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Managing Environmental Impacts from Blast Noise Sources in the UK

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ABSTRACT

Industrial and military operations that produce blast noise require management and control measures to reduce adverse effects. The focus of this paper is on environmental noise as opposed to occupational exposure. We provide a brief overview of relevant scientific literature and draw from decades of field work conducted in the UK. Accurately predicting, assessing and controlling environmental blast noise requires a thorough understanding of the noise source, propagation path, and receiver. However, the characterization of highly transient blast noise sources is often inadequate, predicting propagation paths accurately demands vast amounts of spatial and temporal metrological data that are hard to obtain, and the receiver is often a diverse set of communities. In this paper, we argue that controlling environmental impacts arising from blast noise sources can be best achieved through a combination of measures that reduce the noise from the source, fast and efficient regression-based noise predictions that are augmented by a continuous online monitoring system and maintaining community engagement. Our findings imply that the most effective way to manage environmental impacts from blast noise sources is through the use of formal procedures and best practices implemented on-site.

Keywords: ***Blast Noise, Environmental Noise Management, Environmental Noise Control***

1. INTRODUCTION

Managing environmental noise impacts from industrial and military operations requires various strategies including, prediction, measurement and community engagement. In this paper, we summarize the decades of field work and research done concerning blast noise. Historically, environmental blast noise impacts have mostly associated with military training exercises and activities related to national security. Additionally, substantial work has been done to mitigate impacts from mineral extraction.

Recently, there have been increased efforts to decarbonize industry, transportation, and energy, which has resulted in the testing of major hazards associated with newly developed clean technologies. This has presented new challenges for managing and predicting environmental blast noise impacts. Currently, state-of-the-art propagation models do not accurately quantify near-field source characteristics for the variety of sound sources associated with major hazard testing. Additionally, obtaining the large quantities of input meteorological and ground data that are required for accurately representing propagation of long-range outdoor sound is problematic. Finally, managing community response to adverse environmental blast noise impacts depends not only on acoustical factors but also non-acoustical and societal factors, the research of which is currently underdeveloped.

The aim of this paper is to review previous efforts to manage adverse blast noise impacts, summarize recent work on gunfire and weapons testing noise, and provide an overview of the recent developments of the Gunfire Noise Assessment

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Tool (GNAT). Additionally, we present recent work conducted at the DNV Spadeadam Testing and Research site for the measurement of long-range industrial blast noise and the use of heuristic prediction methods. Finally we summarize the current state of research and offer suggestions for further work required to advance this field.

2. SUMMARY OF UK BLAST NOISE RESEARCH

2.1 Analysis

The University of Salford is internationally recognized for its excellence in field measurements of outdoor sound propagation. Salford is renowned for its technical and measurement capabilities in the areas of occupational impulse noise and environmental blast noise. Impulse noise research at Salford began in 1977 with work for ICI, and continues to this day. It is important to consider that when individuals from the general public express grievances about high levels of noise and annoyance, they are often concerned about the potential damage to their property. In light of this, it is worth noting that Salford's participation in the Concorde historic building and fear of damage project spurred involvement with the quarrying industry and, ultimately, the MOD. Between 1987 and 1996, Salford pioneered a range of field trials that focused on gathering data on the effects of meteorology, topography, and ground terrain on the propagation of blast noise over both short and long range. Researchers involved at the time not otherwise cited in this paper include Roy Ford, Peter Lord, Claire Lomax, Dave Warrington and Dave Anderson. Two phases of trials were conducted: the first at various sites in the UK (Porton Down, Shoeburyness, and RAF Binbrook), and the second on forested, hilly terrain in Norway and later in Canada. The combination of this work led to the development of explosive noise management tools for use at military and testing ranges. These tools are based on explosive scaling laws and extensive meteorological measurements.

2.2 Prediction

The earliest methods for predicting blast noise involved determining a multiplication factor for areas where increased noise levels were anticipated. Field measurements made use of radiosondes, and much of the research focused on the propagation of loud noises created by explosives larger than 100kg over distances greater than 20km. In 1987, Kerry and Saunders [1] created a heuristic model called the Salford Surface Wind (SSW) model to predict noise resulting from artillery fire.

The Acoustic Prediction Package (APP) was developed by West, Turton, and Kerry in 1996 [2]. It included a semi-empirical ray-based prediction method called LARRI. This method could only make predictions for higher frequencies, where geometrical approximations of ray theory are applicable, and where ray foci and subsequent noise enhancements could be predicted. LARRI was also limited by the effects of interaction over hard ground. Nevertheless, the implementation of LARRI was operationally useful for making blast noise predictions, owing to its speedy calculation at the time. Additionally, it was useful for general forecasts of problematic enhancement regions.

2.3 Measurement

The development of early heuristic and computational prediction tools established Salford's authority and credibility as a major research institution in the field of blast noise propagation. Later work throughout the early 2000s focused on developing more complex computational models, including sound prediction using parabolic equation methods (PE) over varying terrain, range dependent meteorology and atmospheric turbulence. Field trials in this period utilized coded signals for the measurement of ground impedance, sonic anemometers to measure atmospheric turbulence, and LIDAR and SODAR to investigate the usefulness of range-dependent meteorology for comparing GTPE predictions to measurements taken over 1km under stable boundary layer propagation schemes at Honnington and Salisbury Plain [3], as well as hilly terrain at Sennybridge and Larkhill [4]. Later, several months of field trials capturing extensive meteorological data allowed for assessment of temporal and spatial variability in vertical sound speed structure to enhance the applicability of propagation models [5] and [6]. Acoustic, ground, and meteorological measurement techniques were used in collaboration with Qinetiq and the RAF to manage helicopter noise. This included field measurements at Spadeadam and the development of fast, combined ray tracing and PE models [7] and [8]. Other work carried out for Qinetiq's Eskmeals test facility in 2005 on the measurement and management of occupational exposure to blast noise led to involvement with the DNV Spadeadam and Testing Site to manage environmental impacts from major hazards testing. It was concluded that the state-of-the-art models at the time (GTPE, etc.) were not adequate for the prediction of blast noise for the operational goals at the Spadeadam site. A short series of field trials in 2017, known as DABENIM (Development of A Bespoke Environmental Noise Impact Method), identified issues with the accuracy and speed of prediction and highlighted the need to develop new heuristic prediction methods. This led to the most recent and current work [9-11] through an industrially-sponsored PhD at Spadeadam, which is expanded upon in section 4.

3. DEVELOPMENT OF GUNFIRE NOISE ANALYSIS TOOL (GNAT)

The need for a rapid method to assess gunfire noise predictions arose from the Otterburn Training Area (OTA) Public Inquiries held in 1997 and 1999. The inquiries considered applications for new gun spur developments at OTA, which were needed to support a revised training regime that would provide more realistic field firing scenarios for various mobile field guns and rockets, including the movement of weapons systems around the extensive training area.

It was recognized that military training, especially that involving the use of large-caliber weapons like those to be deployed at OTA, inevitably generates high levels of impulsive noise at both the point of firing and, for explosive ammunition, also at the target. It was also recognised that, whilst noise levels at source for a given weapon system and charge configuration remain relatively consistent and repeatable, the resulting noise levels at publicly accessible and/or residential locations lying on or beyond the range boundaries can be highly variable. This variability is typically dominated by the effects of meteorological conditions along the propagation path between source and receiver which, at a granular level, can vary not just from day to day but minute to minute.

The use of facilities like OTA could have undesirable effects on surrounding communities, even at distances of several kilometres from the range activities. However, depending on the meteorological conditions experienced during any given training exercise, these undesirable effects may or may not occur. Range controllers needed a reliable way to predict the likely off-range noise impacts of a given training exercise before it began. This information could be used to identify noise effects that were predicted to be above any given threshold of significance before they occurred. Range Controllers could then proactively intervene to mitigate these effects by modifying the training exercise accordingly.

GNAT was developed specifically for use by range controllers. It was designed to produce an easy-to-understand graphical representation of noise levels around the training area in a matter of minutes. The system was designed to use inputs such as the type and charge of the weapon system, its firing position and target area, the type, charge and height of shell detonation within that target area, and importantly, wind and weather conditions.

GNAT outputs noise level contours and receptor-specific noise levels in terms of the Max Peak dB Linear metric, which accounts for the impulsive nature of gun noise. These noise contours are calculated before the start of each day using the specifics of the day's training exercise, as input by Range Control. The measured or forecast meteorological conditions for the range in question are automatically downloaded from the UK Meteorological Office. The facility was also included to update noise level calculations as new meteorological measurements/forecasts became available throughout the training exercise.

If GNAT predicts that agreed noise levels will be exceeded, the Range Officer can then modify the training scenario by any combination of the following:

- Limiting the extent of the firing area(s).
- Limiting the extent of the target area(s).
- Reducing the weight of the shell charge(s).

If none of these actions are sufficient to reduce noise levels to an acceptable level, then firing activity can be postponed until such time as the meteorological conditions change and the calculated boundary noise levels reduce to an acceptable level.

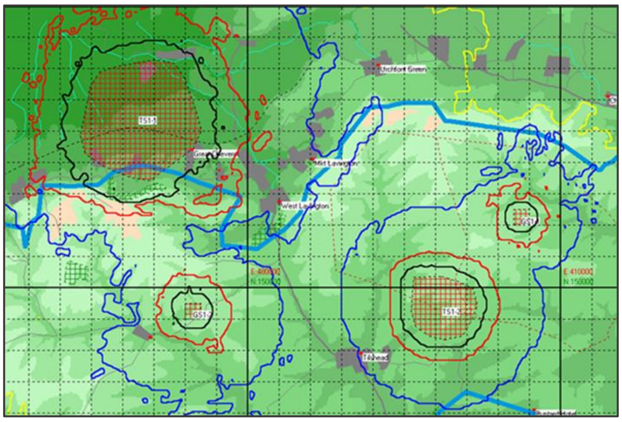


Figure 1 - Screenshot of GNAT noise contour output.

In the late 1990s, there were a variety of methods available to calculate long-distance sound propagation. These methods included numerical, analytical, and empirical (engineering grade) calculation methodologies. However, none of these methods could provide rapid assessments of noise from range activities while also accounting for the effects of temporally and spatially varying meteorological conditions between the source and the receiver, especially over distances of ten kilometers or more. Numerical models that could account for such effects typically took several hours to run on a computer. Furthermore, these numerical calculation procedures assumed an unrealistic level of detail about the varying meteorological and ground conditions along the entire sound propagation path. In reality, only estimates, or at best measured snapshots in both space and time, of such information were actually available. The goal of GNAT was to provide noise level predictions within seconds or at most a couple of minutes, while still adequately accounting for the key propagation factors that influence received sound levels, including meteorological and ground effects.

The specific input data for the various weapons in use at OTA included the FH70, AS90 and the potential to use multi launch rocket systems (MLRS) which also included a reduced range practice rocket. In order to derive appropriate source terms for the various weapons systems, noise monitoring was carried out in close proximity to the weapons when fired and also at positions remote from the firing locations to derive a sound power level including the noise spectra. Noise monitoring to obtain the source terms for the GNAT model was variously carried out at Otterburn for large calibre firing noise, Shoeburyness for ground and air burst and Kirkcudbright for the firing of rockets. The basic equation for the noise model can be simplified as:

$$SPL = L_w - A_1 + A_2 + A_3 + A_4 + A_5 + A_6 \qquad (1)$$

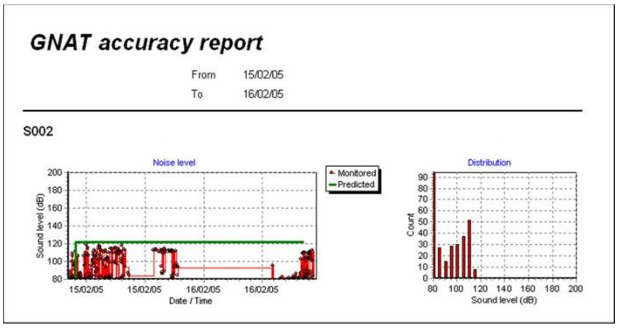
Where, L_w is the source sound power level, A_1 the geometric spreading factor, A_2 the directivity factor, A_3 the barrier attenuation factor, A_4 the air absorption factor, A_6 the wind and temperature factor, *and* A_6 the ground attenuation factor. The wind and temperature factor is calculated using an analytical ray tracing algorithm.

3.1 Comparison of Measured and Predicted Levels

A validation exercise between measured and predicted noise levels was carried out at Salisbury Plain Training Area which identified that, in the main, the GNAT model mostly over-predicted noise levels, but with reducing difference between predicted and measured values at higher noise levels.

In 2003 a major upgrade to GNAT was conceived, which was then implemented across three ranges in 2005, these being OTA, Salisbury Plain Training Area and Castlemartin Training Area.

While the calculation element of GNAT remained unaltered from that just described, additional functionality included the automated ingestion and display of measured noise levels. These measured noise levels were acquired from a series of remote noise monitors located around the boundaries of each range. These measured noise levels, which were available in close to real time, enabled the accuracy of the GNAT noise level predictions to be evaluated on a continual basis, as per the below example screenshot of the GNAT display. These ongoing validation comparisons have consistently demonstrated the GNAT calculation methodology as predicting noise levels at the upper end of the measured noise levels.


GNAT accuracy report

From 15/02/05

To 16/02/05

S002

Figure 2 - GNAT screenshot of measured vs calculated noise levels.

The measurements recorded by the GNAT system also provided factual evidence of actual noise levels in the event of queries being raised. In this regard, all noise monitoring systems were specified to Type 1 accuracy using low sensitivity microphones (>150 dB capable) with the facility for remote auto-calibration plus regular manned maintenance checks. The remote systems were also fully ruggedized to protect against the extremes of weather and animals in their often harsh, exposed locations.

Notwithstanding the additional benefits of the upgraded system, the practical limitations of remote connectivity via GPRS resulted in limited bandwidth and data transfer capabilities. This limitation meant that separate GNAT systems were hosted by each range on an individual basis, with no connectivity between these individual systems and with data only be pulled separately on request by each range; data was not pushed via an always-on connection and was not available centrally. A consequence was that any issues with the remote noise monitoring stations were only identified as and when data transfer requests were initiated by the particular range in question.

3.2 Latest Implementation

More recently, in 2021, GNAT has undergone a further upgrade to overcome the aforementioned shortcomings. The upgrade has seen new remote noise measurement hardware based around the 01dB Cube sound level meter. All remote noise measurement systems feature always-on 3.5G communications (now being upgraded to 4G due to the 3G switch off) which continuously push data to a central server. This data can be universally accessed from any internet connected device via a bespoke, security access controlled web-portal.

This upgrade has seen the system extended to now cover 15 UK ranges, plus the introduction of portable remote noise monitoring systems deployable anywhere in the world. All systems incorporate GPS for time synchronisation and locational details meaning that, on switch on, the remote systems automatically synchronise with the central portal, with location and noise data commencing transfer within a few minutes of deployment.

Figure 3 - Sample images of the current GNAT Noise Monitoring Systems showing permanent installation in the upper images and portable systems in the lower images. Both feature extensive wind noise rejection measures. The locations of the permanent systems are also indicated.

The increased bandwidth of the upgraded communication network also means that the noise data ingested by the GNAT central portal has been expanded to now include as standard $L_{Zpk,1min}$, $L_{Cpk,1min}$ and $L_{Aeq,1min}$, with a range of other indices also possible. Given the operational pressures on range staff, a key requirement is ease of use such that the GNAT system does not distract from the primary focus on range safety. Working alongside range controllers, simple and user friendly controls were developed that require minimal training and guaranteed deployment, with simple exceedance alerts being automatically generated where required.

3.3 Comparison of C and Z-Weighted Levels

There is an ongoing issue with GNAT because it predicts linear levels (unweighted/Z), but health and safety thresholds are now updated to reflect the use of C weighting. However, there is still a need to retain measurement of unweighted peaks for the assessment of the potential for structural damage from the occurrence of an excessive peak overpressure. However, because the GNAT system is now able to measure and record both indices, a feature built into the software is an automated comparison between C and Z weighted levels, as shown in the image below.

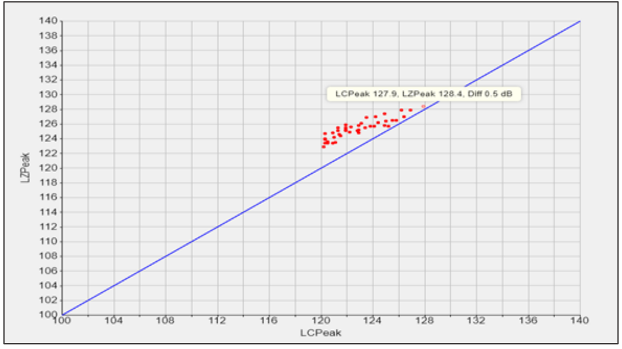


Figure 4 – Showing the difference between L_{ZPeak} and L_{CPeak} noise levels.

The graph shows that the Z weighted levels are generally higher than the C weighted levels. This is because C weighting takes into account the fact that human hearing is less sensitive to low frequencies.

On the topic of frequency weightings, there are continuing challenges in measuring unweighted gunfire noise in windy conditions due to the high levels of low frequency energy also present in wind noise. The initial development of the GNAT system did include extensive tests on advanced signal processing techniques aimed at automating the identification of firing noise events over wind-induced noise events. However, the final solution involved the development of bespoke triple-layer foam windshield systems to reduce as much as possible high pressure fluctuations resulting from the interaction of wind gusts on the measurement systems.

4. MANAGEMENT OF INDUSTRIAL BLAST NOISE

4.1 Major-Hazards Testing at DNV Spadeadam

A recent PhD project at the DNV Spadeadam Testing and Research site in Cumbria, UK, investigated the management and prediction of blast noise. The site is located within the

MOD range, RAF Spadeadam, and conducts major hazards fire, explosion, and blast testing for a variety of sectors, including renewable energy, oil and gas, maritime, and defense. The site's varying topography and ground conditions, combined with diverse meteorology and testing activity, make it difficult to predict environmental noise impacts using current methods.

In addition to the challenges of predicting blast noise through complex transmission environments using computational methods, the operational requirements of the site require predictions to be made much earlier than those required for most military training. Full-scale major hazards trials involve logistical challenges, such as deploying instrumentation, arranging for customers to travel and witness the trials, and deconflicting with RAF activity. These challenges require accurate noise impact predictions several days in advance. DNV and the University of Salford collaborated to implement noise monitoring infrastructure at sensitive residential receptors. As part of this process, a dedicated community engagement program was introduced to manage community noise impacts from DNV's activities. An automated notification system was implemented to alert sensitive receptors to adverse noise impacts, including specific test information and times, which are updated for test delays if necessary.

4.2 Live Monitoring Network (LMN)

In parallel to the GNAT system, a network of web-enabled Class 1 Sound Level Meters was implemented around the Spadeadam site to monitor environmental noise levels at sensitive residential receptors. The network, and an example monitoring unit is shown in Figure 5. A number of 24 Acoustics Intelligent Noise Monitors (INMs) were deployed at the most sensitive receptors based on prevailing weather conditions over the site, and the frequency of complaints from specific geographic areas. The INMs are Raspberry-Pi based systems designed to run continuously on mains power, with the advantage of storing and transferring audio data over 4G for remote human validation of blast noise.

From December 2021 to December 2022, the LMN recorded the peak sound level (L_{ZPeak}) of a variety of industrial blast noise sources at the site. These sources included:

- EDH: Explosive Depth Hardening 5-10kg TNT
- Pad C: Various blast testing 5-100kg TNT
- CVE: Confined Vented Explosion Chamber:
- HYD: Hydrogen detonation : 7kg TNT

Figure 5 - Live Monitoring Network (LMN) of Intelligent Noise Monitors (INM) at Spadeadam. Left: Permanent (red) and supplementary (blue) INM stations. Right: Example of INM unit.

The number of far-field measurements associated with each test type is shown in **Table 1** below.

Table 1 - Measurements of blast events for specific test types carried out at the DNV Spadeadam site.

EDH	Pad C	CVE	HYD	**Total**
857	113	55	27	**1,052**

4.3 Heuristic Predictions

In addition to collecting acoustic data, the LMN also collected measured and forecast meteorological data associated with each test. The following base meteorological parameters were collected:

- Wind Speed and Direction; u, φ
- Temperature; T
- Relative Humidity; RH
- Barametric Pressure; P

Additional parameters, such as cloud cover, gust parameters and surface heat fluxes were collected where available from the services detailed in tables 2 and 3. The measured meteorological data is shown in table 2.

The UK Meteorological Office's DataHub service (MO DataHub) provided forecast data at the time of each test from a number of days ahead. Daily forecasts were collected at 0600Z of 2-D range dependent slices of the atmosphere centered over the Spadeadam site, with a spatial resolution of 2km^2. The aforementioned base meteorological parameters were collected as a minimum to derive effective vertical sound speed profiles and calculate atmospheric absorption. Forecasts of additional parameters such as boundary layer depth and surface fluxes were captured for some time steps. Later in the trials, some longer term forecasts were captured from the ECMWF Atmospheric Model High-resolution 10-

day forecast (ECMWF-10), which has a spatial resolution of 0.1° x 0.1°.

Table 2 - Measured and archived weather data sources used to collect meteorological data for each test event.

Source	Averaging Period	Location
DNV AWS[1]	1 minute	DNV Site (1-2km)
RAF AWS[2]	1 hour	RAF Berry Hill (approx. 2km)
ERA5 Reanalysis data on pressure levels and land[3]	1 hour	Regular Lat-Lon grid at 0.25° x 0.25°

Table 3 - Forecast meteorological data captured for the Spadeadam measurements.

Source	Forecast timesteps (and averaging period)
MO DataHub	0-24 hours (1-hourly)
	51-117 hours (3-hourly)
ECMWF-10	0-144 hours (3-hourly), 150-240 hours (6-hourly).

Extensive monitoring has resulted in a database of measured acoustical data and large quantities of measured and forecast meteorological data. An evaluation of the performance of an existing heuristic prediction model, the SSW model from [1], was performed on longitudinal data gathered by the LMN. The model's ability to predict impacts from industrial operations beyond its development scope was presented in [11]. This work found that up to 5 days ahead of testing, the SSW model had root-mean-square errors for receivers at a range of 4-14km of approximately 10dB for EDH and Pad C explosions and approximately 7.5dB for CVE and HYD associated with hazard awareness training. However, large over and under predictions (>30dB) occurred when validating the model on operations beyond its development scope, such as predicting impacts from charge sizes below 1kg TNT. Additionally, the significantly smaller sample size for hazard awareness and Pad C activity limited the analysis to a smaller set of propagation scenarios. The extensive data gathered at Spadeadam presents an opportunity to develop new prediction tools for industrial blast noise.

5. CONCLUSIONS

This paper presents a thorough review of scientific literature and fieldwork on blast noise in the UK. Our extensive fieldwork led to the development of rapid noise management tools and advanced noise prediction models. The GNAT and LMN monitoring systems were significant in managing environmental blast noise by combining long-term measurements and meteorological records with prediction methods. Results show that on-site procedures and best practices are most effective in managing environmental impacts. We recommend future research focus on improving prediction models. Combining blast noise management tools with community engagement strategies and exploring new technologies to control noise generation should also be prioritized. Overall, this paper provides valuable insights and practical recommendations for managing environmental impacts from blast noise sources.

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