Waterfall low-frequency vibrations and infrasound: implications for avian migration and hazard detection

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I do not have any.

Availability of Data and Material

The measurements were made using a PC with the Cornell Raven software and a microphone detailed in the manuscript. These data are in a standard format.

Code Availability

The Raven software developed by Cornell is available on-line.

Authors Contributions

Not Applicable

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Alfred. J. Bedard Jr.[1]

Abstract

Many researchers have suggested that birds may use natural infrasound sources for navigation and hazard avoidance. However, there is a need to define the sound levels and frequencies to characterize potential infrasound sources. This paper summarizes new measurements from Niagara Falls which define a stable, powerful infrasound source that could be detected by birds on a regional scale of over 400 kilometers. Measurements made in the vicinity of Niagara Falls show that exceptional infrasonic pressure levels can occur in the regions of large waterfalls (>100Pa at a range of about 500 meters). This paper reviews investigator assessments of avian use of infrasound. A review of the results of Cornell researchers on pigeon hearing provides a basis for estimating avian detection ranges of waterfalls. It is possible that migrating birds use sounds from waterfalls as beacons- a component of their "navigation toolbox" as well as infrasound for hazard avoidance.

Key Words: avian navigation · infrasound · waterfalls · weirs · hazard avoidance

Introduction

There have been a broad set of infrasonic sources identified in the atmosphere (Bedard and Georges, 2000). Many of these are quite transient, only lasting for minutes. Examples of these signals are small explosions, meteors, avalanches and those related to storm electrical discharges. Another transient set of infrasonic signals, while of longer duration (tens of minutes to hours), can involve moving sources (e.g. radiation of infrasound from severe weather); as well as sounds from volcanoes, earthquakes, or large explosions. In addition, there are sources of infrasound of large areal extent. Most notably, these sources are related to air flows interacting with terrain features or originating with turbulence aloft (Bedard, 1978). In addition, large areas of interacting ocean waves at sea or alternatively waves abruptly stopping on shore lines can provide infrasound arriving from a broad azimuth sector. Chanson (2009) has documented low frequency, rumbling sounds accompanying tidal bores. On the other hand, unique, continuous infrasound sources could easily have gone unnoticed in the midst of the detection of acoustic energy from larger areas of radiation. Often, past infrasonic monitoring was restricted to a specific range of frequencies. Frequently, monitoring has been episodic or focused on a specific source (e.g. tornado detection). This paper addresses waterfalls as unique, essentially continuous geophysical sources of infrasound and considers possible sound generation mechanisms.

There are dual goals in this review paper. One goal is to define the sound levels created by natural waterfalls, and explore sound generation mechanisms, contrasting these with sound generation by weirs and dams. A parallel goal is to detail evidence for the sound pressure threshold levels and capabilities of pigeons for infrasound detection and potential avian uses of infrasound.

A significant amount of research has addressed possible avian uses of infrasound. An overview is in the section entitled- Studies focused on possible avian uses of infrasound. This is followed by an evaluation of the potential of pigeons to use infrasound from Niagara Falls and costal waves for navigation in the section entitled- Possible Importance of waterfall infrasound for bird migration.

Waterfall infrasound quantitative measurements

This section documents the exceptional infrasound levels observed from Niagara Falls, as well as lower levels from San Rafael Falls and Boulder Falls. The summaries and analyses of processes causing powerful sounds caused by hydraulic processes appear in appendices 1 and 2

Johnson et al. (2006) measured the infrasound associated with the San Rafael Ecuadorian waterfall. They observed almost continuous infrasound from the waterfall between 2 and 3 Hz. To my knowledge, this was the first instrumented detection of a natural waterfall.

Data at Niagara Falls were taken on 16 June 2009 for four 1-minute intervals separated in time by about 5 minutes. Data were displayed as time series and spectra using RAVEN (A sonogram display program developed by Cornell Laboratory of Ornithology). Data files were archived for additional processing. Figure 1 is an example of one of the data sets recorded. These levels were at a distance of about .5 kilometer from the falls- Horseshoe and American.

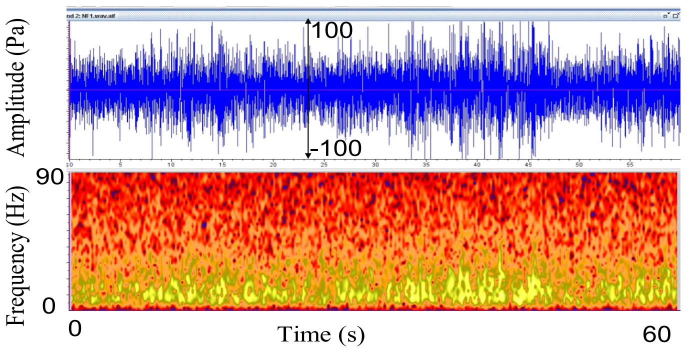

Fig.1 This shows data taken about 500 meters from Niagara Falls. The upper trace is a time series for a one minute interval of data. The lower display is a spectrogram covering a frequency range from 0 to 90 Hz. The scale for the time series is +/- 100 Pa. (Color online)

In Fig.1 the spectral energy scale is that black indicates no energy and white the greatest energy. Therefore the greatest energy is around 10 Hz. All four 1-minute measurement intervals showed strong peaks in energy between 5 and 20 Hz, much stronger than the energy in the audible range (producing a continuous roaring sound). There were no winds during the measurement period.

The amplitude scale of the Raven sonogram display is in arbitrary units so there was a need to calibrate the scale. The microphone used was an Avantone, large capsule/USB Cardioid FET. We measured the microphone sensitivity in the frequency range between 10 and 40 Hz. The sensitivity was 0.3 divisions/Pa between 30 and 40 Hz, falling off below 20 Hz to < .03 division/Pa at about 10 Hz.

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At Niagara Falls measured levels were above 30 divisions in the 5 to 20 Hz range, corresponding to pressures >100 Pa.. Assuming an inverse range dependence for geometrical spreading, amplitude levels of 0.5 Pa and 0.05 Pa will occur at ranges of 100 and 1000 km from the source respectively. Levels of 0.1Pa are typical background amplitudes for locations with low wind conditions. Figure 2 contrasts Niagara Falls data with data taken in Colorado under low noise conditions. The constant tone at 24 Hz was from a woofer-organ pipe combination at a range of 762 meters.

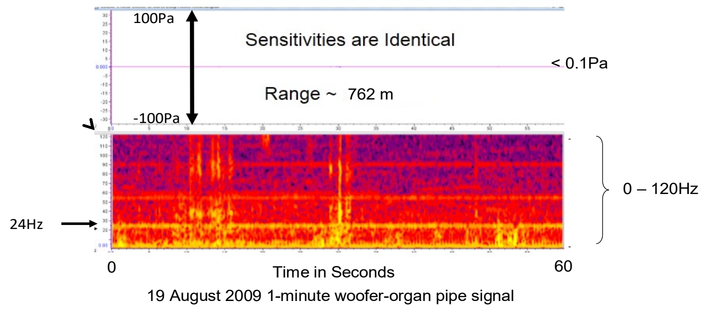

Fig.2 The figure was recorded at the Boulder Atmospheric Observatory (BAO) in Colorado using identical instrumentation and sensitivity settings The level at the BAO of <0.1 Pa is typical for low wind conditions The constant tone at 24 Hz is from a woofer/organ pipe combination at a range of 762 meters The 24 Hz test signal pressure level shown was ~0.01 Pa (Color online)

Using the hardware deployed at Niagara Falls measurements were made on 11 August 2009 at a range of 30 meters from Boulder Falls, Colorado. Infrasound occurred between 10 and 30 Hz at a pressure level of 3 Pa

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Summary of waterfall quantitative sound measurements

Table 1 below summarizes key parameters for the several waterfalls for which infrasonic data were available.

Table 1. Waterfall infrasound measurements, including waterfall heights, frequencies in Hz, infrasound pressure levels, volume fluxes, and waterfall types.

Waterfall	Height (m)	Frequency (Hz)	Infrasound Pressure Level (Pa) At various ranges	Volume Flux (m^3/s)	Reference/comments
Niagara Falls American	51	5-20	>100 Pa @500m	2407	Block type of waterfall
Niagara Falls Canadian	51	5-20			
Boulder Falls, Colorado	20	10-30	3Pa @ 30m	22	Cascade type of waterfall
San Rafael Falls, Ecuador	145 Tallest single drop 94 m	2-3	.05Pa @ 7.8Km	400	Johnson et al. (2006),Tiered type of waterfall with 2 drops

Sources and possible avian uses of infrasound

This section summarizes efforts to understand the uses birds make of infrasound (and higher frequency sound). There have been many investigators addressing this question. These studies range from establishing that atmospheric inversions can influence homing success, modification of song frequency and timing in the vicinity of surf for communication success, to using infrasound generation to increase communication range in dense vegetation. Berthold (1999) explored the sensory bases for bird's use of environmental factors in migration, including their exceptional sensitivity to atmospheric pressure and an ability to detect infrasound. He concluded that it is likely that differences in atmospheric pressure directly influence migratory behavior.

Observations

Numbers of observations address the possible role of infrasound in avian navigation. Some observations indicate that important sensing abilities (e.g. visual, magnetic orientation) are not sufficient to explain homing skill. Other observations are indirect, indicating that the state of the atmosphere is important. Still other observations show evidence that homing pigeons can detect infrasound, Observations are summarized below, including references.

- The ability of pigeons with degraded vision to home to the vicinity of their loft (Schmidt-Koenig and Schlichte 1972), (Beason and Wiltschko 2015)
- The existence of navigational ability during cloud cover and where pigeons are equipped with magnets, eliminating these options of solar and magnetic orientation (Griffin 1973)
- Pigeons have enhanced sensitivity to infrasound (Kreithen and Quinn 1978)
- Sonic boom disruption of pigeon races from the Concord SST (Hagrstrum 2000)
- For birds with degraded hearing homing abilities were reduced, while under some conditions improved - possibly reducing industrial noise (Schöps and Wiltschko 1994)
- Correlations exist between modeling of good and poor infrasound propagation conditions from loft areas and homing success or failure (Hagstrum 2000, 2007, 2013)
- Pigeons have difficulty navigating when above a cirrus cloud deck associated with a temperature inversion (Griffen 1973), (Wagner 1977), (Hagstrum 2000)
- Homing performance degrades in the winter months, indicating that the state of the atmosphere is an important factor (Gronau and Schmidt-Koenig 1970), (Hagstrum et al. 2016)
- Generation of infrasound by birds (Mack and Jones 2003), (Lieser et al. 2006), (Manley et al. 2011).

Hypotheses advanced to explain observational results and additional uses of infrasound and audible sound with cautionary remarks

There have been theories advanced to explain homing failures, possible sources and uses of infrasound**,** as well as audible sound. In addition, there are increasing concerns about the impacts of civilization sources of low frequency sound.

- Possible explanations of homing failures

A model (e.g. see Hagstrum 2000, 2007, 2013) to explain the frequent homing failures to the Cornell loft area involves the existence of a local, loft centric, sources of sound caused by coupling of microseism energy interacting with local terrain features into the atmosphere. Poor atmospheric propagation from the loft area to a release site will prevent patterned infrasound signals being used. Microseisms and their counterpart in the atmosphere, microbaroms, are ubiquitous features of the wintertime months and are caused by interacting ocean waves. These seismic and atmospheric waves typically occur in a limited frequency range near 0.2 Hz and do not provide a unique spectral signature, while occurring over an extended region. When the homing experiments by Cornell researchers occurred in the 1970's through early 1980's there were no accompanying infrasound measurements and thus we have no direct knowledge of the local infrasound levels or frequency content at the time of their releases. There are two significant waterfalls in the Cornell loft area (Ithaca Falls and Taughannock Falls), but to my knowledge infrasound levels and frequency content have not been documented.

- Are wind turbine sites auditory landmarks?

Mora et al. (2012) describe an experiment where pigeons were released from a wind turbine site. They considered the possibility that wind turbine noise acted as an auditory landmark. They felt it was unlikely that the pigeons relied solely on auditory clues in comparison with visual clues. Wind turbines should be considered as local sources of sound that should not mask long range infrasound navigation clues, even when night time conditions can enhance wind turbine sound propagation. Wind turbines produce unique spectral signatures with multiple harmonic peaks radiated. Measured values at a range of 1 km are typically less than 0.01 Pa (Keith et al. 2018).

- The use of audible sounds from the surface as navigational clues

Griffin (1976) found the sounds of frog breeding choruses are loud enough to be audible to migrating birds up to at least 1 km from their source, both vertically and horizontally, provided that no large obstacles intervene. During May in south-eastern New York State sound pressure levels (A weighting) at altitudes of 200 to 965 m and slant ranges from the frogs of 225 to 1020 m varied from 28 to 52 dB SP. On the other hand, D'Arms and Griffin (1972) concluded that the circumstantial evidence for non-visual orientation is sufficient to warrant consideration of alternate sources of directional information for birds navigating on overcast nights. They reviewed balloonist reports of sounds aloft from the surface of the earth. One example was from the observations of Wise (1873). At an altitude of 10,000 feet above Niagara Falls, Wise (1873) makes the following comment. "It is not a roaring, thundering, dashing, tumultuous sound, but a music of sweetest cadence. Like an Aeolian harp it sends up its vibrations". Jones and Bedard (2015) have modeled sound propagation in an atmospheric downdraft/updraft system showing that enhanced propagation can occur from the surface to higher altitudes**.**

- Cold fronts and high winds over mountains

Carey and Dawson (1999) considered whether birds could predict the approach of severe winter storms. The possibilities reviewed were barometric pressure changes, wind speed and direction changes, infrasound, clouds, and air ion changes. They postulated that infrasound generated by air flow over mountain ranges (Bedard, 1978) could provide clues concerning approaching weather or the existence of strong winds aloft. Also, they wondered if infrasound produced by changes of state during snow storms could provide predictive information. They concluded that there was not sufficient supporting data to unravel possible predictive capabilities. Infrasound related to high winds over mountains occurs frequently during the winter months. At frequencies < 0.1Hz it can represent a source region originating from extended lengths of mountain ranges. The identification of high wind events could have benefits for avian survival and also be useful for navigation. A north-south source 100's of kilometers in length could indicate the presence of mountainous areas and help define a navigation corridor.

- Potential of industrial sources masking infrasound valuable for navigation

For example, there are a large number of gas compressors operating in North America. Habib et al. (2007) and Ludlow et al. (2015) document the large numbers of gas compressor stations in the boreal forests of Alberta (13,555 as of 2008) and effects upon birds. Ortega (2012) recommended that resulting impacts on birds also be evaluated at low sound frequencies.

Possible importance of waterfall infrasound for homing pigeons

There is a history establishing that pigeons and other creatures are exceptionally sensitive to low frequency sound. Griffin (1969) first suggested the possibility that birds may use infrasound for navigation. Figure 3 indicates that the pigeon thresholds of detectability of low frequency sound can be 40 dB below humans.

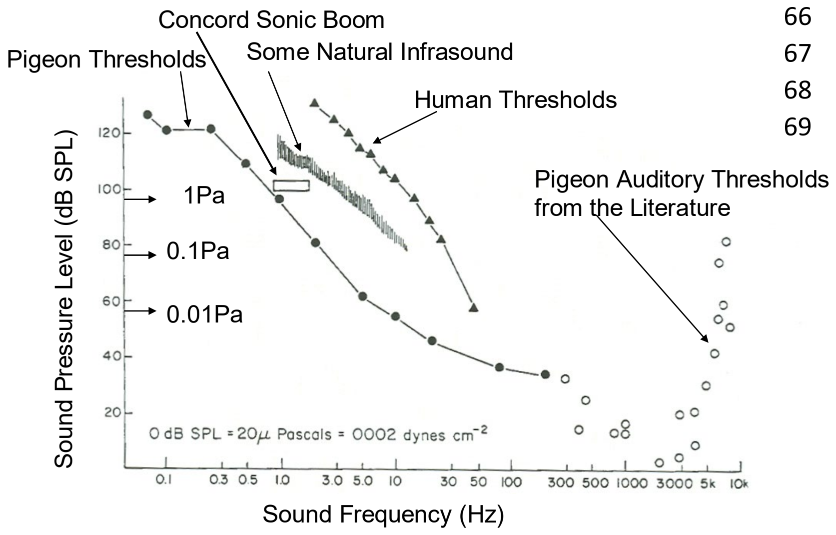


Fig.3 Sound pressure level as a function of frequency with key measurements annotated (after Kreithen and Quine 1979)

Kreithen and Quine (1979) postulated that this sensitivity may have survival value in terms of navigation. They further postulated that pigeons could detect Doppler shifted frequencies to determine sound source locations (Also Quine and Kreithen 1979, 1981). The horn from an approaching train has a higher frequency, followed by a lower frequency as it recedes. Similarly, birds will detect a higher or lower frequency depending upon whether they are approaching or leaving a stationary sound source. But how pigeons exploit their enhanced infrasonic hearing has remained to large extent a mystery. The previous section reviews efforts to understand how birds use infrasound. These results and the laboratory measurements of Kreithen and Quine (1979) and others indicate that homing pigeons can detect infrasound.

To explore the frequency discrimination capability of pigeons to determine the direction from which a sound is originating the following estimate was made. The flight speed necessary to exceed a discrimination threshold of 5% of the frequency is shown in Fig.4. As pointed out by Griffin (1969), the distances between ears is not great enough to use phase shifts at infrasonic frequencies, so that some other explanation is required. The flight speeds of many migrating birds exceed this threshold (e.g. Pennycuick 2001). Pigeon flight speeds measured in wind tunnels exceeded 20 m/s (Tobalske and Dial 1996) in agreement with pigeon race flight speeds and there are numerous reports of flight speeds greater than this (up to 50 m/s). Once a waterfall has been identified as the target source, a flight azimuth will either deviate to higher or lower frequencies with any deviations from the target direction. Birds will surely depend upon each other for guidance.

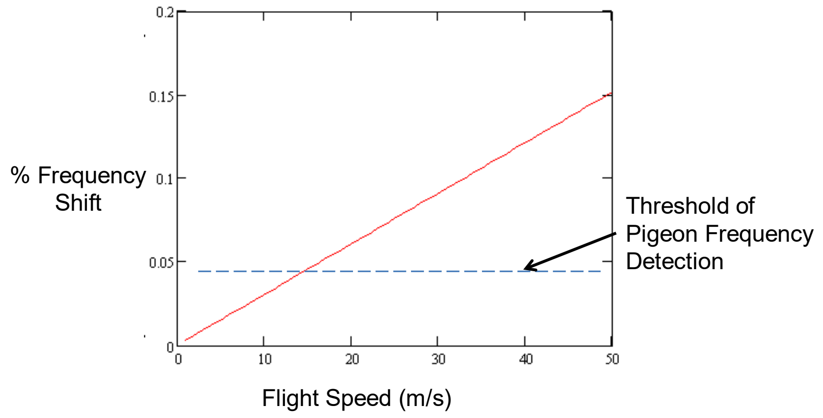


Fig.4 Percentage shift in frequency as a function of flight speed. The fact that major waterfalls can have distinct dominant frequencies could optimize navigation by Doppler shifts permitting triangulation, localizing multiple falls (Color online)

Continuous, concentrated, robust natural sources of low frequency are possible "beacons" that could be exploited by navigating birds in "VFR" (visual flight rule) conditions as well as "IFR" (instrument flight rule) conditions. This follows on a recent paper by Hagstrum (2013) that provides evidence that homing capabilities are dependent upon atmospheric wind and temperature structure.

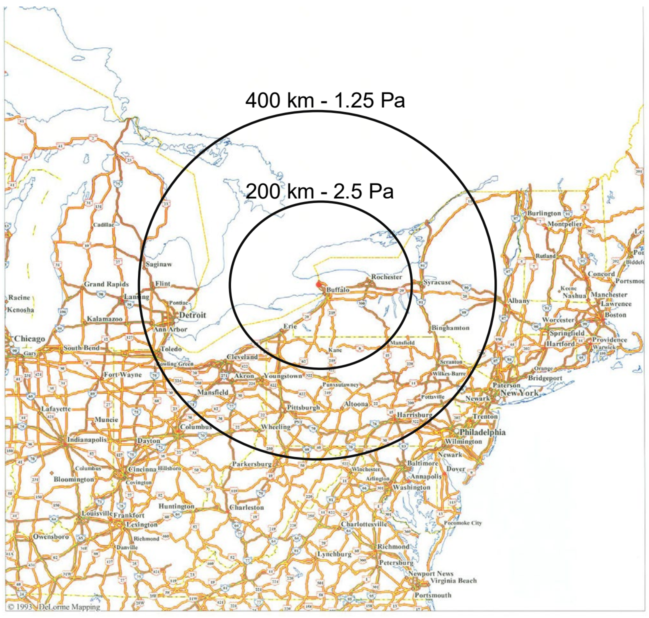


Fig.5 Range rings at 200 and 400 km centered on Niagara Falls with the pressure levels extrapolated assuming an inverse range decrease in amplitude with distance The levels corrected for the response of the microphone at 10 Hz are indicated in parenthesis. (Color online)

The pressure levels shown in Fig.5 are higher than the minimum threshold capability measured for pigeons. 1.25 Pa at 400 Km is almost 2 orders of magnitude larger than the hearing threshold of pigeons shown in Fig.3. Infrasound documented at ranges up to and in excess of 1000 km from the source is influenced by geometric spreading causing the pressure levels to decrease inversely as a function of range. Even smaller reductions can occur because of atmospheric wave guides (Bedard 2005). Attenuation because of absorption is of much less importance at infrasonic frequencies.

However, there is a "zone of silence" from about 20 to 200 kilometers for a standard atmosphere. The temperature decreasing with height causes sound to be refracted upward. This effect can be mitigated by nocturnal inversions which permit robust propagation out to 200 kilometers. Figure 6 after Jones et al. (2004) shows how a low-level inversion can prevent a zone of silence from forming at low altitudes. Conversely, such an inversion layer can prevent sounds from the surface from being detected at altitudes above the inversion layer. The pressure amplitudes of infrasound, although not significantly absorbed by the atmosphere, are affected by temperature structure and winds. The temperature (e.g. Fig.6) and wind structure (e.g. Bedard and Georges 2000) can either enhance or suppress detected sound pressure levels.

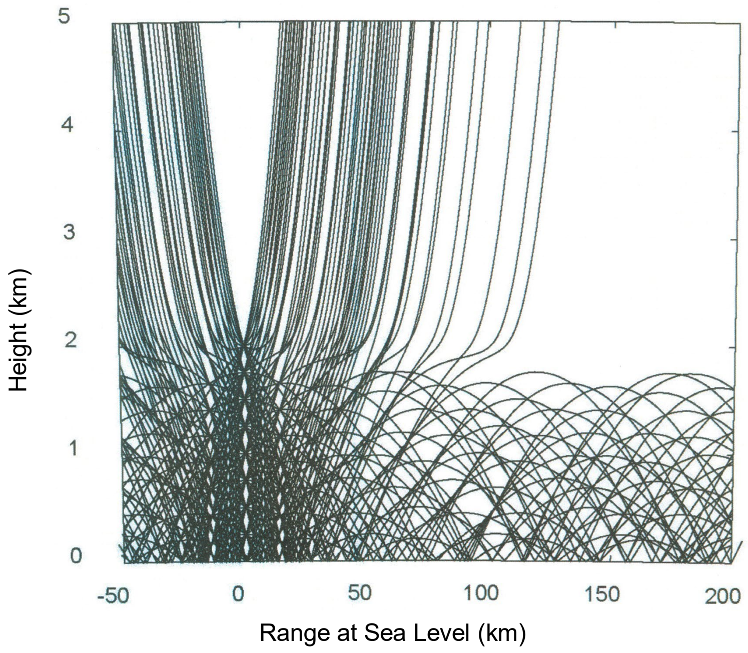


Fig.6 Ray trace simulation showing the propagation from a vertically extended source region as a function of range in the presence of an inversion at 2 kilometers in altitude with an isothermal region below (After Jones et al., 2004)

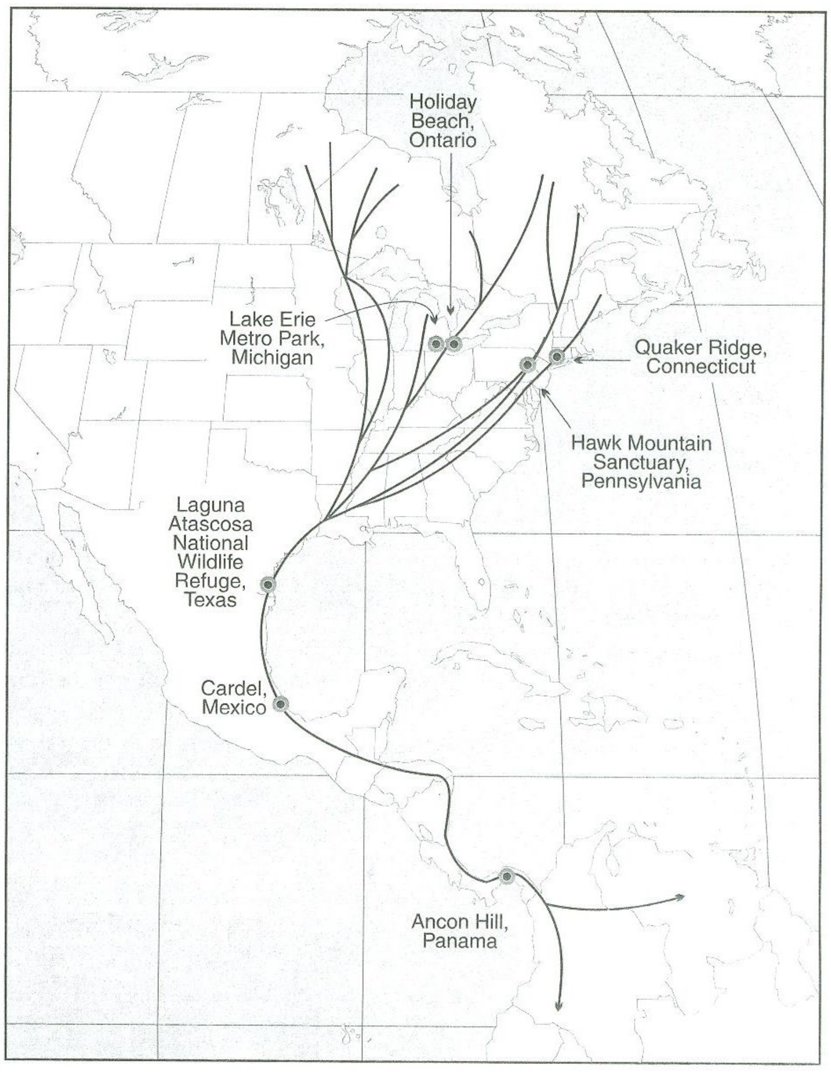


Fig.7 The southbound migration route of broad winged hawks in eastern North America (after Bildstein 1999 his figure 6.1)

Bildstein (1999) shows a map with the fall southbound migration routes in Eastern North America of the broad wing hawk. It shows a convergence from an area including the great lakes. This region is within the infrasound detectability range to Niagara Falls.

In addition to the work of Bildstein (1999) shown in Fig.7, La Sorta et al. (2016) show examples of flyways within the eastern portion of North America. They estimate the migration trajectories in the Western Hemisphere for 119 long-distance migration bird species. Guillaumet et al. (2011) show the migration tracks of 119 cormorants equipped with satellite tracking devices. Most of these nested in the area of the great lakes. Many of the tracks converge in a region east of Lake Ontario.

Comments concerning shore line flyways

The sub-routes in Fig.7 show some signs of convergence in the region of Niagara Falls. The route following the coastline will provide reference sound from wave breaking action at shore lines. Even the audio components of wave breaking could easily be detected at altitudes of several kilometers and provide a reference in the presence of low-level clouds or fog. There are a number of potential sources of sound involved with waves impacting a beach:

- Audible sounds involved with the wave creation of bubble plumes (e.g. Bolin, K. and M. Abom 2010) They found that wave heights below 1.5 meters have a peak frequency at 1 KHz and higher wave heights have spectra dominated by frequencies below 1 KHz. The sound pressure levels at a range of 250 meters were about 50 dB.
- Infrasound in the 1-7 Hz range generated by wave breaking processes (LePichon et al. 2004, Garces et al. 2003). Infrasonic surf noise can occur in the 1 to 7 Hz frequency range with the level proportional to wave height.
- Infrasound at the ocean wave frequency associated with waves abruptly stopping at a beach (Cook (1963 1969). Evidence for the existence of such waves is provided by Barruol et al. (2006).They found a relationship between infrasonic amplitude and swell height. Also, observed single frequency (near 0.1 Hz) as well as double frequency peaks (conventional microbaroms near 0.2 Hz).

Shorebird species use a window for sound transmission and reception (Douglas and Conner (1999)). A comparative study of the eastern and western willet showed that the eastern willet has songs of shorter duration and higher frequency than the western willet. This permits more information to be transferred during the periods between bursts of surf noise. They showed an example of a call of a migratory shore bird near 3 kHz occurring in the 3 second interval between bursts of surf noise (< 1kHz to 7 kHz). Katayama (2003) measured surf noise with most acoustic energy occurring between 250Hz and 4 kHz. Shorebirds are quite sensitive to surf noise, which they could also detect at typical migration altitudes. Infrasonic surf components could also be present (especially in the 1 to 5 Hz range) as indicated by Garces at al. (2003), and LePichon et al. (2004).

Concluding remarks

This section indicates observational efforts valuable for defining infrasonic and low frequency sound environments. Also, outlining possibilities for avian uses of infrasound for navigation and hazard avoidance.

Figure 7 in Appendix 1 summarizes significant waterfalls in the United States producing significant earth vibrations and by inference infrasound. These are an important set of waterfalls that will be worth documenting in terms of the sound pressure levels and frequencies measured as a function of the waterfall parameters (waterfall type, height, and volume flux). Observations to date suggest that the waterfall type may be a critical factor in determining acoustic efficiencies, with the cascading and tiered waterfalls being less efficient than the block or plunging types. Although the volume flux is an important factor, the efficiencies of the sound generation mechanisms involved may dominate the sound pressure levels emitted.

In addition to making observations of environmentally important waterfall related infrasound, there should also be parallel observations of low frequency sound from industrial processes detectable at long ranges. Since there is no Federal Communications Commission equivalent monitoring acoustic energy or assigning bands at low acoustic frequencies, there could be a potential that future, episodic industrial or other processes could produce sound masking important geophysical sources. The addition of a dam at a critical river point involving a natural waterfall could possibly have impacts on avian navigation guidance.

Conversely, robust, continuous civilization sound sources could possibly be exploited for avian navigation or perhaps by other creatures as well. A possible example of this is the infrasound radiated by a bridge as vehicles pass over (Donn et al. 1974). Could birds be "encouraged" to not populate aviation flight routes? There is an important need to define the characteristics and roles of acoustic sources potentially used in avian navigation.

Possibilities for hazard avoidance

Streby et al. (2015) presented the first documentation of obligate long-distance migrant birds undertaking a facultative migration, wherein breeding golden-winged warblers (*Vermivora chrysoptera*) carrying light-level geolocators performed a >1,500 km 5-day circumvention of a severe tornadic storm. The birds evacuated their breeding territories >24 hr before the arrival of the storm and atmospheric hazards associated with it. The probable cue, they postulated was infrasound radiating >1,000 km from tornadic storms perceived by birds and influencing bird behavior and movements.

Wiedenfeld and Wiedenfeld (1995) describe a tornadic storm that killed an estimated 40,000 birds of 45 species in Grand Island Louisiana in April 1993. A key factor was that the storm arrived at the time when large numbers of birds were arriving after migrating all night across the Gulf. McClure (1945) describes an impact of a tornado that hit Portsmouth, Iowa at 3 AM on 9 July 1940 with about 1000 birds killed. From the damage description (no one was killed and homes were damaged but not destroyed) the tornado was apparently short-lived and did not affect nearby towns.

The observations of Streby et al. (2015) suggest that birds need to have recovered from migration and encounter longer-lived tornadic systems to make optimum use of infrasound weather warning clues. Bedard et al. (2004) have detected infrasound at long range from tornadic storms. Some of these storms radiated infrasound continuously for long periods, while cyclically producing tornadoes. It may be possible to use archived infrasound measurements for comparisons with homing or migration anomalies.

Measurements made using co-located seismic and infrasound sensors 38 meters from the channel in the Grand Canyon identified three distinct seismic sources. An infrasonic sensor measured a 6.25 Hz peak corresponding to one of the seismic peaks (Schmandt et al (2013). The peak discharge for the controlled flood was 1300 m^3/s. They interpret the 6.25 Hz peak as related to fluid/air interactions involving breaking waves. The infrasound increased to 18dB above the background level. The sound level estimated at 500 meters based upon the measurements at 38 meters was 0.6 microbars, less by a factor of 10 than the levels for waterfalls summarized in Figure 11 of this paper. Nevertheless, birds could detect nearby rivers or follow the course using radiated infrasound.

In summary, there is a range of potential avian uses of infrasound for navigation as well as hazard awareness and avoidance.

These include:

- Triangulation on fixed sound sources for navigation (Major waterfalls are a continuous source of high-level infrasound.)
- Following coast lines in the presence of obscuring cloud cover
- Detecting and following rapidly flowing streams and rivers (Schmandt et al. 2013)
- Tornado avoidance (Streby et al. 2015), (Bedard et al. 2004)
- Cyclone avoidance behavior by foraging seabirds (Weimerskirch et al. 2019), (Thielbot et al. 2020)
- Turbulence and high wind avoidance (Bedard 1978), (Schermuly and Klinke, 1990)
- Warnings of regional fires (Jones et al. 2004), (Bedard and Nishiyama 2002)

Atmospheric turbulence has significant effects on bird flight (Nisbet, 1955). The burden produced when maximum flight speed falls below the level of turbulent velocity fluctuations means birds will not be able to fly safely in winds. "In high winds birds are often reluctant to fly at all". Measurements of infrasound from turbulence, regions of high wind, and fires produce sound pressure levels greater than the pigeon thresholds shown in Fig.3. It will remain a challenge to understand the extent to which these potential uses of infrasound are actually applied in nature.

Acknowledgements

The measurements in the vicinity of Niagara Falls presented here were enabled by Dr. and Mrs. Peter F. Regan the 3rd. The application of this work to avian migration was inspired by a series of papers by J. T. Hagstrum.

Appendix 1: A summary of past observations of waterfalls, weirs, and dams

This summary provides information on sounds from falling water, distinguishing between systems of large horizontal extent and those for which the heights are greater than the widths. This summary provided valuable insights helping to interpret measurements made in the vicinity of Niagara Falls. Whereas a horizontal organ pipe model explains sounds radiated by dams and weirs, this model does not apply to major waterfalls.

A compilation of the works of John Muir by Diadem Books (1992) provides an important resource of observations from this early conservationist, who died in 1914. He wrote vividly of the Yosemite waterfall in California. "At the top of the fall they seem to burst forth in irregular spurts from some grand, throbbing mountain heart". "This noble fall has far the richest, as well as the most powerful voice of all the falls of the valley". "The low bass, booming, reverberating tones heard, under favorable conditions, five to six miles away". His complete descriptions suggest the possibility of a variety of sound source mechanisms.

Heim (1874) documented tones associated with a series of waterfalls, as noted by Charlie (1998). Trained musicians were able to identify tonal acoustic energy and made estimates of the musical notes corresponding to the tones. Perforce, the tones detected were in the audible and could have been harmonics of lower frequency energy. They noted the following observations:

- There was a striking similarity of tonal structure for a variety of waterfalls
- The more the fall of the water mass the stronger the tone
- The lower frequencies were heard behind various barriers and at longer ranges than the higher frequency tones.
- Tones were purist and clearest when the free water crashes into a pool below
- No tones were heard when there was only rushing stream of water
- They documented the tones detected for 14 waterfalls. Some waterfalls had lower frequency components (e.g. 2-87 Hz), while others showed mostly higher frequencies (>3-174 Hz).

Unfortunately there is not enough information to relate the details of these waterfalls (e.g. height, volume flow) to the frequencies documented. Nonetheless, the work documented was a pioneering effort in the area of waterfall acoustics.

Many persons with high musical dictation, score very well on tests for absolute pitch (Dooley and Deutsch 2010 their Figure 2). Bachem (1955) observed professional violinists obtaining accuracies to 1/16 of a semi-tone. Leite et al. (2016) found a high correlation between advanced musical skill and absolute pitch for Brazilian musicians.

The observations of waterfall sound frequencies (Heim 1874) represent the consensus of a number of trained musicians. The studies of individuals with absolute pitch indicate that the waterfall musician observations should be considered accurate, in spite of the lack of electronic spectrum analyses in the 1800s.

A summary of ground vibrations from waterfalls and their possible interpretation

Reinhart (1969a) used geophones to measure earth vibrations from a number of waterfalls. Figure 8 is from his paper showing that the dominant frequency measured is inversely proportional to the height of the waterfall.

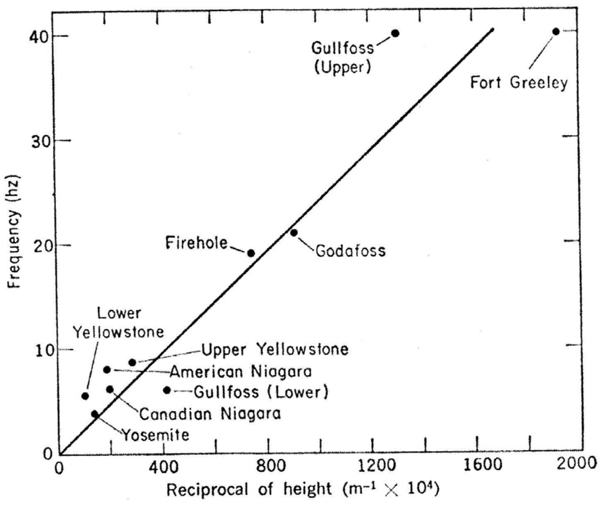


Fig.8 Predominant vibrational frequency as a function of the reciprocal of waterfall height (after Reinhart, 1969a)

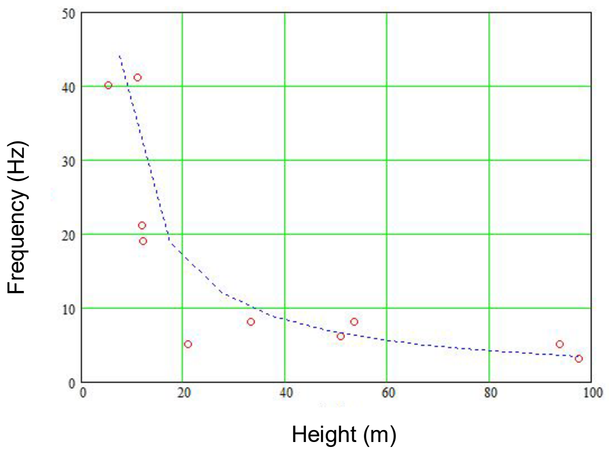


Fig.9 Plot of the dominant frequency data of Reinhart (1969a) as a function of waterfall height The line superimposed on the figure was determined assuming the frequency was equal to the speed of sound in air divided by the waterfall height (Color online)

The fairly good agreement shown in Fig. 9 suggests that the time it takes a sound wave to propagate from the waterfall base to the top controls the frequency, indicating that an acoustical feedback mechanism is present. An energetic sound wave emitted from the impact of water at the base could propagate in air to the top and modulate the water discharge. This also implies that atmospheric sound measured in the vicinity of waterfalls will tend to follow the earth vibrations measured by Reinhart.

Weir/Dam acoustics

A weir is an overflow type of dam commonly used to raise the level of a river or stream. A nappe is a sheet of water flowing over a weir. Weirs have a history of being sources of annoying vibrations and evidence of this is often visible in the nappes. Loomis (1843) summarized observations of 6 sets of dams, all associated with the generation of vibrations and annoying effects such as vibrating windows and doors. The dams involved similar effects:

- The vibrations occurred for a restricted range of water heights above the dam
- Gentle breezes can enhance the vibrations, while strong winds destroy the vibrations
- Obstacles at the top of the dam impede the effect
- The effect is great when the water falls in an unbroken sheet
- Window vibrations have been induced at ranges of 2.5 miles from a dam.

There were 3 cases where estimates were made of the vibration frequency. A Cuyahoga Falls, Ohio dam was 27.4 feet long, producing frequencies between 12 and 15 Hz. An East Windsor, Conn dam was a 100 foot long, straight dam with an estimated frequency of 5 Hz. A dam at Springfield, MA was a 450 foot, straight dam with an estimated frequency of 1 Hz. These dams produced frequencies consistent with an organ pipe mechanism, open at both ends.

Loomis suggested alternate methods for estimating the frequencies observed. For frequencies below about 4-5 Hz he recommended counting the number of beats over a fixed time. For higher frequencies he suggested creating a reference with a calculable frequency (e.g. Use a string of variable length with a weight and match observed frequency vibrations). documented

Sound and earth vibration from a Ringwood, New Jersey dam was documented by Blade and Blade (1969). The dam was about 20 meters long, 5 meters high and produced a strong frequency at flood time at about 10 Hz, in disagreement with the observations of Rinehart (1969a). Rinehart (1969b) suggested that, in this case, the frequency may be controlled by the dam length rather than the height from which the water falls.

Some weirs and dams can produce a horizontal, hollow column of air that, as will be shown, functions as a horizontal organ pipe. In this set of water features, the heights of water column fall distances are less than the lengths (widths). For some dams the flow release can be a spillway, underwater or above water jets with no resonant column involved. The purpose of studying infrasound observations from weirs and dams is to provide a context and help understand sound generation by natural waterfalls.

Table 2 summarizes well documented measurements from dams and weirs. These data provide valuable insight into a hydrodynamic process producing significant infrasound. These data are plotted in Fig.10, indicating that a model of an organ pipe open at both ends fits the observations.

Table 2. Observations from the literature of weir infrasound, including weir dimensions.

Weir	Dimensions	Frequency (Hz)	Observed Levels	Volume Flux	Reference/Comments
River Reno	60m long 2m high,	8	Vibrations sensed at a range of 4 to 5 Km		Bragadin et al. (1988) Frequency decreases as discharge increases
Japanese dam	~100 m long	1,5, 5-10	.063 Pa at 300 m	30 to 350 m^3/s	Tokita et al. (1977)
Cuyanoga Falls, Ohio	27.4m long 4 m high	12-15			Loomis (1843)
East Windsor, Conn	30.48m long 1.5m high	5			Loomis (1843)
Springfield, Mass	137.1m long 3.65m high	1	Vibrations sensed at a distance of 4.02 kilometers		Loomis (1843)
Ringwood Creek dam, New Jersey	20m long 5m high,	~10			Blade and Blade (1969)
Holyoke, MA dam	307m long	~1-40		Frequency proportional to water depth	Snell (1859)

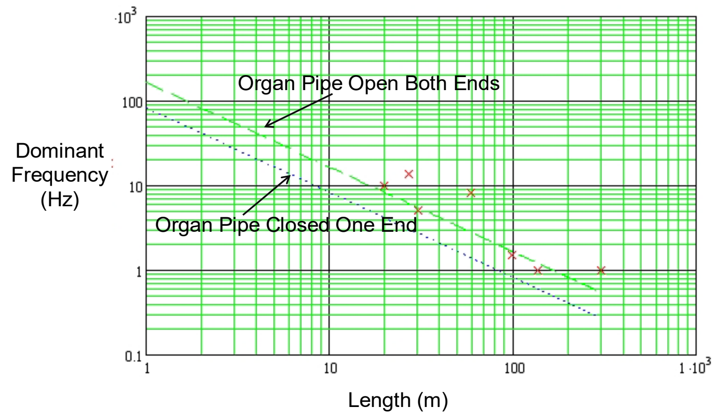


Fig.10 Dominant observed frequencies for weirs as a function of weir length These data are compared with calculations of the fundamental frequencies of organ pipes as a function of length (Color online)

However, in addition to the evidence for a horizontal organ pipe mechanism shown in Fig.10, there could be more than one sound generation process possible. For example, Casperson (1993, 1993, 1994) developed a model involving small displacements of the water sheet being amplified by a Helmholtz mechanism as the sheet moves downward. The large amplitude motions at the base in turn compress the air trapped behind the nappe and affect the water surface at the top. The combination of amplification and feedback can lead to the formation of sustained oscillations. Liszka (1974) identified hydroelectric power plants as a source of infrasound theorizing that the sound was radiated by oscillating masses of water.

Appendix 2: Relationships between waterfall hydrodynamic and acoustic powers

The goal of this section is to relate the waterfall hydrodynamics to the sounds emitted. Even if the absolute magnitudes of relationships are not obtained, it will be valuable to identify important relationships.

The pressure, *dP*, produced by the impact of the flux of water is:

$$dP = \frac{1}{2}\rho_w U^2 \tag{1}$$

where *U* is the flow speed and, ρ_w, is the water density.

The work, W, performed in moving a distance *dx* is:

Where V is the volume and A is the area

$$W = Fdx = dpAdx = \frac{1}{2}\rho_w U^2 dxA = \frac{1}{2}\rho_w U^2 V \tag{2}$$

The hydrodynamic power is:

$$P_h = W/t = dpAdx/t = \frac{1}{2}\rho_w U^2 \frac{dx}{t} A = \frac{1}{2}\rho_w U^3 A = \frac{1}{2}\rho_w U^2 Q \tag{3}$$

where *Q* is the volume flux.

The acoustic power Pac is:

$$P_{ac} = 4\pi R^2 dp^2 / \rho_a c \tag{4}$$

Where *R* is the distance from the source, *dp* is the sound pressure level, ρ_a is the density of air, and c is the speed of sound in air.

The efficiency of the production of acoustic power from hydrodynamic power, ε , is the ratio of the expressions

$$\varepsilon = \frac{P_{ca}}{P_h} = \frac{8\pi R^2 dp^2}{\rho_w \rho_a c U^2 Q} \tag{5}$$

Now an expression may be found for the sound pressure level *dp*

$$dp = \left[\frac{\varepsilon \rho_w \rho_a c w h}{8\pi}\right]^{1/2} \frac{U^{3/2}}{R} = \left[\frac{\varepsilon \rho_w \rho_a c Q}{8\pi}\right]^{1/2} \frac{U}{R}, \tag{6}$$

where *w* and *h* are the width and the depth of the water respectively, *ε* is the ratio of acoustic to hydrodynamic power,

ρ_a and ρ_w are the air and water densities, c is the speed of sound in air, U is the stream flow speed, R is the source-receiver distance, and Q is the volume flux. This relationship provides guidance for organizing data sets that include information on waterfall sound pressure level and flow volume flux as presented in Fig.11.

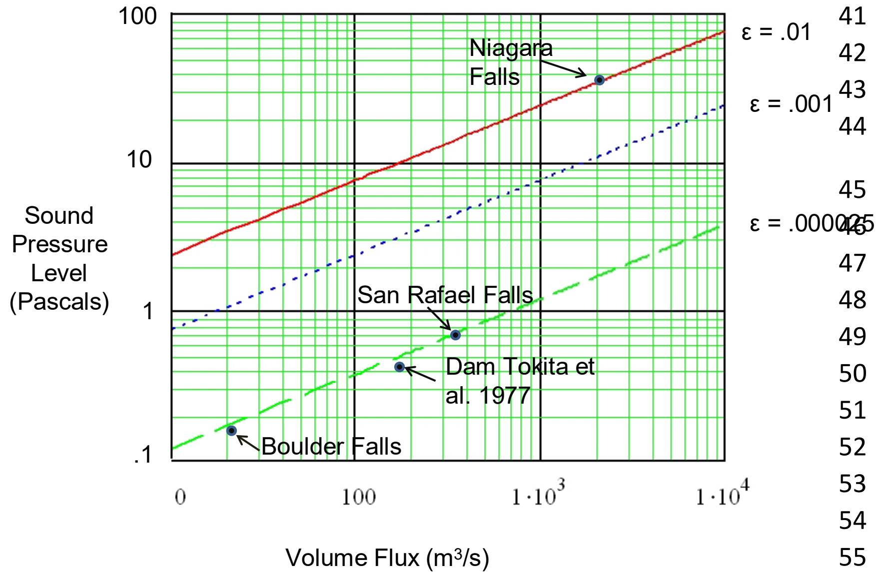


Fig.11 Plot of the sound pressure level as a function of volume flux for efficiencies of 0.01, .001, and .000025 All data were adjusted to a range of 500 meters (Color online)

Figure 11 indicates that there are great differences in the efficiencies of waterfall sound generation processes with ε = .01 for Niagara Falls compared with ε= .000025 for Boulder Falls, San Rafael Falls (Johnson et al. 2006), and a spill way 0dam. Niagara Falls is more efficient by a factor of 400 or almost 3 orders of magnitude, suggesting great differences in the sound generation processes. For example, Boulder Falls is a cascade type of waterfall with no clear resonances involved and an ensemble of incoherent sound sources including flow interactions with obstacles as well as eddy structures and bubble plumes, all at relatively small scales. The San Rafael Falls is a tiered type of falls. A video of this waterfall shows the lowest level to be highly turbulent before striking the pool of water at the base. The dam details described by (Tokita et al. 1977) indicated two sound generation processes. One of these was highly turbulent like a cascade falls. It is not surprising that these latter sources are relativity inefficient. More detail from the research of Tokita et al. (1977) is shown in Fig.12.

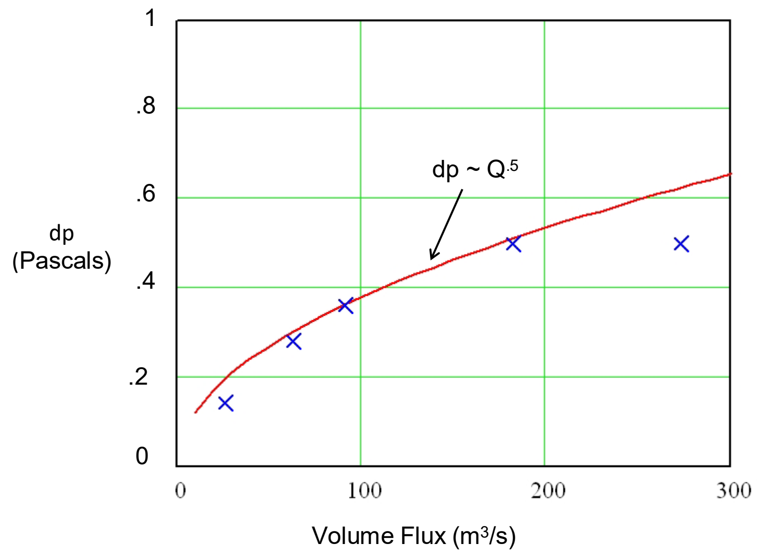


Fig.12 Data points obtained at a distance of 500 meters from a dam (Tokita et al. 1977) and levels predicted for an efficiency of 0.000025 (Color online)

A best fit to their observations (Figure 12) is dp=0.025 $Q^{.56}$. These data of Tokita et al. (1977) indicate good agreement with the predicted $Q^{.5}$ relationship. However, their measurements also indicated that at higher discharge rates (above 200 meters cubed per second), the sound levels flattened off and slightly decreased. This suggests a reduced acoustic efficiency, possibly as a result of an increase in flow turbulence.

Major waterfalls with high volume rates may enhance the efficiencies of sound generation processes. Measuring acoustic energy near Niagara Falls involves a complex sound generation environment with both the American and Canadian Falls nearby. There has been historical documentation of unusual physical effects involving Niagara Falls. For example, Barlow (1877) describes jets of water which were projected vertically from the base of the falls. These frequently rose from 10 to 30 feet above the top of the falls. These jets were apparently related to observations of doors and windows being vibrated one quarter to one half of a mile away.

Doi and Kaku (2004) exposed windows to a variety of infrasonic waveforms. They found that the window response was a complex function of the details of the infrasonic signals used. For hinged windows exposed to a triangle wave the threshold of rattling was between -18 Pa and 92 Pa.

Naka et al. (2008) experimentally studied the response of windows to sonic booms. They found that typical sonic boom N-waves with durations of 100 and 200 milliseconds and pressure amplitudes of 1 PSF (47.9 Pa) and 2 PSF (95.7 Pa) can induce significant window vibrations. These pressure levels are in the range of the >100Pa measured at a range of about .5 km from Niagara Falls.

In comparison to waterfalls having orders of magnitude smaller volume flow rates and complex descents to the base of the falls (e.g. involving a more gently sloping fall interacting strongly with terrain), it is probable that greatly differing acoustic efficiencies and sound generation processes may occur. Ostrovsky and Bedard (2002) estimated the sound pressure levels produced by large objects falling into water and estimated the sound production efficiencies involved. This work was focused on estimating the possibility of infrasonic detection of ice calving. They estimated a wide range of efficiencies depending upon the source type and object size. Using an efficiency of 8×10^{-4} corresponding to a monopole source they estimated a sound pressure level of 5 Pa at a range of 1 km from a 100 meter radius object. Richardson et al. (2010) documented an infrasonic signal of 2 Pa associated with ice calving at a range of about 3 km. The details of the sound production process for this case were not observed.

Bubble plumes as sound sources

Kolaini et al. (1993, 1994) described a series of experiments where various heights of water in cylindrical containers were released to impact liquid surfaces. Hahn et al. (2003) and Carey et al. (1993) also studied the sounds produced by falling jets of water. Kolaini et al. found a correlation between the total low frequency acoustic energy radiated under water from the resulting bubble plume and the potential energy of the water jets. The plumes generated were bubble clouds that oscillated collectively. They found the radiation efficiency (a ratio of total radiated acoustic energy to the initial potential energy) was within the range of 10^{-6} to 10^{-7}. They noted a sharp increase in efficiency at higher potential energies, possibly resulting from an increased production of bubbles. In addition, the laboratory measurements of Kolaini et al. (1994) examined the acoustic energy as a function of potential energy of the impacting fluid elements (Their Fig.9). They observed a discrete change in acoustic efficiency as the potential energy increased above a threshold point, the acoustic energy increased an order of magnitude for an increase of 2 in potential energy. Prior to this threshold being crossed there was a linear relationship and quite low efficiencies.

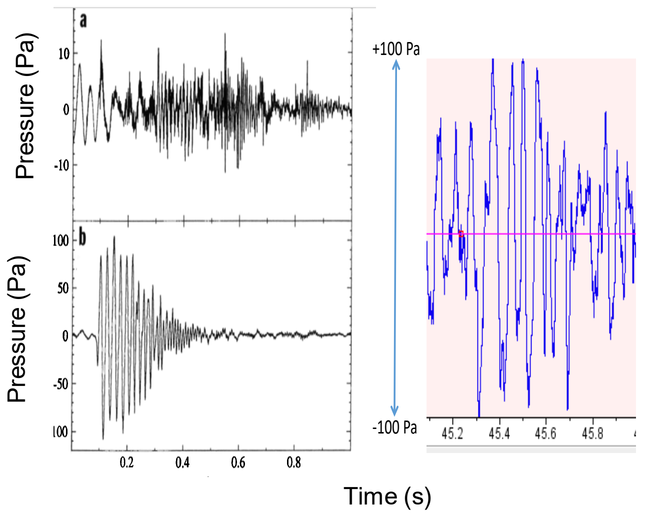
Kolaini et al. (1993, 1994) also studied the dominant frequencies produced by the resulting bubble plumes. They obtained an expression for the frequency as a function of plume radius, which agreed well with experimental data at low frequencies. The frequency depended on the plume radius *a*, ambient pressure *P0*, the water density ρ_w, and the void fraction β. The expression they found was

$$F = \frac{\left(\frac{3P0}{\rho_w \beta}\right)^{.5}}{2\pi a}. \tag{6}$$

This expression predicts frequencies between 10 and 20 Hz corresponding to bubble plume radii between 40 and 20 centimeters. This estimate was made for a void fraction, β of about 50%. A model used by Chanson (2016) to explain the dominant acoustic frequency range generated by a tidal bore (57 to 131 Hz) is the collective oscillations of bubble clouds.

Unlike organ pipes with solid walls, a waterfall can produce a vertical cavity with one side the rock face of the falls and the other the surface of the falling water. A key question is whether this closed tube resonance can modulate the falling water sheet and produce pulses of fluid producing sound from resonating bubble clouds when impacting the base of the falls and/or act to increase the sound pressure level through resonance.

The left panel of Fig.13 shows times series of pressure from the laboratory measurements of Kolanai et al. (1994) their Fig.7. The upper plot (a) shows the pressure levels for a fairly continuous stream of 3.66 liters impacting the water. The lower plot (b) is for an impulsive impact of a volume of 3.66 liters of water. Note that the impulsive impact produced about an order of magnitude greater sound pressure level than the more continuous stream. The form of the time series was in this case a number of sinusoidal waves at a constant frequency followed by a decay to the background level. Other runs could best be described as damped sine waves. The right hand panel of Fig.13 shows a view of a segment of the Niagara Falls sound measurements shown in Fig.1. This is for a 1 second interval focused on one of a series of impulses that occurred throughout the complete interval shown in Fig.1. The expanded time series shows a series of about 4 waves at about 10 Hz before being lost in the background of other sounds related to the falls. This time series expansion is typical of other impulses examined for the complete 1 minute time period (Figure 1) as well as other intervals recorded.



After Kolanai et al.(1994) their Figure 7 showing sound from release of 3.66 liters of water (a) as a continuous flow (b) as an impulsive release

Expansion of a segment of the 60 second time series of sound waves measured in the vicinity of Niagara Falls (Figure 1) from 45 to 46 seconds

Fig.13 Comparison of the sound generated by the laboratory experiments of Kolanai et al. (1994) and an expanded view of one of the impulses of infrasound measured from Niagara Falls shown in Fig.1 (color online)

Niagara Falls height ranges from 21 to 34 meters (70 to 110 feet) from the top of the falls to the top of the rock pile at the base. Photographs of the base of the falls show large rocks inter-dispersed with pools of water. For these waterfall conditions a vertically oriented organ pipe model with both ends closed is considered to estimate the dominant frequencies radiated. The fundamental frequency for these conditions ranges from 8.1 to 5 Hz. The 1st harmonic ranges from 16.2 to 10 Hz. The 1st harmonic pressure field is depicted in the schematic view shown in Fig.14. As shown in the schematic (Fig.14) there will be antinodes created at the top and bottom of the column with strong pressure gradients along the height.

Estimating the sound pressure level dp at the base of the impacting sheet of water to be 1000 Pa, we can calculate the particle velocities induced by the sound wave. For a particle velocity v, and air density ρ, and sound speed in air c, v = dp/ρc or 2.5 m/sec. Such particle velocities can produce significant effects on a falling water sheet. This pressure level is equivalent to a head of water of about 10 centimeters.

The vertical fall speed of the water at Niagara Falls (estimated at 9 m/s) will mean that a fluid parcel will take about 5 seconds to fall from the top to the base of the falls. The time scale is much larger than the ~ 0.1 second involved with the observed sound frequency time scale.

A conceptual view of a process causing waterfall infrasound is shown in the Fig.14.

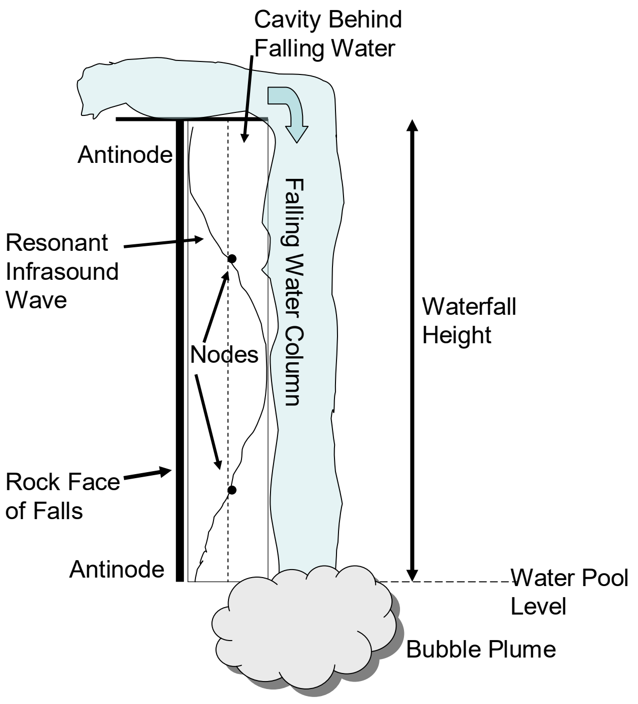


Fig.14 A conceptual view of a process causing waterfall infrasound. The water striking the surface creates a bubble plume generating an intense sound wave The sound wave propagates to the top of the waterfall modulating the water flow release A pressure change of 1000 Pa is equivalent to several inches of water column height (color online)

In summary, this model involves the impact of a surge of water on the pool at the base of a water fall creating a bubble plume and the resulting sound wave propagates to the crest of the fall, behind the falling curtain of water. The column of air trapped is resonant for select frequencies, acting as a vertical organ pipe closed at both ends. The powerful sound waves can disturb the curtain of water causing surges of flow, which in turn can create impulses of sound when the disturbances reach the pool at the base of the fall. Figure 1 shows periodic bursts of infrasound observed at Niagara Falls. It will be valuable to model this process in the laboratory. For example, Schwartz

(1965) shows a photograph of a laboratory nappe oscillation which may result from a process similar to that described above. Figure 1 after Schwartz (1965) is reproduced here as Fig.15.

Fig.15 Oscillating nappe in a 6-foot wide laboratory flume with a transparent side panel There are 1-inch squares on the side wall (after Schwartz 1965 his Fig.1)

Because of the effects of turbulent flows and complex geometries, there will probably be a range of sound frequencies generated.

There is also the possibility of using waterfall infrasound sources as a resource for documenting sound propagation under differing environmental conditions, and comparing observations with ray trace and other model predictions.

Waterfalls also provide opportunities for direct study of hydroacoustic processes or to test the process of waterfall sound generation outlined in this paper. It will be valuable to make simultaneous measurements at the base and top of a waterfall and compare signal phase and spectra. For a smaller waterfall it may be possible to modify the flow impact details to change the dynamics of underwater bubble plumes.

This analytical appendix should help with the interpretation of results presented in earlier sections.

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