1 **OSIRIS—Gamma-Ray Spectroscopy Software for On-Site Inspections**
2 **under the Comprehensive Nuclear-Test-Ban Treaty**

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13
14 **Abstract**

15 We have designed and tested software for the acquisition and analysis of high-resolution gamma-ray
16 spectra during on-site inspections under the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The On-
17 Site Inspection RadioIsotopic Spectroscopy—OSIRIS—software filters the spectral data to display only
18 radioisotopic information relevant to CTBT on-site inspections, e.g., ¹³¹I. A set of over 100 fission-product
19 spectra was employed for OSIRIS testing. These spectra were measured where possible, or generated by
20 modeling. The test spectral compositions include non-nuclear-explosion scenarios, e.g., a severe nuclear
21 reactor accident, and nuclear-explosion scenarios such as a vented underground nuclear test. Comparing
22 its computer-based analyses to expert visual analyses of the test spectra, OSIRIS correctly identifies
23 CTBT-relevant fission product isotopes at the 95% level or better.

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25 *Keywords:*

26 Automated gamma-ray spectrum analysis

27 Comprehensive Nuclear-Test-Ban Treaty

28 Fission-product gamma-ray spectroscopy

29 Nuclear nonproliferation

30 On-site inspection

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32 **1. Introduction**

33 We have developed and tested software for the acquisition and analysis of high-resolution gamma-ray
34 spectra that could potentially be used during on-site inspections (OSIs) under the Comprehensive
35 Nuclear-Test-Ban Treaty (CTBT) [1][2]. The On-Site Inspection RadioIsotopic Spectroscopy—
36 OSIRIS—software measures, analyzes, and filters gamma-ray spectral information. OSIRIS gamma-ray
37 energy spectra are not visible to the user; instead, the displayed information is limited to radioisotopes
38 relevant to CTBT on-site inspections.¹ OSIRIS also reports spectral lines of selected natural background
39 isotopes and energy-calibration checksources to help assure users of correct operation.

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41 An ORTEC Trans-SPEC-DX-100T mechanically-cooled HPGe spectrometer [3], shown in Fig. 1, serves
42 as the OSIRIS prototype instrument.

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44 In this paper, we describe the OSIRIS software design in detail, and we report the initial OSIRIS test results
45 on over 100 fission product and/or natural background gamma-ray spectra. Other hardware, software, or
46 procedural approaches to restricting radionuclide information in a CTBT OSI can be envisioned, and
47 acceptable approaches will rely on input from many CTBT signatory nations.

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49 **2. CTBT On-site Inspections**

50 Each State Party under the CTBT undertakes not to carry out any nuclear weapon test explosion or any
51 other nuclear explosion, and to prohibit and prevent any such nuclear explosion at any place under its

¹ OSIRIS is programmed to report only these fission-product isotopes: ¹⁴⁰Ba, ¹⁴¹Ce, ¹⁴⁴Ce, ¹³⁴Cs, ¹³⁷Cs, ¹³¹I, ¹³²I, ¹⁴⁰La, ⁹⁹Mo, ⁹⁵Nb, ¹⁴⁷Nd, ¹⁴⁴Pr, ¹⁰⁶Rh, ¹⁰³Ru, ^{99m}Tc, ¹³²Te, ⁹⁵Zr.

jurisdiction or control. Each State Party has the right to request an on-site inspection in accordance with the provisions of the CTBT and its Protocol in the territory or in any other place under the jurisdiction or control of any State Party or in any area beyond the jurisdiction or control of any State, and the treaty and Protocol detail the process to be followed for the approval and execution of such inspections.

The treaty and its Protocol allow the use of gamma-ray spectroscopy during the conduct of an OSI, and they also allow for measurement restrictions as a managed access tool by the Inspected State Party. The OSIRIS software represents a prototype information filter of spectral information measured during an OSI so that only information related to certain isotopes deemed relevant to the purpose of the inspection (“CTBT-relevant radionuclides”) is revealed to the user.

3. Measurement Data Filters

A notional spectroscopic measurement data filter, termed by others an “information barrier” [4], is depicted in Fig. 2. The data filter hardware and software hide full spectral information from users, revealing only treaty-relevant information on its display device. Radiation measurement data filters have been designed for nuclear arms-limitation treaty-related purposes, including the Brookhaven National Laboratory CIVET system [5]; the Oak Ridge National Laboratory NMIS instrument [6]; and the Sandia National Laboratories TRADS instrument [7]. OSIRIS uses an enhanced version of the data filter in the Idaho National Laboratory PINS Chemical Assay System [8], developed for the Chemical Weapons Convention.

The OSIRIS data filter is implemented almost entirely in software; future developments will include hardware and procedural safeguards for the measured spectra, plus means for assuring users and inspected parties that the spectroscopic results are correct. While OSIRIS software identifies the gamma-ray peaks from natural background isotopes, other fission products not deemed relevant, and other radioisotopes, it only presents users with information on treaty-relevant fission-product gamma-ray peaks and calibration

radioisotopes, e.g., ^{152}Eu . Limited information on natural background isotopes such as ^{40}K is also presented to the operator, as assurance of normal operation.

The fission-product spectrum measured from an experimental reactor fuel sample is shown in Fig. 3. OSIRIS limits information about this complex spectrum to the simple bar chart of Fig. 4. For each of the seventeen treaty-relevant fission products, a vertical bar is drawn, and the bar height for each fission product is proportional to the area of that isotope's most intense gamma-ray peak. The bar chart also includes information on three of the more-intense natural background isotopes. During data acquisition, the bars grow in height, in real time, as the treaty-relevant fission-product peak areas grow.

Additionally, if a user clicks one of the buttons atop the bar display with the mouse pointer, summary data for that isotope is displayed in a separate window. The ^{134}Cs - ^{137}Cs information window for the reactor fuel sample spectrum is shown in Fig. 5.

At the termination of data acquisition, OSIRIS saves summary data of the sort displayed in Fig. 5 for each of the treaty-relevant fission-product isotopes in a text file. The actual gamma-ray spectrum is not saved or displayed, and the OSIRIS graphical user interface can be described as "spectrum-blind."

4. OSIRIS Software Details

The OSIRIS program supervisory logic is shown in Fig. 6. Following energy calibration, a gamma-ray spectrum is acquired. Next a peak search is performed, and based on the detected and required peaks, the peak-fitting regions are determined. After region-by-region peak fits, the radioisotopes evident in the spectrum are identified by peak energy and the corresponding peak areas and peak area uncertainties noted. Finally, information on the treaty-relevant fission products is pushed across the data filter for display to the user.

4.1 Energy Calibration

The gamma-ray spectrometers used in on-site inspections should be calibrated as needed with gamma-ray check sources. Alternatively, an OSIRIS spectrometer can be calibrated with natural background radiation if a check source is not available. After the user selects the calibration source type, OSIRIS energy calibration is entirely automatic. During the energy calibration procedure, the calibration gamma-ray peaks are displayed in a separate window as they grow, in real time, as shown in Fig. 7 for an ^{152}Eu source, but no other gamma-ray peaks are displayed.

4.2 Peak Search

Next, OSIRIS conducts a peak search using Black's "zero-area square-wave" cross-correlation algorithm [9], similar to wavelet analysis methods. Fig. 8 depicts a zero-area square wave. If one of the required peaks listed in Table 1 is not found within one-half of the peak-width, i.e., $\text{FWHM}/2$, a directed peak fit is performed at the required peak energy.

4.3 Peak Analysis

Peak region determination and peak fits are carried out with the GAUSS gamma-ray spectrum analysis algorithms of Helmer. [10] Similar spectrum analysis codes include GAMMAVISION [11], HYPERMET [12], and SAMPO [13].

GAUSS peak analyses use nonlinear least-square fits, a method especially suitable for the analysis of complex fission-product spectra. Fig. 9 displays a GAUSS fit of overlapping peaks in the 650- to 680-keV region of the reactor fuel-sample spectrum. For peak detection, OSIRIS requires the peak area to exceed the peak background uncertainty by a factor of 3.0 or more.

4.4 Interfering Peaks

In complex spectra, it is important to avoid peak interferences. OSIRIS does not use peaks in the X-ray region, near Compton edges, or near coincidence sum peaks. Even then interferences can be difficult to avoid. For example, the highest intensity ^{106}Rh peak is found at 511.86 keV, and to avoid interference with the 511.00 annihilation peak, the second-highest intensity ^{106}Rh peak at 621.93-keV is used instead. But the 621.20-keV ^{132}I peak can interfere with the 621.93-keV ^{106}Rh peak, and additional program logic vetoes ^{106}Rh identification if strong ^{132}I peaks are present in the spectrum.

5. Testing OSIRIS

OSIRIS has been tested on a select set of gamma-ray spectra. Each spectrum contained fission-product peaks, natural-background isotope peaks, or both, and each spectrum was analyzed twice. The first analysis was performed visually by an experienced spectroscopist. Each spectrum was then analyzed by the OSIRIS software. Finally, a computer program compared the visual and OSIRIS spectral analyses.

The principal spectral compositions used for testing the OSIRIS software include non-nuclear-explosion cases, for example, a severe nuclear reactor accident, and recent-nuclear-explosion cases such as a vented underground nuclear explosion. The test spectra used span the time range from 1 to 100 weeks after an event. A set of over 100 fission-product spectra has been assembled for OSIRIS testing, measured where possible, or generated by modeling.

5.1 Non-Nuclear-Explosion Case Test Spectra

As a baseline, seven spectra recorded from nuclear reactor experimental fuel samples were included in our test analyses. The reactor fuel samples were irradiated in the Advanced Test Reactor at Idaho National Laboratory, and the sample cooling times after irradiation prior to gamma-ray spectral measurement ranged from 6 to 24 months. Fig. 3 displays one of the reactor fuel-sample spectra.

Other measured non-nuclear-explosion case spectra utilized measured spectra associated with reactor accidents (Chernobyl and Fukushima), old nuclear test debris, and nuclear fuel rods. These spectra were combined with measured dirt spectra from Richland, WA over a range from nearly-all-signal to nearly-all dirt (to reflect different concentrations). No simulated terrestrial background for measurement conditions was needed in this case. Each spectrum was then re-generated by pseudo-random bin-wise sampling from a Poisson distribution with mean given by the original “template” spectrum, so that all spectra for a different type, and all across different types, are statistically independent.

5.2 Nuclear-Explosion Case Test Spectra

Recent underground nuclear explosion spectra were simulated using the spectrum synthesis tool SUPERSYNTH [14] to generate input decks for MCNP6 [15] gamma-ray radiation transport models. MCNP6 models were then run with sufficient particle histories to yield statistical uncertainties of the order of a few percent in each spectrum energy bin. Spectra were simulated for the ORTEC Trans-SPEC-DX-100T (HPGe) spectrometer. In the simulations, appropriate radionuclide inventories were mixed with 300g of simulated “crustal abundance” dirt at a signal/background ratio of total counts in various amounts from 10^{-3} to 10^3 (to reflect different concentrations). A simulated terrestrial background was also added to reflect normal measurement conditions – this was necessary in part so that there would be a continuum in the spectra above the 1461-keV ^{40}K line. Each spectrum was generated by pseudo-random bin-wise sampling from a Poisson distribution with mean given by the as-modeled counts for that bin in the summed (analyte + soil background + terrestrial background) “template” spectrum. With this prescription in effect, all spectra of different concentrations for a given type, and all across different types, are statistically independent.

Example non-nuclear-explosion case and nuclear-explosion case spectra are shown in Fig. 10.

6. Test results

The radioisotopes detected by OSIRIS are displayed in Table 2. Notably, all seventeen treaty-relevant fission products were represented in the test spectra and identified.

The treaty-relevant fission-product true positive and true negative correct-identification fractions, in percent, are displayed for each spectrum in Fig. 11.

Summed over all of the spectra, the OSIRIS isotope identification scores are presented in Table 3.

7. Conclusions

We have developed OSIRIS, a new gamma-ray spectroscopy software suite intended for potential use for a CTBT on-site inspection. The software uses a data filter to limit the spectral information presented to the user. Only information on seventeen treaty-relevant fission products is displayed and stored. In particular, OSIRIS is spectrum-blind: the user cannot view spectra being acquired. At the end of data acquisition, each spectrum is erased from the spectrometer and the data-acquisition computer. The software does retain summary information regarding CTBT-relevant fission products and energy calibration files.

Initial tests of OSIRIS have been conducted with a set of 107 fission-product and/or natural-background spectra, and in these tests, the OSIRIS correct identification rate exceeded 95% for CTBT-relevant fission product isotopes.

The initial OSIRIS results are encouraging, but other tests will need to be conducted before settling on this or any approach for acquisition and analysis of high-resolution gamma-ray spectra during CTBT on-site inspections.

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Table List

Table 1

Required OSIRIS gamma-ray peaks. If the search routine fails to find a peak within half of the full-width at half-maximum (FWHM/2) of a peak, OSIRIS performs a directed fit at the peak library energy.

Isotope	Peak library energy (keV)	Branching ratio (%)
¹⁴⁰ Ba	537.26	24.4
¹⁴¹ Ce	145.44	48.2
¹⁴⁴ Ce	133.51	11.1
¹³⁴ Cs	604.70	97.6
¹³⁷ Cs	661.66	85.1
¹³¹ I	364.49	81.5
¹³² I	667.72	98.7
¹⁴⁰ La	1596.21	95.4
⁹⁹ Mo	739.5	12.1
⁹⁵ Nb	765.81	99.8
¹⁴⁷ Nd	531.02	13.1
¹⁴⁴ Pr	696.51	1.3
¹⁰⁶ Rh	621.93	10.0
¹⁰³ Ru	497.08	91.0
^{99m} Tc	140.51	100.0
¹³² Te	228.16	88.0
⁹⁵ Zr	756.73	44.2

Table 2

Radioisotopes identified in the test spectra.

Type	Isotopes Detected
Treaty-relevant fission products	¹⁴⁰ Ba, ¹⁴¹ Ce, ¹⁴⁴ Ce, ¹³⁴ Cs, ¹³⁷ Cs, ¹³¹ I, ¹³² I, ¹⁴⁰ La, ⁹⁹ Mo, ⁹⁵ Nb, ¹⁴⁷ Nd, ¹⁴⁴ Pr, ¹⁰⁶ Rh, ¹⁰³ Ru, ^{99m} Tc, ¹³² Te, ⁹⁵ Zr
Other fission products	^{110m} Ag, ¹³⁶ Cs, ¹⁵² Eu, ¹⁵⁴ Eu, ¹²⁵ Sb, ⁹¹ Y
Other radioisotopes	²⁴¹ Am, ⁶⁰ Co
Natural background isotopes	²²⁸ Ac, ²¹² Bi, ²¹⁴ Bi, ⁴⁰ K, ²¹² Pb, ²¹⁴ Pb, ²⁰⁸ Tl

Table 3

Overall OSIRIS correct and incorrect isotope identification scores. Only treaty-relevant fission product information, is revealed to the OSIRIS user.

Isotope type	True positive fraction, %	True negative fraction, %	False positive fraction, %	False negative fraction, %
Treaty-relevant fission products	98.1	96.2	3.8	1.9
Other fission products	86.5	94.9	5.1	13.5
Other radioisotopes	95.0	96.8	3.2	5.0
Natural background isotopes	83.5	89.7	10.3	16.5

Figure Caption List

Fig. 1 ORTEC Transpec-100 mechanically-cooled gamma-ray spectrometer.

Fig. 2 Data filter. Only treaty-relevant spectral information passes through the data filter to the display device.

Fig. 3 Nuclear reactor fuel-sample fission-product spectrum, measured 24 months after reactor irradiation.

Fig. 4 OSIRIS graphical user interface main screen. The thermometer bars display the areas of the most intense treaty-relevant fission-product gamma rays. The bars and element buttons are initially white, and they are shaded successively darker as peak detection confidence increases.

Fig. 5 OSIRIS ^{134}Cs - ^{137}Cs information display window for the spectrum in Fig. 3. This window appears when the user clicks either the ^{134}Cs or the ^{137}Cs button above the thermometer bars in the OSIRIS main screen of Fig. 4.

Fig. 6 OSIRIS program supervisory logic. The data filter passes to the display information on treaty relevant isotopes, for example, ^{134}Cs and ^{137}Cs . Information on the non-treaty-relevant isotope ^{60}Co is blocked by the data filter from reaching the display.

Fig. 7 OSIRIS energy calibration window for a Eu-152 gamma-ray check source.

312 **Fig. 8** Zero-area square wave used in OSIRIS peak searches.

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316 simulated nuclear explosion fission-product spectrum was synthesized with the MCNP6 and SUPERSYNTH
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318 **Fig. 11** True positive (upper bar chart) and true negative (lower bar chart) fractions, in percent, for OSIRIS
319 identifications of treaty-relevant fission product (TRFP) isotopes, by spectrum. Spectra containing no
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isotope	library energy	measured energy	net area	t*
Cs-134	569.31	569.18	874692.8	839.7
Cs-134	604.70	604.64	5312730.7	2251.9
Cs-134	795.85	796.19	3651670.9	1740.4
Cs-134	801.93	802.28	363554.6	539.8
Cs-137	661.66	661.59	5664162.0	2330.1
Cs-134/Cs-137 Ratio				
ratio = (5312730.7/5664162.0) · (0.851/0.976) = 0.82				

Fig. 5 OSIRIS ^{134}Cs - ^{137}Cs information display window for the spectrum in Fig. 3. This window appears when the user clicks either the ^{134}Cs or the ^{137}Cs button above the thermometer bars in the OSIRIS main screen of Fig. 4.

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Fig. 11 True positive (upper bar chart) and true negative (lower bar chart) fractions, in percent, for OSIRIS identifications of treaty-relevant fission-product (TRFP) isotopes, by spectrum. Spectra containing no treaty-relevant fission-product isotope peaks are indicated by diagonally-striped bars