it might be approaching a constant value. It was generally assumed either that the temperature was constant above these altitudes or that, above this isothermal layer, the temperature continued to decrease.

A more palatable option than an increase in temperature at high altitudes was the idea of a "hydrogen atmosphere." It made perfect sense that lighter gases in the atmosphere would rise and heavier gases would sink. The upper atmosphere should be rich in hydrogen[7]. Since the sound speed in hydrogen is much higher than in air, this wonderfully plausible hydrogen atmosphere should refract sound downward from extreme altitudes.

The hydrogen atmosphere was doomed, though. In 1918 F. J. W. Whipple wrote, "The beautiful theory of von dem Borne that explains the existence of the outer zone of audibility by the refraction of the sound-rays on reaching the regions in which hydrogen is the principal constituent of the atmosphere…has been severely criticized on the ground that the transmission of sufficient energy through such a diffuse medium back into the lower atmosphere was impossible. [Also] the tendency of the outer zone of audibility to lie on one side of the source is a recognized difficulty in the way of this theory. Obviously it can offer no explanation of the shifting of the zone from season to season."

Furthermore, the kinetic theory of gases was reaching maturity and Sir James Jeans showed that the molecular velocities in hydrogen were high enough that hydrogen would escape rapidly into space instead of accumulating at the top of the atmosphere.

Whipple did not realize that the hydrogen atmosphere itself was untenable. Nonetheless, he did propose an alternate solution: "In the absence of any other hypothesis, it may be suggested that the winds at great heights, say 20 km or more, may be sufficiently strong and sufficiently regular to cause the observed effects. It is known that wind-speed generally reaches a maximum at the base of the stratosphere and falls off rapidly above that limit, but it is possible that there is a régime of much stronger winds at higher levels and that they blow with the regularity of the Monsoons." As it turns out, he was half right. Seasonally reversing winds in the stratosphere do produce a seasonal variation in the zones of audibility but this is coupled with an increase in temperature at high altitude. Wind would produce zones of audibility only in the direction toward which the winds were blowing. The observed zones of audibility often extended in full or almost full rings around the source so wind could not be the sole agent of refraction.

Although it was the least "reasonable" of the mechanisms for high-altitude refraction, it seemed that a high-altitude temperature increase was the only mechanism compatible with the observations. What could produce such a temperature increase?

In 1923, F. A. Lindemann and G. M. B. Dobson published their predictions of the temperature and density of the upper atmosphere based on observation of visible meteor tracks: "…existing observations enable us to say with considerable certainty that the density at heights above 65 km is very much higher than is commonly supposed, and that the temperature must increase from its value of something like 220° [K] at heights between 12 and 50 km., to something like 300° [K] at these heights…"

Edward Gowan followed with a paper in 1928 suggesting that ozone was the cause of this upper atmosphere temperature increase: "Lindemann and Dobson have calculated the density of the atmosphere from observations of meteors. From the abnormally high values obtained they conclude that the temperature above 60 km is of the order of 300° K…The author's [Gowan's] suggested explanation of the occurrence of a high temperature at such heights was the strong absorption of solar energy in the ozone[8] that has been observed. Whipple refers to the zones of audibility that occur at some distance around big explosions. Assuming a reasonably sharp transition of temperature from 220° to 280° K at a height of about 60 km., he makes a rough estimate of the minimum radius of the outer zone audibility. This agrees well with observations that have been made."

A decade later, Gutenburg gave one of the strongest endorsements of the role of acoustics in upper atmosphere research: "The best information regarding the temperature between 30 and 60 km is derived from observations that give the velocity of sound waves at these altitudes. [However] at higher levels the absorption of sound increases so fast with elevation that the usefulness of sound waves for temperature determinations decreases rapidly above the level of 60 to 70 km."

Gutenburg continues: "Many attempts have been made to explain the high temperatures at heights between about 40 and 60 km…there is little doubt that absorption of the solar radiation by ozone and water vapor play the major roles in

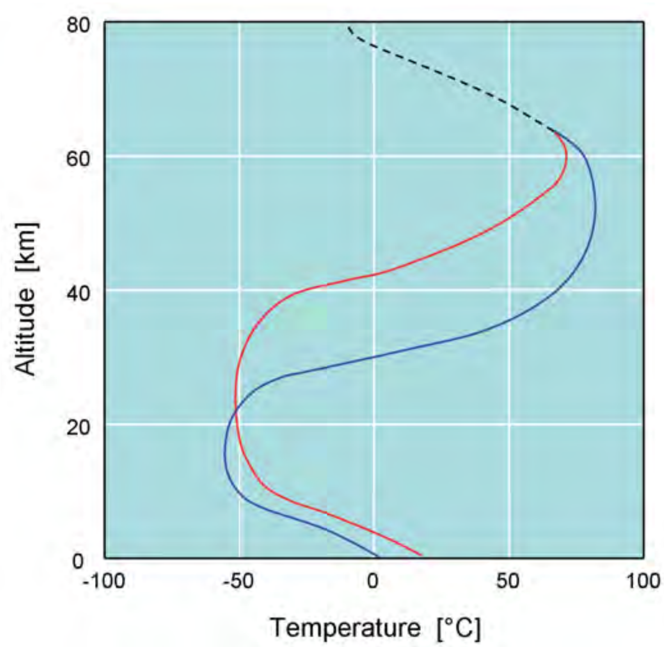

Fig. 11. Once refraction was understood, the propagation of sound became an important method for probing the upper atmosphere. This graph shows the variation in temperature with altitude inferred from measurements of sound in Northern Germany (adapted from Gutenberg, 1946). The winter profile is shown in blue; the summer profile in red. At the time of Gutenberg's work, the variation in temperature above 60 km was conjecture. Later work verified the decrease from 60 to 80 km and a subsequent increase in temperature above 80 km. The temperature profiles from the ground to 10 km were determined from balloon measurements.

producing these high temperatures."

While other methods of atmospheric research were being developed, refraction of sound remained one of the cornerstones. Any proposed structure for the atmosphere that did not explain long-range refraction of sound was unacceptable.

Into the 20th century

By the early 1900's, refraction of sound in the atmosphere was accepted widely. Extensive direct measurement by balloons, kites, and airplanes had exposed the major temperature and wind variations with altitude in the lower atmosphere. Innovative indirect observations of sound, meteor trails, and high-altitude clouds had established the gross features of temperature and wind variations in the stratosphere. By the end of World War II, high-altitude balloon flights confirmed the already suspected seasonal wind direction reversal in the stratosphere—flow toward the west in the summer and toward the east in the winter.

Infrequent and expensive manned balloon flights gave way to regular measurements from unmanned balloons, airplanes and, later, rockets. Sounding rockets probed altitudes much higher than balloons but the problem of temperature measurement was not solved merely by flying a temperature sensor on a rocket. At extreme altitudes the sensor may reach thermal equilibrium with solar radiation instead of with the tenuous air surrounding the sensor. Furthermore, any temperature reading must be corrected for the compressional heating produced by the fast-moving nose of the rocket.

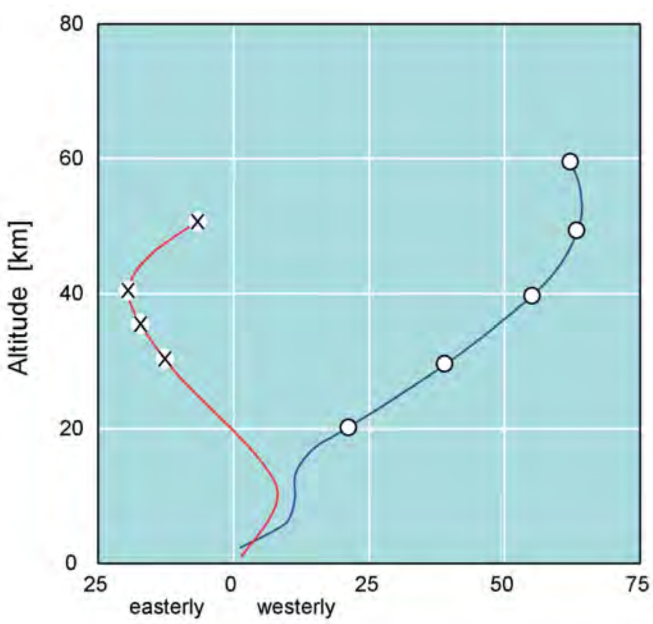

Fig. 12. The seasonal change in wind direction and speed in the stratosphere was also determined from measurement of sound propagation from explosives. A. P. Crary determined these wind speed profiles for the summer (red) and winter (blue) in Alaska in 1948 and 1949. The points indicated by the circles and x's were determined from acoustic measurements. The regions below 20 km are representative of historical measurement by balloon. Many other experiments verified this general behavior—the reversal in direction of stratospheric winds from summer to winter. (The Jet Stream occurs at altitudes generally between 10 and 15 km in the region of non-reversing winds.) The temperature and wind speed variations in the upper atmosphere explained both the occurrence of zones of silence and zones of audibility and the shifting of those zones with season. (Adapted from Crary, 1950.)

Density measurements offer a less intuitive but more reliable method for high-altitude temperature determination. The temperature can be calculated from the density if the altitude and molecular weight of the air are known. The density can be inferred from a dynamic pressure ("pitot") probe on a rocket. A more creative approach is to eject an inflatable sphere during the rocket's ascent. Aerodynamic drag on the sphere controls its subsequent path. By tracking the trajectory of the sphere, the density can calculated from the sphere's acceleration and drag coefficient. (Osborne Reynolds would be pleased: the coefficient of drag for a sphere is a function of the "Reynolds Number.")

The study of atmospheric sound from 1700 to the first half of the 20th century is a fascinating story of the real scientific method—the human method—with the foibles and mis-steps, arguments and experiments, errors and corrections of science and scientists. Derham's "expert opinion" in the early 1700's hindered understanding for more than a century. Scientists in the mid-1800's rebutted these opinions but replaced them with other errors: the new explanations were attractive and plausible but wrong. Later, evidence for refraction overwhelmed other arguments and the often strange observations were reconciled. The hydrogen atmosphere came and went but, ultimately, the study of sound exposed the general structure of winds and temperature in the upper atmosphere well before direct measurement was possible.**AT**

Comments

1. Dava Sobel's *Longitude* (1995) is an excellent popular account. Rupert Gould's *The Marine Chronometer* (1923) is harder to find but worth reading for the technical detail.
2. Many other fascinating accounts of the influence of acoustic propagation on battle strategy in the Civil War are contained in C. D. Ross, *Civil War Acoustic Shadows* (White Mane Books, Shippensburg, PA, 2001) and, by the same author, "Outdoor sound propagation in the US Civil War," Applied Acoustics **59**, 137-147 (2000).
3. Tyndall did not embrace the concept of refraction. It is curious that Kean's letter is reproduced apparently in its entirety in Tyndall's 1874 paper but the remarkable statement about hearing the battle sounds 100 miles away was omitted when Tyndall quotes from the letter in his 1908 book, *Sound*.
4. At least he was questioning the prevailing views and challenging the scientific literature.
5. Artwork from the battle and reports from the Signal Corps agree that the smoke of the battle dispersed very slowly; however, it is not out of the question that a light wind played some role in the refraction.
6. The story of the development of atmospheric acoustics is interesting not only for the science but also for the people. Reynolds is best known not for his work in acoustics but for his work on turbulence in fluid flow and Schrödinger for his work on quantum mechanics. Werner Heisenberg—also a name from quantum mechanics—published on atmospheric science: he found a lower limit to the size of eddies in turbulence in the atmosphere.
7. If buoyancy alone were the controlling factor, argon—heavier than either oxygen or nitrogen – would produce an uninhabitable blanket of gas near the ground. But Lord Rayleigh didn't publish his discovery of argon until 1894.
8. This statement gives the impression that ozone is a natural component of the atmosphere that happens also to absorb solar radi-

ation. We now know that ozone exists at these altitudes *because* of exothermic photochemical processes driven by solar radiation. But these were the early days with regard to understanding atmospheric ozone.

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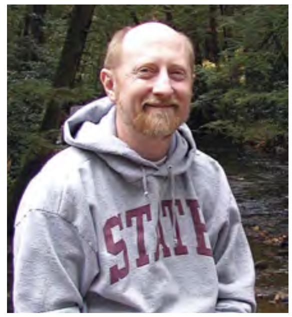

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