Testing Acoustic Rain Gauges in inland and coastal waters

G. D. Quartly[a], K. M. Shannon[a,b], T. H. Guymer[a], K. G. Birch[a], J. M. Campbell[a]

[a] *Southampton Oceanography Centre, Empress Dock, Southampton, Hants, UK,*
e-mail: gdq / kmsh / thg / kgb / joc @soc.soton.ac.uk
[b] *Also at University of Wales, Cardiff, UK*

Summary

This paper analyses the underwater ambient noise records at two very different sites, noting how the acoustic intensity varies with frequency and wind speed. For a given wind speed, the more sheltered inland location has a much quieter acoustic signal, but with greater variability especially at low wind speeds. This is the case both when examining the variability within each hour and when comparing mean spectra for the same nominal conditions. The slope of the acoustic spectrum for wind-only conditions was found to vary slightly with wind speed, but changes in its value can be used for the detection of rain. There was little rain during the trial at the more exposed coastal location, so the analysis there is only for wind and wave dependence. The observed site-dependent changes in the magnitude and shape of the spectrum need to be better understood in order that the rain algorithms can be made more accurate.

1. Introduction

Rain at sea is an important component of the freshwater exchange with the atmosphere. When the ingress exceeds the evaporative losses, the surface waters will become fresher and less dense. This has implications for the overturning circulation of the ocean which is controlled by changes in density. However, precipitation is one of the least accurately measured of all climatic parameters, on account of its large variability on short temporal and spatial scales. Conventional land-based instruments cannot be used for monitoring rainfall at sea, making measurements in this environment even more scarce. Satellites do provide a global view, but many spaceborne sensors (e.g. SSM/I) only view a region a few times a day. There are also wide disparities in the rainfall rates derived from such data, according to the assumptions behind each of the algorithms[1]. *In situ* rain-monitoring devices are thus required to provide an independent evaluation of the various satellite algorithms, and also to provide frequent sampling in selected locations, so as to assess the diurnal variations. An offshore network of such sensors could also be of benefit in real-time forecasting of approaching storms.

Since rain creates a characteristic underwater acoustic signal, the idea of inverting the observed acoustic spectrum to give rain rate has been mooted for many years[4]. However, wind is a key generator of underwater sound, and a good understanding of the various factors affecting its spectra is needed before one can fully characterise the contribution due to rain. There has been some success in comparisons of prototype acoustic rain gauges (ARGs) with the satellite-borne SSM/I sensor[8], but there still remains the need for well-constrained trials in which ARGs can be compared with other rain-measuring systems, so as to assess errors and determine those factors that bias the measurements. This paper describes two such trials, where a suite of other sources for recording rain rate, wind speed etc. were available.

Our equipment is based on sensors and circuitry developed by *Metocean Ltd* of Nova Scotia, which, every 1.5 minutes, records the acoustic intensities in 16 channels spanning 500 Hz to 50 kHz. The instrumentation is described in more detail in our earlier paper[10]. Here we first discuss the mooring sites and then (in section 3) intercompare the spectra observed in rain-free conditions. The acoustic contribution of rain is considered in section 4, with an overall discussion being provided in section 5.

2. Layout of deployments

The two trials discussed here were held in very different environments. The first of these was in Loch Etive, a deep saltwater loch in Scotland (Fig. 1a). The hydrophone was placed at 20 m depth in 50 m of water, at a location ~50 m from the shore. The data used here are from November and December 2000, when the surface waters, which contained recent run-off from the land, were somewhat colder and fresher than the deep water. The second trial discussed here was in 23 m of water ~8 km off the West Wales coast. A redesigned larger surface unit was used, but the electronics and hydrophone were as before, except that the depth of the latter was ~11 m. This deployment was short-lived (10 days) due to the loss of the hydrophone from the ARG. In both trials there were a variety of simultaneous meteorological measurements; to compare these two deployments we will restrict the ancillary data to rain records from the Met Office weather radar (scans every 15 minutes provided on a 5 km x 5 km grid) and wind speeds from a met buoy (20-minute or hourly samples).

3. The effect of wind

We discuss first the acoustic intensities generated by wind, as its contribution is nearly always present. The meteorological records from the buoy site at Aberporth were only available at hourly resolution, so, for both trials, we consider acoustic spectra in hourly ensembles. Both sets of data have been screened for rain (using the rain radar data), and for Loch Etive we only use night-time data to minimise possible anthropogenic noise.

Figure 2 shows the mean acoustic intensities at channels 4, 8 and 12 (2 kHz, 6 kHz and 20 kHz) plotted against wind speed. Loch Etive had been chosen for early trials as it was known to be an exceptionally quiet environment, with little wave activity or noise from shipping. The observations in Fig. 2a show that at low wind speed the observed intensities were typically 17 dB less than at Aberporth for the same conditions. The discrepancy is less for higher wind speeds and frequencies. Loch Etive was a sheltered location, such that wind speeds above 8 ms^{-1} were rare. On the other hand, such winds were more common at Aberporth, enabling the mean intensity curve to be determined for higher wind speeds than in the first trial.

The mean curves for Aberporth show intensity increasing smoothly with wind speed, albeit that the rate of increase is reducing. [If the intensity is expressed in absolute units (i.e. not in dB), it increases faster than wind speed at low frequencies, but at a slower rate at higher frequencies.] Above about 6 kHz, there is no apparent wind speed dependence below 2 ms^{-1}, but such a dependence exists at the lower frequencies. However the most striking observation from the intercomparison of the two datasets is the degree of scatter in the Loch Etive data. This is brought out more clearly in Fig. 3, where the two curves for each dataset show i) the variation between different hourly averages for similar wind speed conditions, and ii) the mean variability detected within each hour.

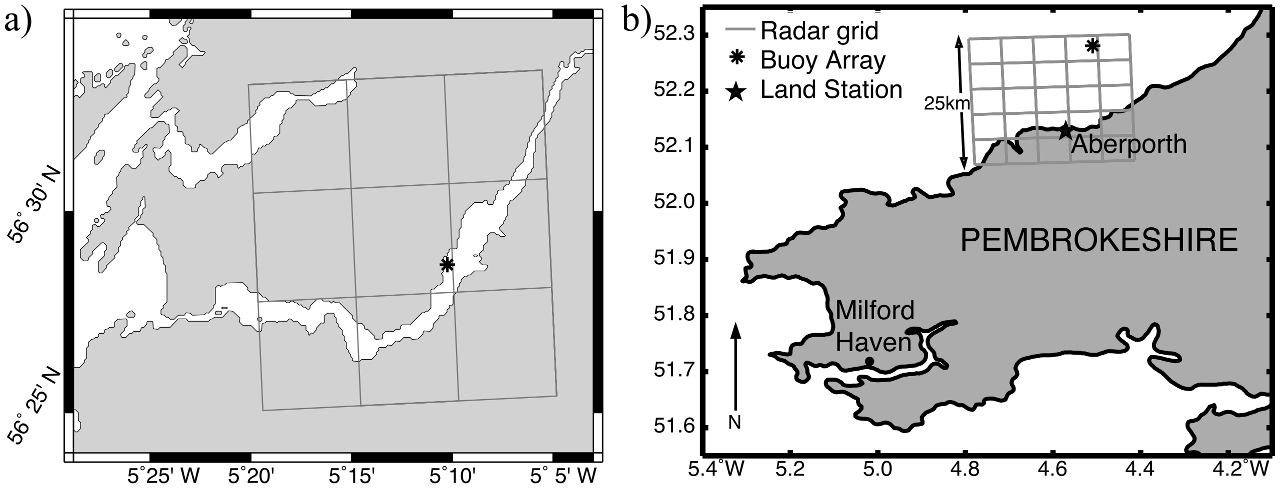

Figure 1. Location of mooring arrays (ARGs and met buoys), with overlaid grid showing the 5 km x 5 km pixels of the Met Office's radar data product. a) Loch Etive site b) Aberporth site.

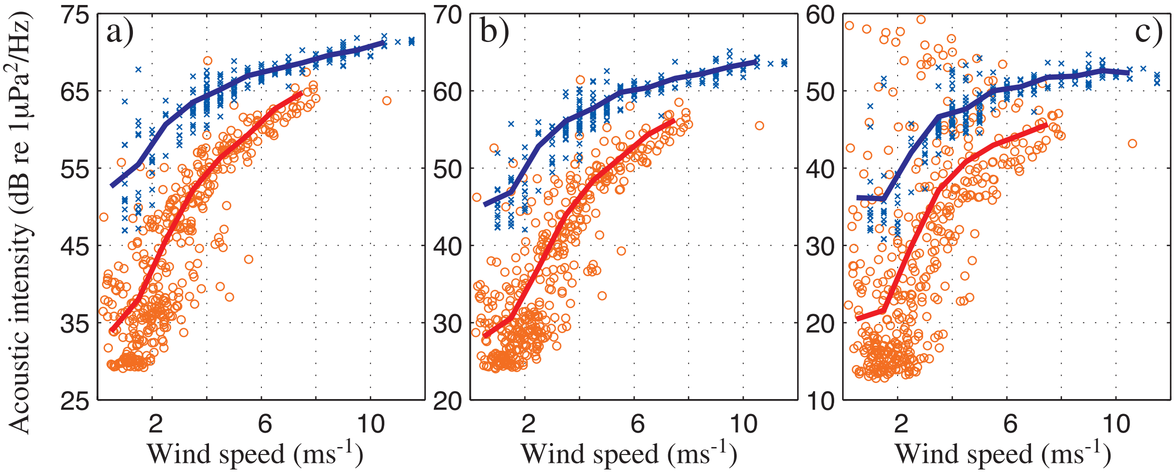

Figure 2. Observed acoustic intensities as a function of wind speed at a) 2 kHz, b) 6 kHz and c) 20 kHz. (Note the scaling on the y-axes are different.) The orange circles (blue crosses) show individual hourly averages for Loch Etive (Aberporth), and the red (blue) line shows the average intensity for each 1ms^{-1} bin. [Note the wind speed data from Aberporth is quantized at 0.5 ms^{-1}.].

All the plots show greater variability at low wind speeds (not surprising given the use of logarithmic units), but the variability at Loch Etive remains high over a larger range of wind speeds. In nearly all cases, the hourly averages for a given set of conditions (wind speed and location) show a greater degree of scatter than the individual 1.5-minute records do within an hour. This indicates that wind field alone is not sufficient to explain the observed acoustic levels.

The mooring array at Aberporth included a buoy that measured wave height and period. To determine a possible wave height effect, we calculated mean acoustic spectra for waves of different height (~1m and ~2m), but within the same range of wind speed (7-9 ms^{-1}). There were few observations in these overlap conditions, so although the higher sound levels were associated with the higher waves, it cannot be deemed significant. This is an area we hope to address with data from future trials.

Figure 4a shows the acoustic levels at all 16 frequencies for two sets of wind speed conditions for the two sites. At a mean wind speed of 2 ms^{-1}, the data from Loch Etive are 10-20 dB quieter at all frequencies than those from Aberporth, with the size of the discrepancy being less at the higher frequencies. At 8 ms^{-1}, the offset is only ~5 dB, and nearly constant over the whole frequency range.

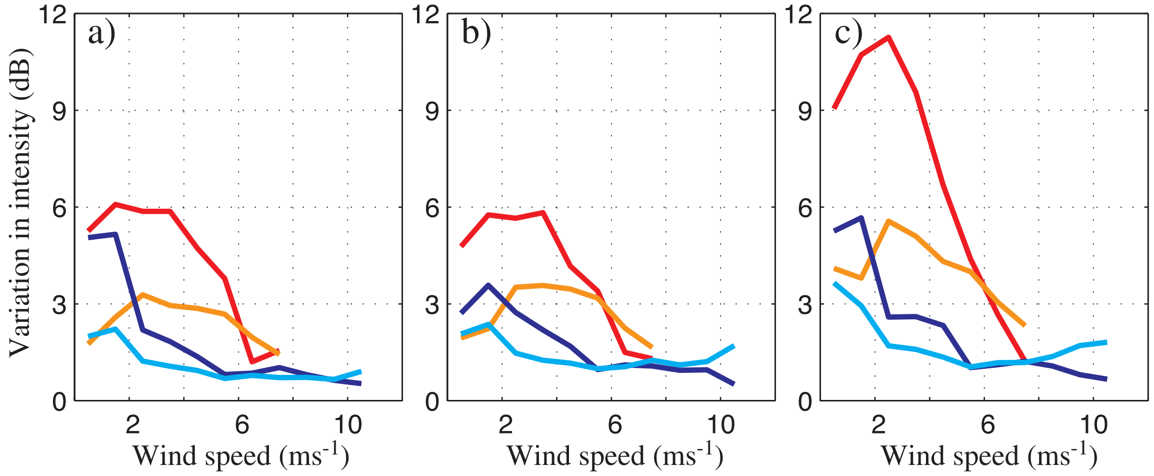

Figure 3. Variability in acoustic intensities (r.m.s. of fractional change) at a) 2 kHz, b) 6 kHz and c) 20 kHz. The red (dark blue) line shows the spread (s.d.) between hourly averages for the Loch Etive (Aberporth) data; the orange (light blue) line gives the mean of the spreads (s.d.) within each hourly ensemble for Loch Etive (Aberporth).

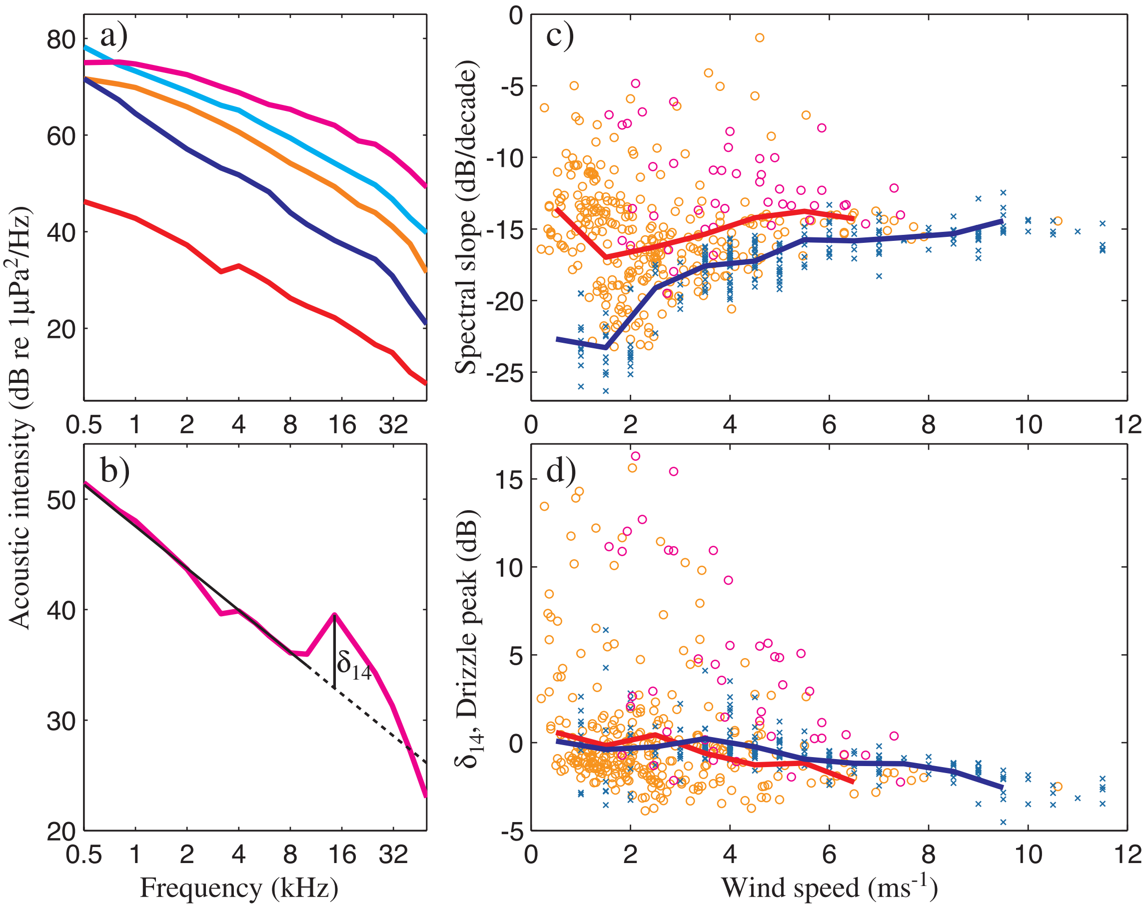

Figure 4. Acoustic spectra as a function of wind speed and rain rate. a) Mean spectra at Loch Etive for winds of 2 ms^{-1} (red) and 8 ms^{-1} (orange) and for Aberporth (dark blue and light blue respectively). The pink curve is for a short period downpour at Loch Etive. b) Schematic illustrating the determination of two spectral parameters. The pink curve is an example from Loch Etive showing the characteristic drizzle peak, with the solid black lines emphasising the fitted spectral slope between 0.5 and 10 kHz and the magnitude of the 'drizzle peak' at 14.5 kHz. c) Spectral slope as a function of wind speed. Individual wind-only points for Loch Etive (Aberporth) are shown by orange circle (blue crosses), with a red (blue) line for the mean in each 1 ms^{-1} bin. The pink circles are for rain-affected spectra at Loch Etive. d) Drizzle peak as a function of wind speed, with colour/symbol code as for 4c)

4. The effect of rain

Rain generates sound through a number of mechanisms[3,6,7]; the key point is that light rain and drizzle predominantly contain small raindrops which generate a characteristic peak around 14 kHz (see Fig. 4b), whereas heavy rain contains a wide variety of drop sizes and increases the sound level at all frequencies and reduces the magnitude of the spectral slope (see Fig. 4a). Here we determine spectral slope by the rate of change of acoustic intensity between 0.5 and 10 kHz (see fitted black line in Fig. 4b). We define δ_{14} (the 'drizzle peak') as how much louder the intensity is at 14.5 kHz than predicted by a continuation of that line.

We examine the derived parameters of spectral slope and δ_{14} as a function of the environmental conditions (wind and rain). Data are deemed to be 'rain-affected' or 'rain-free' purely on the basis of the rain radar data rather than some acoustic classification. [There was little rain during the 10 days at Aberporth, so those data are not plotted.]

In our data, the spectral slope (Fig. 4c) is found to be typically around -16 to -17 dB/decade, with the slope being less steep for the Loch Etive data. Data from both sites show the magnitude of the slope to decrease slightly as the wind speed increases. This is in conflict with many of the simple models of environmental noise, which assume the spectral curves to be linear to at least 10 kHz, and that this slope is constant for all wind speeds. A greater fall-off in intensity above 10 kHz is expected for high winds due to the production of sub-surface layers of bubbles, which will attenuate the higher frequencies more than the lower ones[2].

Rain is shown to be associated with lower magnitude spectral slopes (consistent with the example shown in Fig. 4a). Once again the data from Aberporth show less variability for given conditions than those from Etive. A plot of the spectral slope of the Aberporth data as a function of time (not shown) revealed a 12.5-hour periodicity for a few days. This may be due to strong tidal currents past the hydrophone.

The peak at 14.5 kHz is a good indicator of light rain (Fig. 4d), but will show no signal for heavier downpours. The magnitude of this peak also drops rapidly with increasing wind speed. This is partially due to the background level attributable to the wind increasing, but also caused by wind reducing the generation of ringing bubbles[5] that produce the 14.5 kHz peak. There is good agreement between the 'wind only' curves for Loch Etive and Aberporth, indicating that in the absence of rain the acoustic spectra at both sites are close to linear above 10 kHz. The increasingly negative values at higher wind speeds are believed to be caused by a growing layer of bubbles[2].

5. Discussion

We have tested ARGs in Loch Etive for a number of years because the sheltered location and steep topography afford deep deployments close to the shore. We used a tipping bucket gauge close to the shore to provide high temporal resolution validation data[9,10]. However the conditions in Loch Etive were unusually quiet especially at the lower frequencies. The deployment at Aberporth provided rougher conditions, which proved a greater challenge to the instrument's on-board algorithms, which were originally developed for calm tropical locations[8].

As well as the absolute power levels being different in the two locations, the spectral slopes differed a little. A feature in common to both sites is the gradual change in spectral slope as wind speed increases. However, our results can be explained by a wind component of constant spectral slope plus a background term of steeper slope that is only significant at low wind speeds. In a homogenous body of water, the depth of the hydrophone should have little effect on the perceived signal level. However, the very quiet sound levels observed in Loch Etive at low wind speeds may be due to the development of a strong thermocline above the hydrophone depth, with consequent refraction of the sound rays. [Unfortunately, because of battery failure, we gathered few data from experiments in Loch Etive on varying the hydrophone depth.] For both sites, the sound level at high frequencies showed no dependence upon wind speed for winds less than 2 ms^{-1}, whereas some dependence was apparent at the lower frequencies. However the greatest variability was noted for Loch Etive data at low wind speeds. This was somewhat surprising given that the deeper the hydrophone, the less variable the signal is expected to be.

The acoustic signature of rain seemed quite detectable, although it is less clear at high wind speeds. To handle the two datasets similarly, the analysis in this paper has been based on hourly-averages of the spectra and the ancillary measurements. However the large footprint of the radar grid may reflect processes not occurring right at the mooring site. In an earlier analysis at Loch Etive, we found the radar sometimes gave values 50% less than our tipping bucket gauge[9]. For the Aberporth trial, the comparison of the rain radar output over the land station showed the radar to then be reading twice that of other instrumentation. Such radar data are necessary for testing how well ARGs can infer rain rates, but the radar data themselves need to be quantitatively evaluated against other *in situ* sources.

6. Conclusions

Many researchers have gathered and presented environmental acoustic data from one site. Here we have collected many days of acoustic and ancillary data from two very different sites. Our particular interest is in developing instrumentation for routine monitoring of rainfall at sea, but a greater understanding of the ambient spectrum due to wind has been shown to be required. There are a number of aspects that differ between the two sites — depth of site and of hydrophone, thermal profile of the water column, wave conditions (e.g. fetch), as well as factors affecting the drop size distribution of the rain. We have examined the shape of the acoustic spectrum to determine which properties appear to vary little between the two sites, and noted the changes brought about by the presence of rain. A quantitative evaluation of rain rate algorithms is difficult because of the lack of suitable *in situ* measurements providing rain data at sufficient temporal and spatial resolution.

Acknowledgements

We thank all those who were involved in the preparation of the equipment and its various deployments. We are especially grateful for the help of James Gregory who did much of the initial processing, and Simon Keogh who provided the Met Office radar data. Local supervision of sites was undertaken by John Holmyard (Loch Etive), Kevin Griffiths and Richard Graves (Aberporth).

References

[1] R. F. Adler, C. Kidd, G. Petty, M. Morissey, and H. M. Goodman: Intercomparisons of global precipitation products: The third precipitation intercomparison project (PIP-3), Bulletin of the American Meteorological Society, **82** (2001) pp. 1377-1396.

[2] D. M. Farmer and D. D. Lemon: The influence of bubbles on ambient noise in the ocean at high wind speeds, Journal of Physical Oceanography, **14** (1984) pp. 1762-1778.

[3] T. G. Leighton: The acoustic bubble, Academic Press., 1994, Ch. 3.7.2 pp. 220-234.

[4] J. A. Nystuen: Rainfall measurements using underwater ambient noise, Journal of the Acoustical Society of America, **79** (1986) pp. 972-992.

[5] J. A. Nystuen. and D. M. Farmer: The influence of wind on the underwater sound generated by light rain, Journal of the Acoustical Society of America, **82** (1987) pp. 270-274.

[6] J. A. Nystuen, C. C. McGlothin, and M. S. Cook: The underwater sound generated by heavy rainfall,. Journal of the Acoustical Society of America, **93** (1993) pp. 3169-3177.

[7] J. A. Nystuen and H. Medwin: Underwater sound produced by rainfall: Secondary splashes of aerosols,. Journal of the Acoustical Society of America, **97** (1995) pp. 1606-1613.

[8] J. A. Nystuen. and H. D. Selsor: Weather classification using passive acoustic drifters,. Journal of Atmospheric and Oceanic Technology, **14** (1997) pp. 656-666.

[9] G. D. Quartly, J. W. Gregory, T. H. Guymer, K. G. Birch, D. W. Jones, and S. J. Keogh: How reliable are acoustic rain sensors? Proceedings of Acoustical Oceanography, Southampton, UK, Inst. of Acoustics, 2001, pp. 142-148.

[10] G. D. Quartly, T. H. Guymer, K. G. Birch, J. Smithers, K. Goy, and I. Waddington: Listening for rain: Theory and Practice, Fifth European Conference on Underwater Acoustics, Lyon, France, 2000, pp. 723-728.