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► To cite this version:

L. Bjørnø. Underwater rain noise : sources, spectra and interpretations. Journal de Physique IV Proceedings, 1994, 04 (C5), pp.C5-1023-C5-1030. 10.1051/jp4:19945225 . jpa-00252911

HAL Id: jpa-00252911

<https://hal.science/jpa-00252911>

Submitted on 1 Jan 1994

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Underwater rain noise: sources, spectra and interpretations

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Abstract: An overview over the most important results obtained over the past of noise produced in water by impacts of single droplets, artificial rain and real rain is presented. Two distinct sources form the major contributors to rainfall produced noise in the sea. The raindrop impact and the pulsations of entrained air bubbles. The impact sound is produced by raindrops of all sizes, while the bubble pulsations are connected with regular entrainment of small gas bubbles, leading to the characteristic peak spectral level between 14 and 16 kHz, and by irregular entrainment of larger gas bubbles produced by impact of large raindrops. The noise spectra are discussed and interpretations of their relations to the raindrop size and impact mechanisms are given. Relations between noise spectra and rainfall rates are discussed and some still unsolved problems are pointed out, particularly related to estimation of light and moderate rainfalls using underwater sound measurements.

Introduction

When rain falls onto a large body of water it produces a dominating underwater sound covering a broad range of audio frequencies. This underwater sound produced by raindrops and rainfalls have intrigued scientists for more than a century. Worthington [1] took primitive flash photographs of drop impacts in the 1890's, while Mallock [2] and Bragg [3] suggested several theories in an attempt to describe the sound produced. Their theories were mainly based on the resonance of an open-ended cavity produced by the impact and are now known to be incorrect. Following Bragg's suggestions, Minnaert [4] studied the sounds produced by running water, and he discovered that these sounds are primarily due to oscillations of bubbles entrained into the flow. He also derived a formula for the resonance frequency of a gas bubble in a liquid, which is still regarded as a good approximation.

The first thorough study of sounds produced by drop impacts was performed by Franz

[5]. He used high-speed movie photography to show water behaved during the impact process. At the same time, he recorded the sound generated in the water, and he was able to show which features of the sound trace were associated with each phase of the impact. He discovered, that the main sources of underwater sound from a splash were (1) the impact and passage of the body (the water droplet) through the free water surface leading to the establishment of a flow, (2) the resonance vibration of the body, if it has rigidity, and (3) volume pulsations of air bubbles in water. The initial impact sound was a sharp pulse, while the bubble sounds were decaying sinusoids. Franz, moreover, observed, that bubbles were not produced by every drop and that their occurrence was more or less random.

Franz found that the sound pressure radiated by the initial entry of the droplet increases systematically with increases in droplet size and impact velocity, and that the half-octave spectra of the impact sound in water show a broad maximum in the frequency range between 1 and 10 kHz. He also showed that drop impacts seem to behave as dipole sources with vertical axis, as one should expect for a simple source near a free water surface.

In addition to his work on single water drops, Franz studied the sound produced by spray of water forming a sort of artificial rain. He attempted to predict the acoustic power spectrum of rain from his results, suggesting very broad, flat spectra, which peak at 3 kHz. His predictions do agree with some more recent field measurements related to heavy rainfalls, Nystuen et al [6].

Underwater noise produced by real rain.

One of the first attempts to describe the underwater noise spectra produced by real rainfalls was published by Heindsmann et al [7], who found that, during the heaviest rainfall, the sound pressure spectrum level was approximately constant at 77 dB re. 1 μ Pa from below 1 kHz to above 10 kHz.

A study of the underwater noise produced by precipitation on the surface of a small, shallow lake was published by Bom [8] for the frequency band 0.3 - 9.6 kHz. He found that the noise level in dB versus the logarithm of the rain rate in the interval 1 - 25 mm/h could be represented by a straight line. A comparison with Franz's predictions shows a significant difference in absolute level, in particular at low frequencies. However, Bom's underwater noise spectrum levels seem to peak at 3 - 4 kHz for several rain rates, as Franz predicted.

Scrimger [9] recorded the power spectrum of natural rain falling onto a lake. He observed a feature that had gone unnoticed by previous authors, namely a spectral peak at about 13.5 kHz, with a steep slope at the low-frequency side and a more gentle slope at the high-frequency side. Nystuen [10, 11] reported similar results and developed a theory in order to explain the observed phenomena. He used a numerical

model for the drop splash flow field that allows a study of multiple free surfaces to be performed and that permits variation in surface tension, viscosity, and droplet shape to be introduced. This model enabled him to predict the shape of the initial short, high-amplitude acoustic pulse and the non-acoustic dynamic pressure that is associated with the flow field. He also discussed Franz's description of the initial impact pulse, which disagreed with his own. Nystuen explained the 14- 16-kHz peak that he observed in the spectrum of rainfall in terms of the initial impact sound alone, ignoring bubbles on the basis, that not every drop produces them.

Scrimger et al [12] made an extensive study of the spectral characteristics of underwater noise generated by rain falling onto the surface of a freshwater lake. Their measurements were made using a bottom-mounted hydrophone at a depth of 35 m. For wind speeds less than 1.2 m/s, that authors found the rain noise spectra to have a sharp peak at 13.5 kHz with a 9-dB/oct falloff on the high-frequency side and a 60-dB/oct falloff on the low-frequency side. These results confirmed the presence of the 14- to 16-kHz peak observed by Nystuen. These spectra also showed many features in agreement with Bom's data between 2 and 10 kHz.

Shonting et al [13] made an observation at sea, where they found that the level at 15 kHz was a good indicator of the presence of rain, but they had difficulty in explaining, why the sound level associated with the lowest rain rate was higher than the sound level associated with the highest rain rate.

The theoretical conflict between the two points of view (1) that the drop impact is the dominant source of sound as found by Nystuen, or (2) that the bubble oscillations are contributing the major acoustic power to the underwater noise produced by rainfall was partly solved by the papers by Pumphrey, Crum & Bjørnø [14-16]. In studies of artificial and real rain in light and moderate rainfalls the authors showed that the 14- to 16-kHz spectral peak is caused by bubbles entrained in the water by the drop impact. The existence of the drop impact as a potential source of sound was recognized, but its importance at low rainfall rates was considered to be small compared to noise contribution arising from regular entrainment of bubbles produced by raindrops in a fairly small size range of 0.8 - 1.1 mm in diameter, being common in most types of rain. By lowering of the surface tension, the authors showed that the spectral peak disappeared, which created evidence for that the peak was caused by pulsations of bubbles. The authors, moreover, showed that the irregular entrainment produced by the impact of larger raindrops may lead to bubble pulsations at various times after the drop impact, or not at all, see figure 1.

The dramatic influence on the acoustic power spectra of real rain from adding a small amount of sulfo detergent to the water in order to reduce the surface tension may be seen from figure 2, while figure 3 shows the gradual reduction in the spectral peak by a gradual lowering of the surface tension.

Figure 1. Irregular entrainment. Sounds produced by drops of 5.2 mm in diameter impacting at a velocity of 6.8 m/s. (Ref. 15)

Figure 2. Acoustic power spectra of real rain falling into clean water (closed circles) and water with sulfo detergent added (open circles). dB reference level is arbitrary. (Ref. 15)

The explanation on what caused the characteristic spectral peak between 14 and 16 kHz brought the research a step forward, but it did not explain the rain noise spectrum variation below and above this frequency range and, moreover, it turned out to be very difficult to relate rainfall rate (in mm/h) with the spectrum level in the range 14 to 16 kHz. However, the characteristic spectral peak formed an indication on, that it was a rain caused feature, as spray from wind interaction with the sea surface will not produce regular entrainment of bubbles.

Figure 3. Acoustic power spectra of spray of water falling onto a large tank of water at various surface tensions. Open squares: 72 dyn/cm (clean water); closed circles: 61 dyn/cm; open circles: 48 dyn/cm. dB reference level is arbitrary. (Ref. 15)

Laboratory and field tests of rain drops falling at oblique incidence due to the influence of the wind showed that the bubble creation probability was decreasing rapidly with increasing angle of impact [17], thus reducing the characteristic spectral peak dramatically. The bubble generation mechanisms described in Refs. 14 - 16 will for the small drops (0.8 to 1.1 mm) depend critically on the surface geometry at the instant of impact. If wind is present, the impact direction will be changed from nearly vertical forming the basis for the conclusions in Refs. 14 - 16, and the water surface will be roughened by the wind. Observations in [17] produced some evidence for that for wind speeds exceeding 3 m/s, most of the sound generated by light rain is due to the impact of the raindrops on the water surface.

In an attempt to explain the basis for the deviations between the two contradicting theories for rainfall produced noise in the 14 to 16 kHz region, Nystuen's impact theory [10,11] and Pumphrey et al's bubble pulsation theory [15], Laville et al [18] studied the recordings of underwater sound produced in a lake under various rain conditions. They arrived at the conclusion, that the origin of the spectral peak around 14 to 16 kHz is bubble resonances, in agreement with Pumphrey et al's observations, and that the origin of the spectral content outside the 14 to 16 kHz frequency range is mainly raindrop impacts whose impulses are characterized by a broadband spectrum with a negative slope. The last conclusion contradicts Pumphrey et al's statement, that the low-frequency content of the rain noise spectra is produced by a combination of contributions from impacts of larger raindrops and irregularly entrained bubbles. However, the heaviest rain reported in [18] is 6 mm/h, which is "moderate rain" according to the *Glossary of Meteorology*, and this rain should not comprise large raindrops.

Aiming at obtaining a much better correlation between the rain noise spectral levels and the rainfall rates a series of comprehensive studies were performed particularly involving heavy rainfalls comprising a great number of larger raindrops which are carrying greater amount of precipitation than light and moderate rainfalls [19,6].

Medwin et al [19] in a comprehensive paper showed that the complete underwater spectrum of rainfall sound is produced by four acoustically-distinctive ranges of drop diameters D . These are defined in Medwin et al's terminology based on the acoustical output as "minuscule drops" ($D \leq 0.8$ mm), "small drops" ($0.8 \leq D \leq 1.1$ mm), "mid-size drops" ($1.1 \leq D \leq 2.2$ mm) and "large drops" ($d \geq 2.2$ mm). The minuscule raindrops produce only a very weak, almost undetectable, impact noise. Small raindrops radiate measurable broad-band impact sound and a much higher energy sound of a damped microbubble oscillation at peak frequencies around 15 kHz, as originally shown in [15], and with a peak dipole pressure of 0.4 Pa on axis at a distance of 1 m. The mid-size raindrops radiate only impact sound, while the large raindrops, particularly found in heavy rainfalls, produce both impact sound and strongly radiating bubbles having frequencies of the peak energy spectral density from 1.8 kHz to 8.5 kHz for raindrop diameters from 4.8 mm to 2.2 mm, respectively. Large raindrops also frequently produce weaker sounds from secondary bubbles.

Only a small fraction (10^{-6} to 10^{-7}) of the large drop kinetic energy is converted to impact acoustic energy, and the acoustic energy per unit drop volume was in [19] found to be significantly dependent on the absolute difference between the raindrop temperature and the temperature of the surface waters, with increasing conversion efficiency for increasing temperature difference. Medwin et al, moreover, showed that for raindrops of the same temperature as the surface waters, there was a linear decrease of sound energy produced with increasing salinity.

The total rainfall rate (TRR) in mm/h may be determined from:

$$TRR = 6 \cdot 10^{-4} \pi \int_D D^3 V_T(D) N(D) dD \quad (1)$$

where D is the raindrop diameter (mm), V_T is the terminal velocity (m/s), and $N(D)$ is the raindrop size distribution ($\#/m^3$ per diameter increment). The raindrop size distribution may be obtained from Marshall and Palmer [20] as:

$$N(D) = N_0 e^{-\lambda D} \quad (2)$$

where N_0 is a constant ($N_0 = 8000$) and where λ depends on TRR as, $\lambda = 4.1 \text{ TRR}^{-0.2}$.

The correlation between rainfall rates and noise spectral levels was studied in [6], where the authors found the best correlation (correlation function about 0.8) for frequencies below 10 kHz - where the greatest influence of large raindrops is found -

and for wind speeds up to 15 m/s. Above 10 kHz the correlation between rainfall rate and spectral level was found to be lower, in particular due to formation of bubble layers near the surface caused by either breaking of waves (at wind speeds above 10 m/s) or impacts of large raindrops. Based on the high correlation between sound level and rainfall rate below 10 kHz, an empirical - site specific - expression was proposed in [6] for estimating rainfall rate from underwater sound as:

$$TRR = 10^{(RS_{5.5\text{ kHz}} - 51.9/10.6)} \quad (3)$$

for $TRR > 10$ mm/h, i.e. for "heavy rain" ($TRR > 7.6$ mm/h). In expression 3, TRR is the total rainfall rate (mm/h) and $RS_{5.5\text{ kHz}}$ is the spectral level at 5.5 kHz in dB re. $1\text{ }\mu\text{Pa}^2/\text{Hz}$. Expression 3 represents, fundamentally, an estimate of the rainfall rate from large raindrops rather than the total rainfall rate.

Conclusions

The sources of underwater noise produced by rainfall are (1) impact sound and (2) pulsations of entrained bubbles. The impact sound is produced by raindrops of all equivalent diameters, with the major noise contribution from large raindrops. The bubble pulsation as a source of sound is found by regular (100%) entrainment of small gas bubbles produced by small raindrops (0.8 to 1.1 mm in diameter) leading to the characteristic peak spectral level between 14 and 16 kHz, and by irregular (not 100%) entrainment of larger gas bubbles caused by large raindrops, particularly contributing to the underwater noise level below 10 kHz. In spite of the fact, that the sources of underwater sound by rainfalls and the produced noise spectra are known, there is still a need for more research in order to be able in a reliable and reproducible way to relate the underwater noise to the rainfall rate. Some great steps forward have been made during most recent years by research groups in the US and in Europe, but some important, and still unknown, relations in particular for light ($TRR \leq 2.5$ mm/h) and moderate ($2.5 \leq TRR \leq 7.6$ mm/h) rainfall rates have to be found in order to be able to estimate these rainfall rates from their underwater noise spectra. The problems still left over are not easy to solve, and they form a challenge to underwater acousticians and to meteorologists in the years to come.

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