VALIDATION OF *IN SITU* OBJECT COUNTING SYSTEM (ISOCS) MATHEMATICAL EFFICIENCY CALIBRATION SOFTWARE

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ABSTRACT

The ISOCS calibration method is a convenient tool for calibrating the detector efficiency as a function of energy for a wide variety of source geometries and activity distributions. The ISOCS method consists of a Canberra characterization of the detector, user input of source geometry data, and the ISOCS software which uses these to produce the efficiency calibration. During the characterization, a MCNP model of the detector is developed. The model is then independently validated using measurements with a NIST traceable source. Given the validated model, the response characteristics of the detector are mapped out to cover any location inside a sphere of radius 50 meters, centered on the detector, and over a photon energy range of 50 keV through 7 MeV. The ISOCS software contains a series of mathematical models that can simulate a wide variety of sample shapes. The software divides each source region into a number of voxels. Inside each voxel, a point location is defined in a quasi-random fashion. At a given energy, the detector efficiency is calculated for each voxel, taking into account the attenuation due to absorbers both inside and outside the source. The efficiencies for all the voxels are summed up at the given energy. To determine the accuracy of this calibration method, a large number of tests (about 109) were performed. In each of these tests, a reference efficiency calibration was compared to an ISOCS efficiency calibration at the same geometry. The reference calibration was either from a full MCNP calculation, or from a multi-energy radioactive source. The tests were categorized into three different counting geometries, namely, Field, Laboratory, and Collimated geometry. The data for each geometry were further divided into low energy (<150 keV) and intermediate to high energy (>150 keV) groups. The mean ratio of ISOCS/True efficiencies was (i) 1.01 ± 0.007 for the Field geometries, (ii) 0.97 ± 0.007 for the Laboratory geometries, and (iii) 1.09 ± 0.014 for the Collimated geometries. By analyzing the relative uncertainties in the True efficiencies, and the relative standard deviation in the ratios, the average relative standard deviation due to ISOCS is estimated to be 6.5%, 5.4%, and 10.5%, for the Field, Laboratory, and Collimated geometries, respectively. Various sources of bias affecting the data have been identified from this validation process. Improvements have been made in the characterization process and in the algorithms, which will be implemented in future versions of the ISOCS efficiency calibration software.

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INTRODUCTION

In environmental and other *in situ* applications, the objects to be assayed are, frequently, large in size. If gamma spectroscopy is to be used in the assay, the detector efficiency has to be calibrated as a function of energy for such large objects. Construction of laboratory sized calibration standards is relatively simple, but building very large ones can entail significant expense, radioactive waste generation, and safety risks. The ISOCS (*In Situ* Object Counting System) calibration method offers a solution to this problem. It is a convenient tool for calibrating the detector efficiency for a wide variety of source geometries and activity distributions. The ISOCS method consists of a characterization of the detector, user input of source geometry data, and the ISOCS software which uses these to produce the efficiency calibration.

The initial characterization of the germanium detector is performed by Canberra Industries on each individual detector, using the Monte Carlo code MCNP[1]. F. Bronson and L. Wang[2] have documented the satisfactory use of this code for calibrating germanium detector efficiencies. First, an MCNP model of the detector is developed. The model is then independently validated using measurements with a NIST traceable point source. Given the validated model, the detector efficiencies are calculated using MCNP at a large series of point locations in the environment surrounding the detector, over a photon energy range of 50 keV through 7 MeV. The placement of the points in the environment surrounding the detector is done in a quasi-random fashion using the LPt methodology, as originally suggested by V. Atrashkevich and V.V. Kolotov[3]. Using the MCNP calculated efficiencies, response characteristics of the detector are created to cover any point within a sphere 50 m in radius, centered on the detector, and over an energy range of 50 keV to 7 MeV. The end result is a series of mathematical equations describing the absolute efficiency as a function of energy, angle, and distance from the detector.

The ISOCS calibration software contains a series of mathematical models that can simulate a wide variety of common sample shapes (boxes, cylinders, pipes, spheres, stacked boxes, stacked discs, Marinelli beakers, etc.). These models allow easy input of appropriate parameters necessary for efficiency computation. The ISOCS software divides each source region into a large number of voxels (1024). A point location is defined within each voxel. The point location within a voxel is determined in a quasi-random fashion. At a given user-specified energy, the detector efficiency is calculated for each voxel. The attenuation due to absorbers within the source and also in the intervening space between the source and the detector is taken into account. If a shield and /or a collimator is defined in the calculation, the software takes into account the additional attenuation due to those. Finally, the efficiencies for all the voxels are summed up at the specified energy. Then a second iteration is done with 2048 voxels. ISOCS then checks whether the desired convergence criterion has been met. If not, the number of voxels is doubled and the calculation continues at the same energy. Once the convergence criterion is met, the software moves on to the next energy in the user-specified list. If there are multiple source regions, the process is repeated for each source region.

To determine the accuracy of the ISOCS efficiency calibrations, a large number of validation tests (109) were designed and performed.

EFFICIENCY VALIDATION TESTS

The validation tests were grouped into three categories, namely, (1) Field counting geometry, (2) Laboratory counting geometry, and (3) Collimated geometry. Between them, the three categories of tests included 109 different multi-energy sources spanning a large range of sizes and source-detector distances, and both collimated and uncollimated geometries. In each of these tests, a reference efficiency calibration was compared to an ISOCS efficiency calibration at the same geometry. The Monte Carlo code MCNP or the measured data from a multi-energy source was used to generate the reference calibration. The energies of these sources covered the range from low (60-88 keV) to high (1408-1836 keV) energies, with 5-8 energies in between.

The types of validation tests included in the three counting geometeries are listed in Table 1. The type of tests included in the field counting geometry were those that involved large sources (>1 m^3 in volume) and/or large source-detector distances (>1 m). A variety of radioactive source distributions were created inside containers that were shaped like boxes, drums and pipes. The containers were filled with materials that one would typically encounter in the field, such as soil, dirt, water, etc. About half the number of tests were MCNP simulations, while the other half were radioactive source measurements.

The tests included in the laboratory counting geometry were those that involved small sources, located within a distance of 1 m from the detector. Except for one MCNP simulation, all the other tests were performed using multi-energy gamma ray standards. The source geometries included vials, bottles, filter papers, and Marinelli beakers.

The tests included in the collimated geometry were those in which the collimator had at least a 20% effect on the ISOCS efficiency. The detector was shielded by a 2.0 in. thick cylindrical side shield. For a given source geometry, ISOCS and reference efficiency calibrations were generated for collimators with opening angles of 180^o, 90^o, and 30^o. The source-detector distance was typically 1 m. The source dimensions were made large, so that the effect of the side shields and the collimator could be properly tested.

VALIDATION TEST RESULTS AND DISCUSSION

In each validation test, the ratio of ISOCS efficiency to reference efficiency was determined at each source energy. The data set in each test was divided into three groups in terms of energy; (1) <150 keV, (2) >150 keV, (3) data at all energies pooled. For each energy group, a weighted mean of the ratio of ISOCS to reference efficiency was determined. A weighted standard deviation of the ratio was also determined for each energy group. The absolute uncertainties in the reference efficiencies were used to weight the ratio and the standard deviation.

The uncertainties in the ISOCS/Reference efficiency ratio come from the calibration source uncertainties, counting statistics, or the statistical uncertainty in the MCNP results, in addition to the uncertainty due to ISOCS itself. The relative uncertainty due to ISOCS is estimated as follows.

$$[\sigma_{\text{ISOCS eff}} / \text{ISOCS eff}]^2 = [\sigma_{\text{Ratio}} / \text{Ratio}]^2 - [\sigma_{\text{Reference eff}} / \text{Reference eff}]^2$$

It should be noted that the relative uncertainty due to ISOCS for each test indicates the random uncertainty introduced by the ISOCS process. But when taken collectively as an average value over a large number of tests, the ISOCS uncertainty becomes a good estimate of the total uncertainty due to ISOCS, as it also then includes the systematic error in the ISOCS process.

Tables 2, 3, and 4 pool the results of the validation tests for the field, laboratory, and collimated geometries, respectively. The ratios of all the tests belonging to a given geometry, were averaged, and their standard deviation was determined. It is evident that the ISOCS/Reference efficiency ratio comes out reasonably close to unity. The uncertainties (1σ standard deviation) in the ratios from individual tests were averaged to obtain an *expected* standard deviation. If the standard deviation obtained by pooling together the ISOCS/Reference efficiency ratios from all the tests is close to the *expected* standard deviation, then the data distribution approaches a Gaussian. If not, perhaps there are biases in some of the individual tests which make the distribution deviate from the assumed Gaussian shape.

Table 1.
Types of Validation Tests in Various Counting Geometries

Types of Tests in Field Counting Geometry	**Types of Tests in Laboratory Counting Geometry**	**Types of Tests in Collimated Geometry**
55 gallon Drum of water, 1 m away	20 ml vial of Mixed Radionuclide Standard	4 m^3 Dirt Boxes, 2 in. thick side shields, 180˚ Collimator
55 gallon Drum of water, 50% full, a hot spot present	*perpendicular to detector axis, at 0, 5, 10, 20, and 25 cm*	
60 x 30 x 30 cm^3 Box of water, 67% full	*facing the detector end-on, at 0, 5, and 10 cm*	Line source 20 m in length, 1 m away
300 liter Box of water		*2 in. thick side shields, 180° Collimator*
1 m^3 Box of water, 30 m away	125 ml bottle of Mixed Radionuclide Standard	*2 in. thick side shields, 90° Collimator*
1 m^3 Box of water, 1 m away	*perpendicular to detector axis, at 0, 5, 10, and 25 cm*	*2 in. thick side shields, 30° Collimator*
1 m^3 Box of air, 1 m away	*facing the detector end-on, at 0, 5, 10, and 25 cm*	
1 m^3 Box of air, 30 m away		Plane source 20 x 20 m, 1 m away
1 m^3 Box of water, 1 m away, at 90°	Filter Paper in petri dish – Mixed Radionuclide Standard	*2 in. thick side shields, 180° Collimator*
1 m^3 Box of air, 1 m away, at 90°	*facing the detector end-on, at 0, 5, and 25 cm*	*2 in. thick side shields, 90° Collimator*
4 m^3 Dirt Boxes of various densities, 1 m away		*2 in. thick side shields, 30° Collimator*
4 m^3 Dirt Boxes, point source in the center, 1 m away	NIST Certified ^{235}U Standard Reference Material set	
60 x 30 x 30 cm^3 Box of water, a hot spot present	*Atom % of ^{235}U abundances: 0.32, 0.72,1.97, 2.99, 4.52*	Line source 4.8 m in length, at a distance of 1 m
55 gallon Drum of water, facing the detector end-on		*2 in. thick side shields, 180° Collimator*
Hollow Spherical Shell of water, 1 m away	1 liter Marinelli Beaker Standards – 1.15 g/cc and 1.6 g/cc	*2 in. thick side shields, 90° Collimator*
Pipe full of water, contamination plated on the inside wall	*measurements with 20%, 42%, and 60% Ge detectors*	*2 in. thick side shields, 30° Collimator*
In Situ Dirt, with detector 1 m away		
Radium, Thorium, and ^{40}K Calibration Pads (Genitron)	400 ml Marinelli Beaker Standards – 1.15 g/cc and 1.6 g/cc	Measurement of environmental activity from ground
Line source, 4.8 m long, 1 m away	*measurements with 20%, 42%, and 60% Ge detectors*	*2 in. thick side shields, 180° Collimator*
Rotating Calibration Drums, w/line sources inserted		*2 in. thick side shields, 90° Collimator*
Line source, 80 cm long, at various angles and distances	Point source at various on-axis and off-axis locations	*2 in. thick side shields, 30° Collimator*
Plane source, 3’ x 3’, at various angles and distances		

Table 2.
Results for Field Counting Geometry

Result	Data <150 keV	Data >150 keV	All data pooled
Weighted Average of ISOCS/True efficiency ratio	1.02	1.01	1.01
Uncertainty in wtd. mean	0.49%	0.34%	0.66%
Standard deviation of data	14.9%	6.8%	6.6%
Expected standard deviation	9.9%	5.2%	7.5%
Avg. ISOCS standard deviation	8.9%	4.5%	6.5%

Table 3.
Results for Laboratory Counting Geometry

Result	Data <150 keV	Data >150 keV	All data pooled
Weighted Average of ISOCS/True efficiency ratio	1.05	1.02	0.97
Uncertainty in wtd. mean	0.05%	0.19%	0.77%
Standard deviation of data	12.8%	9.9%	9.6%
Expected standard deviation	8.0%	5.1%	6.8%
Avg. ISOCS standard deviation	6.7%	4.5%	5.4%

Table 4.
Results for Collimated Geometry

Result	Data <150 keV	Data >150 keV	All data pooled
Weighted Average of ISOCS/True efficiency ratio	1.10	1.09	1.09
Uncertainty in wtd. mean	0.80%	0.89%	1.27%
Standard deviation of data	27.7%	24.6%	23.9%
Expected standard deviation	8.0%	9.9%	12.5%
Avg. ISOCS standard deviation	7.7%	7.6%	10.5%

It is difficult to pin-point the sources of biases that make the data deviate from a Gaussian behavior. The source of bias could be from ISOCS, the detector characterization process, systematic errors in measurements, systematic errors in the standard source calibration, or systematic errors in MCNP simulation. Every effort has been made to alleviate or eliminate the known biases in the data. For example, in the laboratory geometry, when sources containing nuclides such as ^{60}Co, ^{88}Y, and ^{152}Eu were counted close to the detector (<10 cm), the data was corrected for cascade summing losses in the full energy peaks.

For tests involving thick lead shields and collimators with small opening angles, the ISOCS efficiency is greater than the reference efficiencies, especially at lower energies. This could be because of the algorithm used in ISOCS to estimate the collimator attenuation. A new collimator algorithm has been devised and tested. This new algorithm has improved the efficiencies significantly, and will be incorporated into a future version of ISOCS.

Another source of bias in heavily shielded or collimated geometries, is coherent scattering of photons. Earlier tests using the total photon cross sections gave low ISOCS efficiencies in these cases. The current release of ISOCS now uses cross sections which do not include coherent scattering cross sections. Now, the ISOCS efficiencies are somewhat higher than the true value, but closer to the true efficiency.

CONCLUSIONS AND FUTURE WORK

The validation tests reveal that the ISOCS efficiency calibration is fairly accurate for most applications. In the case of field and laboratory counting geometries, the average ISOCS to reference efficiency ratios was 1.01 ± 0.007 and 0.97 ± 0.007, respectively. For the collimated geometry, the ISOCS to reference efficiency ratio was 1.09 ± 0.014. This is still acceptable for typical ISOCS applications where there are usually other sources of error that are more significant. A new collimator algorithm has been devised and tested, and it has significantly improved the ISOCS efficiencies for collimated geometries. Also, a new detector characterization process has been developed, and is in its final phases of testing. This reduces the ISOCS error component significantly, which should greatly reduce the uncertainties in the laboratory geometries.

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