SAMPLED DATA SPECTROSCOPY (SDS): A NEW TECHNOLOGY FOR RADIATION INSTRUMENTATION

D. Mackenzie C. Odell
Westinghouse Savannah River Company
Savannah River Technology Center, Bldg. 773-A
Aiken, SC 29808

ABSTRACT

A new instrumentation architecture for radiation spectroscopy is in the early stages of development at Savannah River. Based upon the same digital sampling techniques used in sonar and radar, sampled data spectroscopy (SDS) has produced Na(I)/PMT spectra with resolution comparable to conventional PHA systems. This work has laid the foundation for extending SDS techniques to solid state detector applications as well. Two-dimensional SDS processes raw, nonintegrated detector output pulses to produce both energy and shape information that is used to construct a conventional energy spectrum. System advantages include zero electronic dead time to support very high count rates, elimination of pulse pile-up peaks, high noise immunity, and digital system stability and reliability. Small size and low power requirements make 2-D SDS an ideal technology for portable instrumentation and remote monitoring applications. Applications of potential interest at Savannah River include on-the-spot spill analysis, real-time waste stream monitoring, and personnel and area monitoring below background levels.

A three-dimensional sampled data architecture is also being developed. Relying on image analysis and enhancement techniques, 3-D SDS identifies spectral peaks without determining the energy of any individual detector pulses. These techniques also open up a new avenue of exploration for reducing or removing Compton effects from the spectra of single detector systems. The intended application for this technique is waste characterization where lower energy isotopes are often obscured by the Compton scattering from dominant isotopes such as Cs137.

CONVENTIONAL VS. SAMPLED DATA SPECTROSCOPY

Understanding how sampled data techniques apply to radiation spectroscopy requires that the basics of conventional spectroscopy be briefly reviewed. Although this may seem trivial, it is necessary because the two technologies diverge very early in the process of acquiring data.

In conventional pulse height analysis (PHA), the detector is operated in the pulse mode and its output current is integrated in the preamplifier to produce a long tail pulse. That pulse is fed to successive analog electronics modules so that its peak value can eventually be converted by an ADC to a single, high resolution digital value. A basic assumption in such a system is that all of the energy deposited in the detector should be collected. This concept of fully collecting the detector's output current in an integrating stage (generally referred to as "full charge collection") is the heart of detector interfaces for nearly all energy spectroscopy systems. While beneficial to energy resolution, full charge collection removes a significant amount of useful information from the overall PHA system. Pulse shape details are lost which can reveal the presence of a noise spike or close pulse pile-up conditions. The result is that these undesirable events are indistinguishable from legitimate detector events and are erroneously included as counts in the output spectrum.

In addition to its direct effects on the spectrum content, full charge collection carries additional penalties because of its reliance on a single A/D conversion for energy determination. Chief among these are (1) the number of analog electronics stages required to prepare the detector output for conversion at the ADC, and (2) the dead-time contributions of some of these analog stages and the ADC itself. The number of analog stages directly affects the susceptibility of the system to drift with time and temperature. Added to this drift is the necessity of fine-tuning the stages to the count rate and resolution requirements, often making compromises in both. The dead-time is somewhat controllable through pulse shaping choices and careful selection of an ADC, but, again, resolution and count rate must be balanced. High resolution systems are routinely assembled, but they can be difficult to keep calibrated.

Sampled data spectroscopy (both 2-D and 3-D) departs completely from the concept of full charge collection. Instead of integrating the detector's output pulses, SDS processes the short, raw detector output pulse directly. The pulse is amplified and fed immediately to a free-running A/D converter which takes many samples of the instantaneous value of the detector current during the period of the pulse. No further analog processing is required, and the information contained in the high speed stream of digital samples is now available for simultaneous energy determination and shape analysis by paralleled digital processing elements. Figure 1 compares the conventional processing of a detector pulse with sampled data processing of that same pulse. At time t0, an event occurs in the detector and an output current begins to flow. Trace B shows the shape of the raw detector pulse, while trace A shows the conventional integration of the raw pulse from t0 to t1. At time t1, the raw pulse is completed, corresponding to the peak of trace A. During the interval from t0 to t1, the sampled data system has taken a number of amplitude readings in rapid succession (represented by the vertical lines spaced at equal intervals). If (as in 2-D SDS) those readings are integrated by a digital integrator as they are acquired, then the energy value for the pulse has been calculated by t1 and is immediately available for MCA use. Conventional processing in trace A continues beyond t1 as indicated by the Gaussian-shaped pulse produced by the shaping amplifier. The ADC begins its conversion of the shaped pulse's amplitude at t2 and

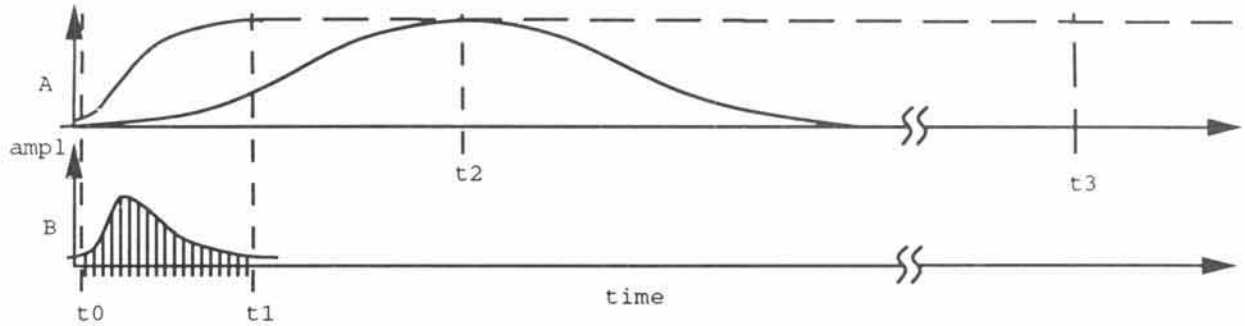

Fig. 1. Conventional (A) and sampled data (B) pulse processing.

completes that process by time t3. At t3, the resulting digital value is ready for normal MCA use. The dead-time for the conventional system in trace A is the full interval from t0 to t3. If a second detector event were to occur between t0 and t1, then the conventional system would not be able to discern that event from the first one and would simply deal with the combination as a higher energy pulse. If, however, a second pulse occurred between t0 and t1 in the 2-D sampled data system, a distinctly different pulse shape would result which could be detected in real-time by a digital shape defect processor. The system could then determine not to include that pulse as a legitimate count in the spectrum.

SAMPLED DATA TECHNICAL CONSIDERATIONS

Several questions about the 2-D sampled data system need to be answered. What determines the resolution of its output? What are the resolution limits? What are the overall limitations of this technology?

Output Resolution and Its Limits

When considering the output resolution and its limits, three factors are important: the number of samples taken per unit time, the amplitude resolution of the individual samples, and the algorithms used to produce an energy value. Consider first the number of samples taken. At the upper limit, an infinite number of samples could be taken at infinite amplitude resolution. The area under the curve would be precisely known because a simple summation would yield a perfect integration. The lower limit is a bit less obvious, but it is governed by the Nyquist criteria commonly used in digital sampling applications. By taking samples at a frequency that is at least twice the highest frequency component of the pulses (usually dictated by the rise time), no undetectable variances in pulse shape could occur. Using a simple method such as trapezoidal integration to calculate the area under curve, reasonable energy results can be obtained. Sampling at even higher frequencies improves the trapezoidal approximation to the exact integral, so it is desirable to do so. Here, the practical limit is governed by available technology in A/D converters and digital processing. The fastest sampling rate used to date in this development has been 1 billion samples per second (1 GSPS), a rate which appears sufficient for use even with solid state detectors.

Besides its dependency on sampling rate, a sampled data system is also dependent upon the number of bits of vertical or amplitude resolution available. Typical ADC's for PHA provide up to 16K channels, or 14 bits of energy resolution to make the single result per pulse as accurate as possible. SDS relies on lower resolution A/D converters operating at up to 1 GSPS to take many samples per pulse. Given an ideal 8-bit converter, amplitudes could be accurately sampled within 1 part in 255 or 0.4% of full scale. Converters are not, however, ideal, so the real amplitude resolution limit is heavily dependent on the converter chosen and the means used to sample the detector pulse. While real world components may not produce research grade resolution, utility grade spectroscopy is possible, such as might be useful in spill or waste stream monitoring, as well as in area and personnel monitoring.

The third dominant factor in the resolution of 2-D SDS systems is the algorithm used to calculate the energy of the sampled pulses. Trapezoidal integration was mentioned briefly, but other algorithms are also possible. The tradeoffs come between speed of calculation and the accuracy of the integration. For detectors with consistent pulse shape characteristics (e.g., scintillator/PMT), algorithms tailored to specific shape characteristics might yield high accuracy results from a minimum number of samples. Other detectors (e.g., solid state) require higher sampling rates since pulse shapes are inconsistent due to charge collection variations. With a sufficiently high sampling rate, trapezoidal approximation appears to be adequate.

Limitations

From the foregoing discussion, some of the disadvantages or limitations of SDS can also be seen. The most obvious of these is the resolution of the A/D converter itself. With only 8-bit resolution and a significant number of pulse samples well below half of the full-scale input range of the A/D, the real resolution of many samples is 1% or worse. While more than 8 bits would be preferable, there are very few A/D converters with higher resolution at the speeds required for SDS. The fastest available parts operate at about 300 million samples per second (MSPS) at 8 bits, 75 MSPS at 10 bits, and 30 MSPS at 12 bits. It is anticipated that at least 10 bits will be required at a sampling rate of at least 200 MSPS to take advantage of the inherent resolution of solid state detectors. Sampling rates as high as 1 GSPS may be necessary in some applications.

Another limitation to 2-D SDS is the problem of handling digital data at very high rates. For example, if reasonable resolution for a scintillator system requires that the 8-bit sampling system operate at 50 MSPS, the free-running A/D converter generates 50 megabytes per second of raw data. In the case of a germanium detector, the pulse width is narrower, and if the data rate is as high as 1 billion samples per second (GSPS), custom or semi-custom integrated circuits must be developed to handle the data stream.

With these limitations, how does one explore the technology without risking large amounts of development time and money?

PROOF-OF-CONCEPT SYSTEM

To define the amplitude and time resolution requirements for a prototype, a proof-of-concept system was assembled, using a digital oscilloscope as the primary component. Digital storage oscilloscopes have been available for a number of years, but the 54510A sampling oscilloscope from Hewlett-Packard uniquely meets the need. With 8-bit sampling at up to 1 GSPS, large internal RAM memory, a GPIB computer interface, and a "raw digitizing" mode of operation, radiation detector data can be acquired in sufficient quantities to emulate the operation of a SDS system. The oscilloscope was interfaced to an IBM AT using an HP GPIB card and controlled by an application program supplied by HP and modified for SDS data collection. The complete system cost less than $15K to assemble, and it is programmed in C.

This proof-of-concept system has been used to take data from a Bicron Na(I) scintillator/PMT detector as well as from an Ortec HPGe germanium detector. The spectra presented here are from the scintillator system, since a non-integrating timing preamplifier was not available for use with the germanium detector.

Although the proof-of-concept system permits experimentation at very high sampling rates, it has one distinct limitation. Because of how it acquires and stores its samples, it ironically has considerable system dead-time! When taking low resolution data, it is capable of acquiring approximately 1000 detector pulses per second; at the highest resolutions, that number is reduced to well under 100 pulses per second. There is, however, a benefit which tends to offset the inconvenience of long collection times: data taken at high resolution can be analyzed as low resolution data, too. The advantage here is that the very same spectrum can be studied for time resolution effects without the statistical variation normally encountered when counting the same source multiple times. The same holds true for algorithm development: the same data can be re-used many times in various ways to see concrete differences without the statistical variations. Once a series of detector pulses has been digitized and saved to disk, it can be used as often as necessary. An added bonus is that the proof-of-concept system can be used directly for very low count rate applications, even for solid state detectors. All of the pulses captured can be either processed for energy values and shape distinctions or stored for later retrieval and examination.

TWO-DIMENSIONAL SDS RESULTS

Scintillator/PMT Results

The term "two dimensional" refers to the form of the output spectrum, by convention a plot of counts versus energy. In 2-D SDS, the samples from individual detector pulses are numerically integrated to obtain the same energy value that would be measured in a conventional system by integrating the detector output on a capacitor. These individual pulse energies are then binned as they would be in conventional PHA. The primary performance advantage over conventional PHA techniques is that pulses of suspect shape (noise, pile-up, etc.) can be filtered out of the spectrum. Figure 2 compares Cs137 spectral results obtained from the same Bicron 802-4W scintillation detector using a conventional PHA system and the proof-of-concept SDS system.

The conventional system elements included a Canberra 2007P preamplifier, Ortec 451 amplifier, Ortec 456 high voltage supply, the Nucleus PCA 2000 MCA board, and version 2.11 of the PCA II software. The SDS system included a Canberra 2007 preamplifier, the Ortec 456 supply, a Hewlett-Packard 54510A digital sampling oscilloscope, and custom software for data capture and reduction. The plots shown in Fig. 2 were made using Canberra's MCAE S100 emulator software, which was also used to calculate peak resolution. Plot A is the PCA reference against which the two SDS plots are compared. Plot B is a "normal" SDS spectrum, taken at an equivalent sample rate of 33 MSPS with 8-bit amplitude resolution. Plot C is the same data, but with a deliberate synchronizing of the data samples to the leading edge of the detector pulses. Table I compares the peak analysis results of the three plots.

The resolution on the 662 keV peak with the conventional system is 6.5%; with the "normal" SDS system, it broadens slightly to 6.9%. The "synchronized" SDS resolution is 6.4%, the difference being that the normal variation in time between the actual leading edge of the pulse and the first sample has been reduced from approximately a 30 nanosecond window to a 2 nanosecond window. The point of this comparison is to show the effect of time resolution on peak resolution, independent of the 8-bit amplitude resolution. Table II further illustrates the effects of time resolution on peak resolution by displaying the results of analyzing the same data at different effective sampling rates.

TABLE I
Peak Resolution Comparison

MCA Type	ROI	Centroid Channel	FWHM Chan.	Resol. %
Nucleus PCA:	1	12.34	3.99	32.3
	2	31.96	4.75	14.9
	3	210.57	13.62	6.5
SDS, 33 MSPS:	1	7.19	1.11	15.4
(normal)	2	25.51	4.48	17.6
	3	223.94	15.50	6.9
SDS, 33 MSPS:	1	13.56	3.14	23.2
(sync)	2	30.97	6.14	19.8
	3	223.54	14.22	6.4

TABLE II
SDS Resolution vs. Sample Rate

Sampline MSPS	Centroid Channel	FWHM Chan.	Resol. %
100	223.65	15.71	7.0
50	223.94	15.55	6.9
33	223.94	15.50	6.9
25	223.63	15.92	7.1
20	223.58	17.81	8.0
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14	227.46	30.02	13
12	227.16	30.99	14
10	225.46	39.73	18

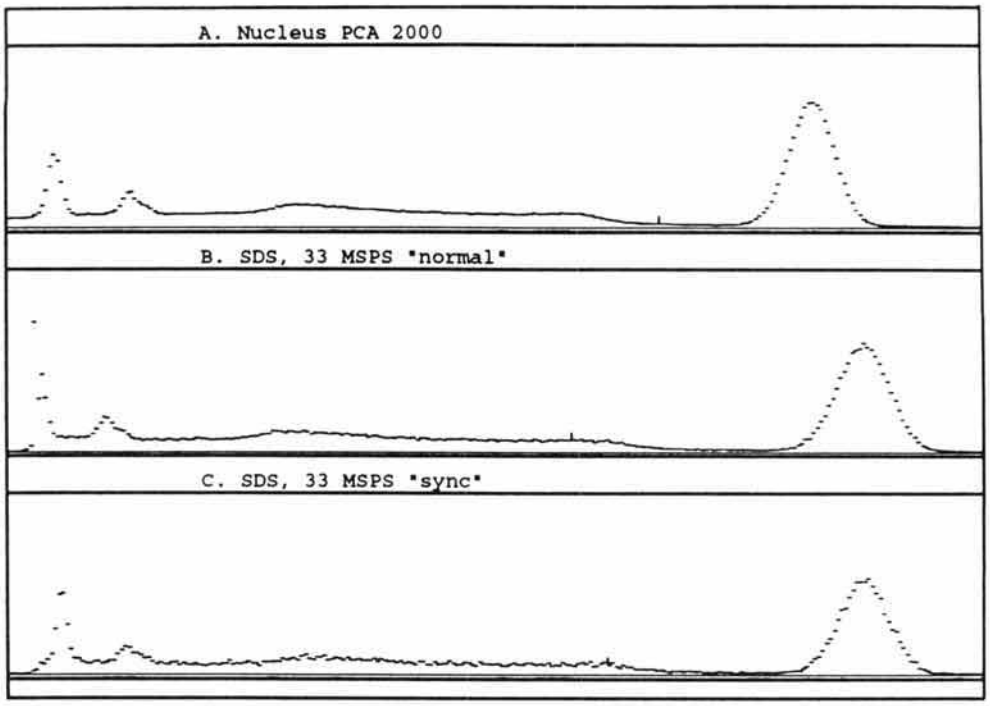

Fig. 2. Comparative spectral plots.

Dropping from 100 MSPS to 50 MSPS, no broadening is seen. Below 50 MSPS, however, the time resolution effects begin to emerge, until at 10 MSPS, the system has broadened the inherent resolution of the detector by nearly a factor of three. At 10 MSPS no useful improvement would be seen even if the 8-bit A/D converter were replaced by a 12-bit device; the problem is strictly one of adequate sampling rate and the leading-edge to first-sample time variations. Above 25 MSPS, however, the conclusion is that an 8-bit converter is adequate for achieving results comparable to conventional PHA systems using Na(I)/PMT detectors. As in conventional systems, however, higher amplitude resolution (10 or 12 bits) makes the peak resolution less susceptible to gain settings. Failure to set the gain to use the full input voltage range of the 8-bit converter does cause peak broadening, just as with conventional ADC's.

Another conclusion that can be drawn from the data is that the pulse shape consistency of these one microsecond timing pulses is quite high and just as representative of event energy as the much longer integrated tail pulses from conventional preamplifiers. By using this raw, short pulse, the analog electronics have been reduced to a simple resistor-capacitor filter network (the timing preamplifier) and a variable-gain linear amplifier (the oscilloscope input amp). All of the routine problems associated with selecting shaping time constants, baseline restoration, dead time correction, and fine-tuning from stage to stage are eliminated. At the same time, the useful count rate of the detector is extended to at least 100,000 counts per second without dead time losses or pile-up errors. This advantage can be exploited by reducing the amount of detector shielding required, making it more practical to do spectroscopy in confined spaces, such as along waste tank walls or between primary and secondary containment vessels.

Solid State Detector Results

To date, only limited exploratory work has been done with solid state detectors. Figure 3 shows only the rise time portion of a number of sampled tail pulses from an Ortec HPGe detector.

Ballistic deficit is easily seen in the contrast between the rapid rise times of some of the pulses and the slower, more rippled rise times of other pulses. While their tails converge (indicating that they are of the same energy level), the vertical width of the "band" that they form is clearly wider than just the band of the rapid rise time pulses alone. In a multiple isotope sample, these bands appear at various levels indicating different energies. Crude PHA can be done on samples taken at the point in the pulse waveforms just past the merging of the various rise times. In order to achieve comparable resolution to conventional systems, however, a SDS system will require a non-integrating preamplifier and a very high rate digitizer. A solid state detector system requires significantly higher sample rates due to several factors. First, the raw pulse lengths are shorter, implying that higher frequencies must be dealt with. Second, the rise time on non-integrated pulses are considerably shorter than with the scintillator/PMT combination, again indicating higher frequency content. Third, there are variations in the charge collection rate due to the non-uniformity of the device itself. The highest frequency component (which dictates the Nyquist sampling frequency) will likely be determined by either the "ripple" effects of multiple deposition captures on the charge collection rate or the rise time of the fastest pulses. Frequency components on the order of 100 MHz or more are possible, although the detector's own internal capacitance and resistance form a limiting filter. If no components exceed 100 MHz, sampling as low as 200 MSPS may be adequate. Matching the energy resolution of the detector, however, may require higher rates for accurate numerical integration.

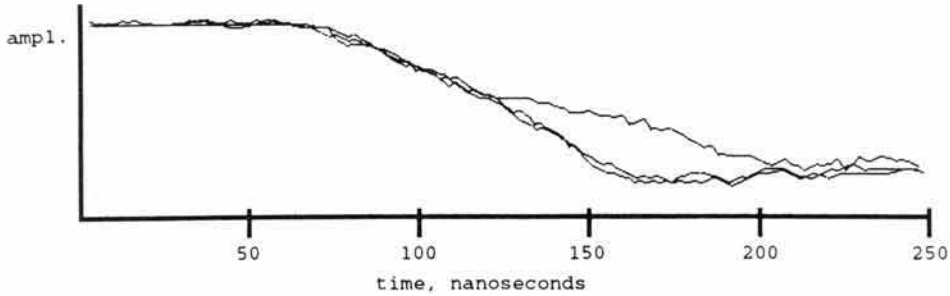

Fig. 3. HPGe preamplifier output risetimes.

THREE-DIMENSIONAL SDS

The term "three dimensional" again refers to the form of the output spectrum which is more correctly referred to as a pulse map. Referring to Fig. 4, the X and Y axes are sample time (relative to the leading edge of the pulse) and amplitude, respectively, while the Z axis is the number of occurrences of any particular time-amplitude combination.

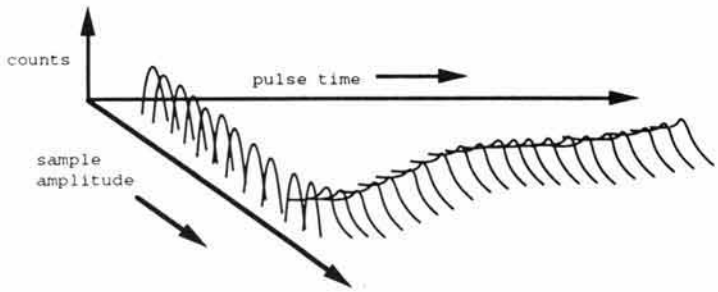

Fig. 4. Three-dimensional SDS pulse map.

The detector pulse samples are taken as in 2-D SDS with the addition of a trigger time which indicates the time between the actual start of the pulse and the time of the first sample taken. This additional timing information permits samples taken from successive pulses to be overlaid to produce the 3-D plot or pulse map. If the pulses are of a relatively uniform shape, as more and more detector pulses are added to the plot, the Z axis begins to resemble rising mountain ranges indicating that multiple pulses of the same energy have occurred. After collecting sufficient pulses, the points comprising the mountain ranges are fed to a curve fitting algorithm to determine the best-fit line. Then the area under that line is calculated to obtain the energy of that particular "peak" in the spectrum. Thus the spectral peaks are identified without having to determine the energy of any of the individual detector pulses. In addition to the reduction in processing required to produce such a "spectrum," image enhancement techniques may now be employed to reduce the random background scatter to accentuate the true "peaks." The only technique tried to date has simply been to reduce the sampling rate to an under-sampled condition, 5 MSPS on the Na(I)/PMT pulses (Fig. 5). Any repetitive pulse activity tends to fill in the points along the same line that a single, high-resolution pulse transcribes. After enough of these same-energy pulses have been sampled, the band that appears reveals the presence of a spectral peak. Non-repetitive events tend to produce a general scatter of points which do not contribute to the formation of the same shape "peaks."

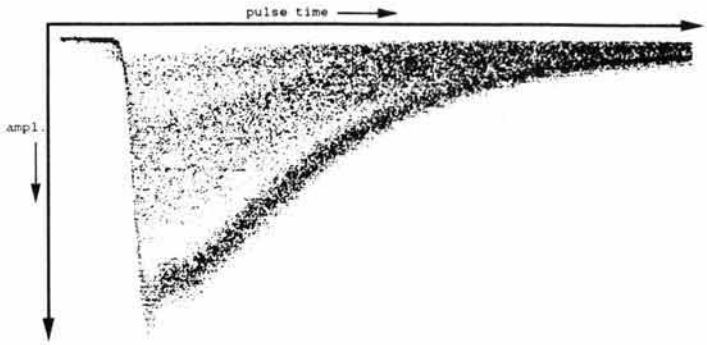

Fig. 5. 3-D SDS, Na (I)/PMT pulse map.

FUTURE DEVELOPMENT PLANS

The development plan has two basic parallel paths to follow. One is the construction of a full prototype for use with scintillator/PMT and other detectors with similar output characteristics. The second path is to evaluate more types of detectors with the proof-of-concept system to determine the minimum sampling rates and amplitude resolutions required to provide acceptable performance. These results will serve to guide the development into the very high frequency solid state detector applications.

From the results achieved with the proof-of-concept system, a 2-D scintillator/PMT prototype could be built with 8-bit digitizing at approximately 30 MSPS. To make it less sensitive to gain settings, it will have sampling capabilities up to 50 MSPS at 10-bit resolution and 30 MSPS at 12-bit resolution. With these higher levels of amplitude resolution, more can also be learned about the future needs for solid state detectors. Digital processing will be implemented in a combination of programmable gate arrays and digital signal processors. This prototype will be evaluated for portable applications, particularly spill monitoring, and also serve as a platform for algorithm development for both 2-D and 3-D SDS.

Because of the higher sampling speed and amplitude resolution requirements anticipated with solid state detectors, it is not appropriate to attempt to build a full prototype for

that application until the actual sample rate and resolution requirements are better defined. Testing on the proof-of-concept system will be conducted at 250 MSPS and higher, but resolution is expected to be limited by the 8-bit digitizer. The data taken with the slower 10 and 12-bit prototypes on scintillator/PMT detectors should permit a reasonable extrapolation to the performance potential at the higher rates.

POTENTIAL APPLICATIONS OF SAMPLED DATA SPECTROSCOPY

SDS should prove useful in complying with DOE requirements to monitor personnel for specific exposures below background levels. For example, traditional count-only systems cannot differentiate between radon/thoron alpha particles and uranium/plutonium alphas. With a low cost, high reliability SDS system, real-time alpha spectroscopy in air monitors and portal monitors would be feasible.

Along the same line, portable instrumentation that can do on-the-spot spectroscopy instead of counting could permit rapid decision making and response to leaks and spills. These miniaturized systems will also be easier to deploy in remote locations and on robots, requiring both less space and less power than conventional systems. At the same time, their reduced dependence on analog electronics increases their stability over time, reducing calibration requirements.

Because of its zero dead-time architecture, SDS can also accommodate high count rates without the need for statistical compensation. Real-time analysis using a FIFO "moving window" spectrum should prove valuable in waste stream monitoring and process control.

3-D SDS's applications are less clear at this point because less is known about its capabilities. It does offer a new means to investigate techniques for background and Compton reduction in spectra. As such, it may bring considerable benefits to waste characterization by allowing lower energy peaks to be seen that are normally masked by the Compton scatter from higher energy ones. The simplicity of the instrumentation matches that of 2-D SDS, and the digital components that make 2-D SDS possible are also well suited to image analysis.

CONCLUSION

Digital sampling technology has been successfully applied to radiation instrumentation under development at Savannah River. Early results demonstrate that this technology can be properly applied to this field to gain the advantages of miniaturization, low power consumption, and digital stability and reliability. Comparisons with existing instrumentation architectures indicate that similar levels of performance can be obtained with the same detectors.

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