Rainfall Measurement using Passive Underwater Acoustical Remote Sensing

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Abstract - Rainfall produces significant and unique underwater sound which can be used as a signal to detect and measure rainfall. The dominant sources of sound from raindrops are tiny bubbles trapped underwater during the splash. Two raindrop sizes regularly trap bubbles underwater: small raindrops (0.8-1.1 mm diameter) and large raindrops (> 2.2 mm diameter). Small raindrops are present in most types of rain and are responsible for the unique 15 kHz sound observed during light rain and drizzle. This sound can be used to acoustically detect light rain and drizzle but can not be used to quantify rainfall rate since the amplitude is very sensitive to wind. Large raindrops are present in heavy rain and produce larger bubbles with lower frequency sound (2-10 kHz) by a different mechanism. The sound produced by large raindrops is highly correlated with rainfall rate and can be used to detect and measure rainfall rate. An acoustical rainfall rate algorithm is proposed for heavy rainfall. This algorithm is sensitive to the relative proportion of large raindrop sizes within the rain drop size distribution.

I. INTRODUCTION

Rainfall is one of the most difficult environmental variables to measure and yet is important to a variety of air/sea exchange and climatological processes. Unfortunately, traditional methods of rainfall measurement are unable to monitor rainfall in oceanic regions. Siphon or tipping bucket raingauges are unsuitable for deployment on buoys or ships and shore-based weather radar provide very limited and possibly orographically biased coverage. Satellite based remote sensing techniques offer

more promise, but lack essential surface truthing. Fortunately, rainfall produces significant sound underwater and this signal can be exploited to measure rainfall in oceanic regions.

Rainfall has long been recognized as a producer of underwater sound [1],[2] and can be detected acoustically at sea even in high sea states [3],[4]. Nystuen [5] showed a high correlation between rainfall rate and underwater sound level during heavy rainfall, but reported a very poor correlation during light rain, "drizzle", conditions. Recent results can explain these observations.

II. LABORATORY RESULTS

Natural raindrops range in size from approximately 0.2 mm to 5 mm in diameter [6] and are well suited for study in the laboratory, provided terminal fall velocity can be achieved. Figure 1 shows some observed raindrop size distributions recorded during light rain or drizzle to very heavy rainfall over Clinton Lake, Illinois. The raindrop size distributions are usually

Fig. 1. Drop size distributions observed during rainfall at Clinton Lake, IL in October 1982.

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exponential (many more small drops), but significant variations occur [6]. Also shown in Figure 1 are the acoustically significant raindrop sizes [7]. Raindrops produce sound underwater by two general mechanisms: the initial impact of the raindrop onto the water surface and by the creation of a bubble during the subsequent splash [8]. When a bubble occurs, it is the dominant underwater sound source, roughly 200 times more acoustically energetic than the impact [9]. At terminal fall velocity, two raindrop size ranges have been observed to produce bubbles underwater: small raindrops (0.8 - 1.1 mm diameter) and large raindrops (> 2.2 mm diameter).

As a raindrop strikes a water surface, a depression or "crater" is formed on the water surface. The bubble creation mechanism for small raindrops [10] requires that this crater be of an exact geometry so that the sides of the crater close together faster than the bottom of the crater rises, causing a bubble to be pinched off at the base of the crater. This mechanism has been modeled analytically [11] and simulated numerically [12]. For small raindrops striking a water surface at normal incidence, bubbles are created 100% of the time and are very uniform in size. As a bubble is created underwater, it "rings" at its resonance frequency, which is related to its size by

$$f = \frac{1}{\pi D} \sqrt{\frac{\gamma P_0}{\rho_0}} \quad (1)$$

where f is the resonance frequency (in kHz), D is the bubble diameter (in mm), P_0 and ρ_0 are the local pressure and water density and γ is the ratio of specific heats for air ($\gamma \approx 1.4$). For small raindrops, the resonant frequencies of the bubbles range from 14-18 kHz.

A different bubble creation mechanism has been observed for large raindrops (> 2.2 mm diameter) [7],[13]. This mechanism requires a very energetic splash in which water is thrown upward and closes above the crater to form a "canopy". These canopies appear to be large "bubbles" floating at the water surface during very heavy downpours. As part of the canopy formation, a turbulent jet is forced downward from the underside of the canopy through the crater bottom. This jet carries air underwater which then pinches off to form bubbles. Although several bubbles are often created, one bubble is usually more energetic than the rest and is referred to as the "dominant" bubble [7]. The size of this bubble is proportional

to the drop size and, consequently, the frequency of the sound generated is inversely proportional to drop size, ranging from 2-10 kHz for raindrops from 4.6 to 2.2 mm diameter, respectively [7]. The other bubbles, referred to as "secondary bubbles" [7], are generally resonant at frequencies above 10 kHz. Bubbles are created by large raindrop splashes approximately 50% of the time.

III. LIGHT RAIN AND DRIZZLE

Light rain and drizzle generally do not contain large raindrops. However, as Fig. 1 shows for the 0.6 mm/hr rainfall rate case, the acoustically important small raindrops are usually present. These raindrops produce sound from 14-18 kHz and are responsible for the unique "15 kHz peak" observed in the underwater sound spectrum during light rain (Fig. 2) [10]. Field observations have shown that the amplitude of this unique sound is dependent on wind speed (All of the spectra shown in Fig. 2 are for the same rainfall rate, 0.6 mm/hr.). In fact, as the wind speed increases, the amplitude of the 15 kHz peak decreases until it is no longer a "peak", but merely a spectral rise relative to the no-rain acoustic spectrum.

Medwin et al. [9] showed that the probability that the small raindrop bubble creation mechanism occurs depends on the angle of impact of the raindrop onto the water surface. As the angle of impact goes from normal to 20° off of normal, the probability of bubble creation drops from 100% to 10%. Assuming that the angle of impact results from the combination of horizontal advection by the wind and the slope of surface gravity waves generated by the wind, Nystuen [14] predicted the

Fig. 2. Observed spectra recorded during light rain. Each case has the same rainfall rate, 0.6 mm/hr, with no raindrops larger than 1.5 mm diameter present. The solid lines show the predicted influence of wind [14].

Fig. 3. Sound spectra recorded by an autonomous acoustic drifter deployed off the coast of California. The spectrum at 2019z indicates light rain or drizzle.

effect of wind on the amplitude of the 15 kHz peak. These predictions are shown in bold lines in Fig. 2. Once the wind speed reaches just 3 m/s, the bubble creation mechanism for small raindrops is suppressed and the sound generated is from the acoustically weaker impact component of the drop splash.

An example of the acoustic detection of light rain at sea is shown in Fig. 3. These data were collected using an autonomous acoustic drifter deployed off of the coast of California from May-Aug 1990. The drifter consisted of a hydrophone suspended 10 m beneath a small spar buoy. Acoustic data was collected once per hour and relayed to shore via the ARGOS satellite data link. Fig. 3 shows the underwater sound spectrum before, during and after the passage of a weak atmospheric front on May 22nd. The sound spectrum at 2019z indicates drizzle. A geostationary satellite image (GOES - visible image) at 2031z showed the drifter located underneath the cloud band associated with the atmospheric front (drizzle likely). The sound spectra prior to (at 1716z) and after (at 2327z) the front are typical of "wind only" generated underwater sound spectrum, i.e., a relatively uniform spectral slope, and can be used to estimate wind speed. Using an acoustic wind speed algorithm [15], the wind speed before and after the passage of the front are 4.6 and 3.0 m/s, respectively.

Note that while light rain and drizzle can be detected acoustically, no attempt should be made to estimate rainfall rate for light rain and drizzle. The influence of wind is too great. On the other

Fig. 4. Sound spectra recorded during heavy rain at the OTP. hand, the sound generated is unique to rain containing only small (and acoustically quiet mid-sized) raindrops. Without any large raindrops the total water volume is generally low, and thus the rainfall rate is probably less than 1 mm/hr.

IV. HEAVY RAIN

When the rainfall rate is greater than 10 mm/hr, large raindrops are usually present (see Fig. 1). Acoustically, heavy rainfall will be defined as rain containing the acoustically significant large raindrops. Several examples of the sound generated by heavy rainfall are shown in Fig. 4. These data were collected at the Ocean Test Platform (OTP), a 12 m diameter buoy operated by the National Data Buoy Center, NOAA, in the Gulf of Mexico near the coast of Mississippi. While small drops are usually present in large numbers, the 15 kHz spectral peak characteristic of light rain and drizzle is absent. When the rainfall rate is extremely high (over 150 mm/hr), the sound levels above 15 kHz actually go down. The best explanation for this reduction in sound level is the presence of a layer of bubbles which attenuate sound traveling from the surface to the hydrophone. Since bubbles attenuate sound principally at their resonant frequencies (1), large numbers of small (high frequency) "secondary" bubbles must be generated by the rain. The presence of a rain produced bubble layer is an indication of surface mixing by rain and will also affect air/sea gas transfer. A similar phenomenon is reported under very high wind speed conditions [16].

Fig. 5 shows two predictions of spectral level for 100 mm/hr rainfall (the solid lines) together with

Fig. 5. Prediction of sound produced by heavy rain (100 mm/hr) using two different drop size distributions. Also shown are the composite OTP data (mean, standard deviation and range (shown by the "+" symbols) at each frequency) for all data with rainfall rate between 80 and 120 mm/hr.

a summary of sound spectra collected during heavy rainfall (80 - 120 mm/hr) at the OTP. The predictions were generated by using

$$RS(f) = \sum_i \pi V_T(D_i) n(D_i) S(D_i, f) \quad (2)$$

where $RS(f)$ is the spectra energy, V_T is the terminal fall velocity for drop size D_i , $n(D_i)$ is the drop size distribution, $S(D_i, f)$ is the average sound spectrum generated by each drop size and π is a factor to adjust for the radiation pattern of uniformly distributed acoustic dipole sources (the raindrops) at the ocean surface [7]. Laboratory measurements of the amplitude, frequency distribution and likelihood of creation of dominant bubbles by large raindrop splashes for each of several individual large drop sizes were used to estimate $S(D_i, f)$ [17]. Two different exponential drop size distributions, each 100 mm/hr, but with different proportions of large drops, were used to generate the two predictions. The drop size distribution with relatively more large drops produced the higher amplitude spectrum (2-3 dB higher at all frequencies).

The OTP data shown in Fig. 5 are the mean, standard deviation and range for each frequency were the rainfall rate was between 80 and 120 mm/hr. The rainfall rate for each data point was measured by an optical raingauge located on the OTP, 70 m away from the bottom mounted hydrophone. In the frequency range that the dominant bubbles from large raindrops produce their sound (2-7 kHz) [7], agreement is good. At higher frequencies, the predictions are low. This is probably due to an underestimation in the laboratory experiments of the number of secondary bubbles created during the splashes of

the large raindrops. As previously mentioned, there is field evidence that these bubbles are created in large numbers.

Between 2-10 kHz, the data collected at the OTP show an empirical correlation between total rainfall rate and spectral level of 0.8 [18]. This high correlation allows an acoustical rainfall rate algorithm to be proposed:

$$RR = 10^{\left(\frac{RS_{5kHz} - 53.3}{10.6} \right)} \quad (3)$$

where RR is the total rainfall rate (mm/hr) and RS_{5kHz} is the spectral level at 5 kHz in dB re 1 $\mu Pa^2/Hz$. However, when (3) is applied to data collected at the OTP, a systematic error is observed (Fig. 6). In the first part of each rain event, (3) overestimates the rainfall rate and then, later in the same event, the rainfall rate is underestimated. An explanation for this

Fig. 6. A comparison of acoustical rainfall rate estimate using (3) and measured rainfall rate using an optical raingauge at the OTP.

observation is a change in the drop size distribution during the rain. In a convective rain, the relative proportion of the rain water volume in large raindrops is higher at the start of the storm (as the large drops fall out of the cloud faster) than at the end of the storm (most of the large drops have already reached the surface). Changing the relative proportion of large raindrops in the drop size distribution (while keeping the total rainfall rate constant) was shown in Fig. 5 to produce a noticeable change in spectral levels (2-3 dB). Apparently sound produced by the largest drops dominate the underwater sound spectrum. Thus, the acoustical estimate of rainfall rate is more properly an estimate of rainfall rate from large raindrops (fortunately, this quantity is highly correlated with total rainfall rate).

An example of the acoustic detection and measurement of heavy rainfall at sea is shown in Fig. 7. Again, these data were reported from an autonomous acoustic drifter. This drifter was deployed in the Atlantic Ocean southwest of Bermuda in April 1992. On the 29th of April, a strong atmospheric front passed over the buoy location (35°N, 65°W). Three sound spectra are shown. The spectrum at 2206z (28 April) and 2145z (29 April), before and after the frontal passage, are typical "wind only" spectra. Using the acoustic wind algorithm [15], wind speed estimates are 3.3 and 12.7 m/s, respectively. These estimates are in close agreement with near simultaneous wind speed estimates, 3 and 11.5 m/s, respectively, from a passive microwave radiometer (SSM/I) on board the Defense Meteorological Satellite

Fig. 7. Sound spectra recorded by an autonomous acoustic drifter near Bermuda on 29 April 1992. The spectrum at 0914z indicates heavy rain.

Program (DMSP) F-11 satellite. At 0951z, the SSM/I indicated "heavy" rain, 5 mm/hr, over the location of the drifter. The acoustic estimate of rainfall rate at 0914z is 63 mm/hr. The mismatch in rainfall rate estimate is not surprising. The SSM/I sensor has a spatial resolution of 50 km², and the SSM/I rainfall rate algorithm suffers from a lack of surface truth available for calibration.

V. CONCLUSIONS

A new technology is presented to provide needed measurements of rainfall at sea for both climatological studies and to provide surface verification for satellite techniques of rainfall estimation. Underwater, rain produces significant and unique sound that can be used as a signal to detect and measure rainfall rate. Two drop sizes are particularly significant acoustically: small raindrops (0.8-1.1 mm diameter) and large raindrops (> 2.2 mm diameter). During the drop splash for both of these drops sizes, bubbles, which are very effective underwater sound sources, are regularly trapped underwater.

Small raindrops are present in most types of rain, including light rain and drizzle, and the bubbles created by the small raindrops are responsible for the unique 15 kHz sound detected underwater during light rain and drizzle. This sound can be used to detect light rain and drizzle at sea, but can not be used to measure rainfall rate because the amplitude of the sound is very sensitive to wind.

Large raindrops are usually present in heavy rainfall (RR > 10 mm/hr). The sound between 2-10 kHz produced by the bubbles created by large raindrops is highly correlated with rainfall rate. This correlation is used to propose an acoustic rainfall rate algorithm. This algorithm is sensitive to the relative proportion of the rainfall that is comprised of large raindrops. Thus, the acoustic algorithm is more correctly an estimate of the rainfall rate from large raindrops, which is highly correlated with total rainfall rate. The sound generated by heavy rain does not contain the unique 15 kHz sound of light rain, but does indicate extensive bubble clouds, evidence of near surface mixing and air/sea gas transfer, when the rainfall rate is above 150 mm/hr.

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