



UNIVERSITY OF LEEDS

This is a repository copy of *Large-scale trials of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup*.

White Rose Research Online URL for this paper:
<http://eprints.whiterose.ac.uk/107318/>

Version: Accepted Version

Proceedings Paper:

Hunter, TN, Cowell, DMJ, Carpenter, T orcid.org/0000-0001-5676-1739 et al. (6 more authors) (2016) Large-scale trials of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup. In: IEEE International Conference on ultrasonics. International Ultrasonics Symposium, 18-21 Sep 2016, Tours, France. IEEE . ISBN 978-1-4673-9897-8

<https://doi.org/10.1109/ULTSYM.2016.7728870>

Reuse

Unless indicated otherwise, fulltext items are protected by copyright with all rights reserved. The copyright exception in section 29 of the Copyright, Designs and Patents Act 1988 allows the making of a single copy solely for the purpose of non-commercial research or private study within the limits of fair dealing. The publisher or other rights-holder may allow further reproduction and re-use of this version - refer to the White Rose Research Online record for this item. Where records identify the publisher as the copyright holder, users can verify any specific terms of use on the publisher's website.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.



eprints@whiterose.ac.uk
<https://eprints.whiterose.ac.uk/>

Large-scale trials of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup

David M. J. Cowell, Thomas Carpenter, Steven Freear
School of Electronic and Electrical Engineering,
University of Leeds, Leeds, United Kingdom
d.m.j.cowell@leeds.ac.uk

Jeff Peakall
School of Earth and Environment,
University of Leeds, Leeds, United Kingdom

Hugh P. Rice, Alastair Tonge, Michael Fairweather
Timothy N. Hunter
School of Chemical and Process Engineering,
University of Leeds, Leeds, United Kingdom

Martyn Barnes
Sellafield Ltd, Warrington, United Kingdom

Abstract— Real time *in situ* characterisation of solids concentration would aid operational understanding and improve efficiency in many industrial systems. This is especially true in the processing of legacy nuclear wastes where hazardous material is encountered. Acoustic methods have been previously demonstrated for the measurement of concentration in solid-liquid systems at a small scale. This study explores the use of the ultrasound array research platform (UARP) for backscatter measurements of concentration at a large scale in a dynamic settling system. The theory of acoustic measurement of solids concentration is described for both backscatter based attenuation and backscatter power methods. Acoustic based backscatter power and attenuation measurements are compared to laboratory analysed samples. Ultrasonic solids concentration analysis is shown to reveal flow dynamics within the settling tank.

Keywords— acoustic backscatter, solids concentration measurement, *in situ* characterisation, industrial measurement

I. INTRODUCTION

There are many industrial solid-liquid separation systems, such as clarifiers and thickeners, where measurement of solids concentration levels would aid operational understanding and highlight performance issues [1]. The processing of legacy nuclear wastes (which are often in the form of particle in liquid sludges) is a particular area of concern, due to radiation greatly limiting any interference with process units. In terms of the UK nuclear industry, projected lifetime cost of decommissioning at Sellafield is estimated at ~£67.5bn according to a UK National Audit Office report of 2012 [2], of which the treatment of intermediate-level and high-level wastes are expected to comprise over 50% of short to medium term costs. Hence, there is a significant need for a remote instrument system to monitor sludge levels in nuclear solid-liquid separators, with the ability for real-time feedback to enhance process optimisation.

Previous research has highlighted the potential of ultrasonic backscatter and transmission systems as *in situ* techniques to

measure batch-scale sediment settling [3-6] and pipe flow segregation [7, 8]; although to date such systems have not generally been applied to industrial environments. This research however, seeks to investigate a large-scale application of an acoustic backscatter system as a solids concentration profiler. Specifically, a new ultrasonic instrument has been developed that allows particulate levels and consolidation to be visualized in real-time from the backscatter echo signal [9].

In this work, a large continual flow clarifier was utilized, which represented a close to full-scale non-active model of an on-site nuclear waste separator at Sellafield, UK. An array of 2.25 MHz immersion transducers were positioned to cover the whole depth of the clarifier, with the strength of the backscattered return echo used to estimate particle levels in comparison to extracted samples, via two different calibration methods.

II. MEASUREMENT PRINCIPLE

The standard expression for the instantaneous voltage of a received backscattered echo, due to a mass concentration, M_w , of suspended particles is shown in Eq. 1 [10]:

$$V_{\text{rms}} = \frac{k_s k_t}{\psi r} M_w^{\frac{1}{2}} e^{-2r(\alpha_w + \alpha_s)} \quad (1)$$

where r is distance from the transducer face, k_s is a particle species dependent backscatter co-efficient, k_t is the transducer constant, a system dependent parameter, ψ , the near field correction factor, while α_w and α_s are the attenuation coefficients of water and the suspended particles respectively.

Rice *et al.* [11] devised a linearized expression for measuring the attenuation coefficient of particle species, known as the *G-function*, as given in Eq. 2:

$$G = \ln(\psi r V_{\text{rms}}) = \ln(k_s k_t) + \frac{1}{2} \ln M_w - 2r(\alpha_w + \alpha_s) \quad (2)$$

Taking the derivative of G with respect to distance, r , allows the definition of the sediment attenuation coefficient, α_s from the gradient slope, as shown in Eq. 3.

$$\frac{\partial G}{\partial r} = -2(\alpha_w + \alpha_s) \quad (3)$$

where the attenuation constant of water, α_w , is constant for a particular frequency and temperature.

The gradient slope (dG/dr) should be a constant value for any systems with a constant dispersion concentration, and its measurement represents a convenient way of correlating particle levels *in situ*.

Alternatively, the backscatter power can also be measured, by integrating the received echo voltage across a depth segment, assuming a greater number of particles will lead to an enhanced backscattered response.

III. HARDWARE DESIGN

A custom ultrasound instrumentation system has been developed and used throughout this study [9] tailored to the technical requirements of eventual deployment in a real-world nuclear or industrial environment as shown in Figure 1. The instrumentation is based around the University of Leeds Ultrasound Array Research Platform (UARP), a flexible modular system designed for the development of novel ultrasound techniques. The UARP modules are built around an Altera Stratix V FPGA and feature commercial off the shelf (COTS) transmit and receive front end integrated circuits.

Transducer excitation is based around five level switched mode excitation at $\pm 100V$, $\pm 50V$ and ground. Arbitrary excitation can be emulated using switched mode excitation in conjunction with harmonic reduction pulse width modulation (HRPWM) [12-16] allowing excitation parameters to be tailored to the measurement, for example frequency modulation, amplitude control and temporal windowing.

The receive path is based around integrated analog front end (AFE) integrated circuits, combining multi-stage amplification, filtering and analog to digital conversion. High speed serial digital data is received by the FPGA and stored in local memory.

System control is performed from Matlab based software where received data is automatically downloaded. Real time data is shown for operator feedback and all raw data is archived for enhanced offline processing.



Fig. 1. Custom built, 16 channel ultrasound array research platform (UARP II) for the characterisation of suspensions through acoustic backscatter.

IV. MATERIALS & METHODS

Flocculated calcium carbonate was used as a non-active legacy sludge analogue in the clarifier settling trials. It is noted that this system is also a common reference material for minerals processing suspensions, and thus results could be correlated to previous research [17-19]. The calcite used was *Omycarb 2* (Omya Industries) with a mean size of $\sim 5 \mu\text{m}$, while the flocculant was a large molecular weight, medium charge density anionic polymer, *AN934SH* (SNF Chemicals Ltd). This particle-polymer system has previously been separated successfully in mineral thickener trials [18].

Large-scale, non-active sludge settling trials were conducted at NSG Environmental in Chorley, UK. A bespoke 9 m^3 settling corral was built, approximately 4.8 m in length, 2.5 m liquid depth and 0.75 m wide, with a baffled inlet offset by 0.5 m to create a separate homogenous mixing zone. Non-flocculated calcite was continuously pumped to the clarifier at a concentration of approximately 30 g/l, with feed rate set at 80 l/min. A line injection port was positioned 5 m from the tank inlet, where polymer was introduced from a 2000 ppm stock at such a rate to give a diluted feed concentration of 6 ppm. An image of the corral is shown in Fig. 2.



Fig. 2. Photograph of 9 m^3 settling corral used for trials.

For the conducted trials, seven channels on the UARP were employed, connected by 8 m long cables to a vertical acoustic backscatter array (ABA). The ABA was an aluminium frame, with probes positioned at 20° to the vertical in designed holders, 20 cm apart. The utilised transducers were 0.25 inch immersion type (V323, Olympus NDT) with a central frequency of 2.25 MHz. Excitation was performed at frequencies of 2.0, 2.25 and 2.5 MHz using 5 μs Hann windowed tone bursts. Each channel was configured to record the return pulse voltage to a maximum depth of 300 mm. In total, 10,000 received waveforms were collected for each excitation setting and stored for post-processing.

Five evenly spaced locations along the settling section of the corral were chosen to measure concentration, both by sampling and through the mounted ABA connected to the UARP. For sampling, extractions were made at five depths (of 27, 47, 67, 107 and 177 cm from the tank base). These depths were also correlated to positions of five of the acoustic transducers. Concentration measurements were made at five distinct time regimes from trial initiation, beginning at 30 minutes from the start and then at regular 50 minute intervals.

V. RESULTS AND DISCUSSION

Two different empirical correlations were used to back calibrate the performance of the UARP in measuring the solids-concentration profiles along the tank at different times. The 10,000 back scattered echo signals received from each of the 7 ABA mounted probes at each of the 5 time intervals were firstly processed within Matlab to produce the root mean square echo amplitude for each time point. The average *G-function* gradient (dG/dr) over a distance of 5 – 25 cm (ignoring the near field) was then calculated for each profile. These values were then compared to corresponding sampled concentrations, with the overall relationship shown in Fig. 3. Alternatively, the backscatter power was extracted for each profile at each time, by integrating the returned backscatter voltage over the same profile distance. Again, these values were calibrated with the measured sample values, and are shown in Fig. 4.

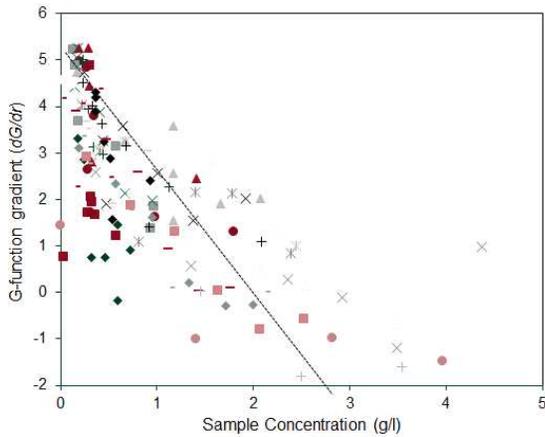


Fig. 3. Correlation between *G-function* gradient and sample concentrations from all large-scale trial data. Dotted line represents linear interpolation.

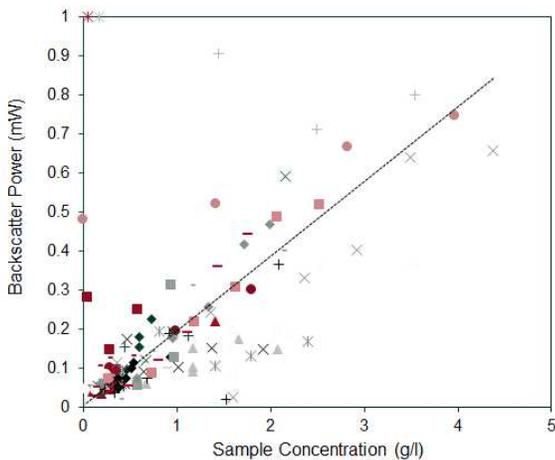


Fig. 4. Correlation between backscatter power and sample concentration from all large-scale trial data. Dotted line represents linear interpolation.

It is fairly evident from examination of Fig. 3 and Fig. 4 that the averaged backscatter power appears to be a more accurate correlation to particle concentration than the *G-function* method for the trial data. It is likely that the main reason for the relatively poor fit of the *G-function* data is the low particle concentrations in the corral. While the feed concentration was 30 g/l, most of the flocculated particles settled very rapidly within the first metre of the clarifier, owing to their large size. Residual particle levels within the bulk of the suspension were largely < 6 g/l, as measured by sampling. Because the *G-function* approach is effectively a measure of suspension attenuation, it will only be accurate in suspensions that do attenuate to a relatively high degree, which generally would be at concentrations > 10 g/l [20].

It is important to note another potential caveat between sampled data and acoustical analysis. While the *G-function* and backscatter power measurements represent distance profile averages of 5 – 25 cm, samples were extractions at single points in the middle of each transducer range. Hence, some degree of variation would be expected if there is significant particle segregation within each sample zone.

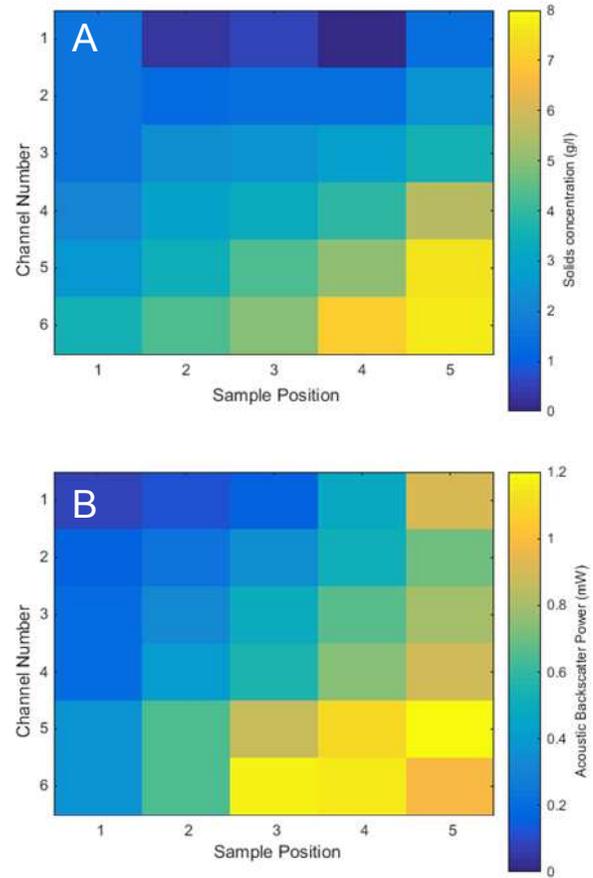


Fig. 5. Interpolated colour plots across the corral at T +230 mins, showing laboratory measured sample concentrations (A) and backscatter power (B).

Using backscatter power as the correlation method with higher accuracy, a more in-depth analysis was investigated to better profile concentration differences along the clarifier. An interpolated colour plot was generated from the backscatter power data for the final time profiles (at T +230 mins) representing values from the top 6 transducers at different depths and five array locations along the corral. The backscatter power data is compared to the corresponding depthwise samples interpolated in the same way in Fig. 5.

Both interpolated samples and backscatter power values highlight an interesting increase in particle levels at the far side of the corral (closer to the outlet) especially at deeper levels. While this result appears slightly counter intuitive, it is assumed that the main reason for this behaviour was recirculation currents within the clarifier. In fact, visual inspection of the tank appeared to correlate with these results, with evidence for a standing current forming, upturning fluid from the end of the clarifier and reversing it back towards the inlet, lifting the suspension upwards at the outlet. The fact that the UARP could measure such dynamic changes in real time, shows its potential as a remote monitoring device for large-scale sludge separation applications [1].

VI. CONCLUSIONS

This paper has presented application of an ultrasound array research platform (UARP) as a concentration profiler in a large-scale clarifier, simulating a real on-site nuclear waste corral. Two methods were used to analyse the backscatter voltage from the acoustic array for solids levels, with the backscatter power proving most accurate for the lower concentrations within the tank. Interpolated colour plots of extracted samples and the backscatter power at the final measurement time, highlighted an enhancement to suspension levels at the clarifier outlet, due to standing recirculating currents.

Collectively, results from these trials proved that the UARP was highly effective in characterising complex and dynamic flocculated suspension systems, of relevance to many industrial systems. It is hoped that these remote monitoring systems will ultimately be applied not only to nuclear waste processing, but more generally to solid-liquid separation operations, such as those found in water treatment and minerals processing.

ACKNOWLEDGMENT

The authors gratefully acknowledge the funding of this work from the Nuclear Decommissioning Authority (NDA), Innovate UK (formally the Technology Strategy Board), the Engineering and Physical Sciences Research Council (EPSRC) and Sellafeld Ltd. Great thanks are also given to NSG Environmental Ltd, especially Thomas Hurst and Fraser Hardy, for help in conduction of the large-scale clarifier trials.

REFERENCES

- [1] G. Olsson, "ICA and me - A subjective review," *Water Research*, vol. 46, pp. 1585-1624, 2012.
- [2] "Managing risk reduction at Sellafeld," National Decommissioning Authority - National Audit Office Report, November 2012.
- [3] J. Bux, J. Peakall, S. Biggs, and T. N. Hunter, "In situ characterisation of a concentrated colloidal titanium dioxide settling suspension and associated bed development: Application of an acoustic backscatter system," *Powder Technology*, vol. 284, pp. 530-540, 11/ 2015.
- [4] A. Deboeuf, G. Gauthier, J. Martin, and D. Salin, "Segregation and periodic mixing in a fluidized bidisperse suspension," *New Journal of Physics*, vol. 13, p. 075005, 2011.
- [5] T. N. Hunter, J. Peakall, and S. Biggs, "An acoustic backscatter system for *in situ* concentration profiling of settling flocculated dispersions," *Minerals Engineering*, vol. 27-28, pp. 20-27, 2012.
- [6] Z. Xian-jian, M. Zhi-min, Z. Xiao-hong, H. Xiang-yang, and T. Wei-liang, "B-scan ultrasound imaging measurement of suspended sediment concentration and its vertical distribution," *Measurement Science and Technology*, vol. 25, p. 115303, 2014.
- [7] H. P. Rice, M. Fairweather, J. Peakall, T. N. Hunter, B. Mahmoud, and S. R. Biggs, "Measurement of particle concentration in horizontal, multiphase pipe flow using acoustic methods: Limiting concentration and the effect of attenuation," *Chemical Engineering Science*, vol. 126, pp. 745-758, 4/14/ 2015.
- [8] J. F. Stener, J. E. Carlson, A. Sand, and B. I. Pålsson, "Monitoring mineral slurry flow using pulse-echo ultrasound," *Flow Measurement and Instrumentation*, vol. 50, pp. 135-146, 8// 2016.
- [9] D. M. J. Cowell, S. Freear, J. Peakall, I. Smith, H. P. Rice, T. N. Hunter, *et al.*, "Development of a real-time acoustic backscatter system for solids concentration measurement during nuclear waste cleanup," in *Ultrasonics Symposium (IUS), 2015 IEEE International*, 2015, pp. 1-4.
- [10] P. D. Thorne and D. M. Hanes, "A review of acoustic measurement of small-scale sediment processes," *Continental Shelf Research*, vol. 22, pp. 603-632, 2002.
- [11] H. P. Rice, M. Fairweather, T. N. Hunter, B. Mahmoud, S. Biggs, and J. Peakall, "Measuring particle concentration in multiphase pipe flow using acoustic backscatter: Generalization of the dual-frequency inversion method," *The Journal of the Acoustical Society of America*, vol. 136, pp. 156-169, 2014.
- [12] D. M. J. Cowell, T. Carpenter, P. Smith, C. Adams, S. Harput, and S. Freear, "Performance of Switched Mode Arbitrary Excitation using Harmonic Reduction Pulse Width Modulation (HRPWM) in Array Imaging Applications," in *Ultrasonics Symposium (IUS), 2016 IEEE International*, 2016, pp. 1-4.
- [13] D. Cowell, P. Smith, S. Harput, J. McLaughlan, and S. Freear, "Non-linear harmonic reduction pulse width modulation (HRPWM) for the arbitrary control of transducer-integrated switched excitation electronics," in *2014 IEEE International Ultrasonics Symposium*, 2014, pp. 807-810.
- [14] D. M. J. Cowell, S. Harput, and S. Freear, "Arbitrary waveform generation based on phase and amplitude synthesis for switched mode excitation of ultrasound imaging arrays," in *Ultrasonics Symposium (IUS), 2015 IEEE International*, 2015, pp. 1-4.
- [15] D. M. J. Cowell, P. R. Smith, and S. Freear, "Phase-inversion-based selective harmonic elimination (PI-SHE) in multi-level switched-mode tone- and frequency- modulated excitation," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, pp. 1084-1097, 2013.
- [16] P. R. Smith, D. M. J. Cowell, and S. Freear, "Width-modulated square-wave pulses for ultrasound applications," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 60, pp. 2244-2256, 2013.
- [17] A. F. Grabsch, P. D. Fawell, S. J. Adkins, and A. Beveridge, "The impact of achieving a higher aggregate density on polymer-bridging flocculation," *International Journal of Mineral Processing*, vol. 124, pp. 83-94, 2013.
- [18] T. N. Hunter, S. P. Usher, S. Biggs, P. J. Scales, A. Stickland, D., and G. V. Franks, "Characterization of Bed Densification in a Laboratory Scale Thickener, by Novel Application of an Acoustic Backscatter System," *Procedia Engineering*, vol. 102, pp. 85-866, 2015.
- [19] B. B. G. van Deventer, S. P. Usher, A. Kumar, M. Rudman, and P. J. Scales, "Aggregate densification and batch settling," *Chemical Engineering Journal*, vol. 171, pp. 141-151, 2011.
- [20] T. N. Hunter, L. Darlison, J. Peakall, and S. Biggs, "Using a multi-frequency acoustic backscatter system as an *in situ* high concentration dispersion monitor," *Chemical Engineering Science*, vol. 80, pp. 409-418, 2012.