Report Number N18765

An Aerial Radiological Survey of the King and Pierce Counties, Washington

Technical Report

July 11-22, 2011

National Security Technologies LLC
Vision • Service • Partnership

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An Aerial Radiological Survey of the King and Pierce Counties, Washington

Technical Report

Prepared for:

State of Washington
Department of Health

Aerial Measuring Systems
Remote Sensing Laboratory
National Security Technologies, LLC

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David C. Colton
Derivative Classifier

ABSTRACT

As the result of a request from the State of Washington's Department of Health, the US Department of Energy's Remote Sensing Laboratory (RSL) Aerial Measuring Systems (AMS) (operated by National Security Technologies, LLC [NSTec]) conducted an aerial background radiological survey of the King and Pierce Counties, Washington. The survey was executed during the two-week period of July 11-22, 2011 and resulted in 23 flights being flown over the King County, which includes city of Seattle, an area of 345 square miles. Five flights were also conducted over the Pierce County, which includes city of Tacoma, covering 60 square miles. The survey crew included personnel from both the RSL-Nellis, Las Vegas, Nevada and RSL-Andrews, Suitland, Maryland locations.

Considering the sensitivity provided by twelve 2" × 4" × 16" sodium iodide thallium-activated NaI(*Tl*) crystals of the aerial acquisition system and flight safety considerations, a survey altitude of 300 feet Above Ground Level (AGL) was agreed upon. The flight pattern consisted of a set of parallel lines 600 ft apart. Several measurements were taken using a pressurized ionization chamber (PIC) and a high-purity germanium (HPGe) spectroscopic system at four specific locations on the ground (test line-runway at the King County airport) to validate the data derived from the aerial measurements.

Collected spectral data were processed and finalized as gross count (GC), man-made gross-count (MMGC), and isotopic extraction data, and are included as the Geographic Information System (GIS) layers in a CD provided to the state Washington Department of Health.

The data from this background survey will be referenced in the State Radiological Response Plan. The baseline of natural background exposure rate values and any radiological anomalies present in the survey areas would be used in the event of a radiological emergency to compare radioactive contamination to the normal levels found during this study. The Washington State Department of Health, Office of Radiation Protection oversaw the project, which was funded by the U.S. Department of Homeland Security.

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1.0 INTRODUCTION

An aerial radiological survey of portions of King County, including the city of Seattle, and Pierce County, including the city of Tacoma, in the state of Washington was conducted during the period July 11-22, 2011 at the request of the Washington State Department of Health. The survey area was divided into two distinctive sites. The first one covered a region of approximately 23 ×15 miles for a total area of 345 square miles and included the city of Seattle and a portion of King County. The second area, a rectangle of 8.6 × 7 miles (60 sq miles) covered the city of Tacoma and a portion of Pierce County. The survey was conducted by an Aerial Measuring Systems (AMS) team from the U.S. Department of Energy (DOE) National Nuclear Security Administration's Remote Sensing Laboratory (RSL), which is maintained and operated by National Security Technologies, LLC, at Nellis Air Force Base in Las Vegas, Nevada, and Andrews Air Force Base, Suitland, Maryland.

The survey was conducted for the Washington State Department of Health and was funded by the U.S. Department of Homeland Security (DHS). The purpose of the survey was to provide the state with current radiation background readings for the specified areas (the largest population centers of the state of Washington). The data from the background survey will be referenced and used as a baseline for the State Radiological Response Plan. The intent of the plan is to coordinate radiological response policies among the responding agencies in the Urban Area Security Initiative (UASI), to provide radiological response and recovery guidance, and to provide a series of Protective Action Recommendations that can be used to coordinate various response and recovery activities.

The RSL aerial survey data products are presented in the form of contour maps superimposed on maps of the surveyed areas. The products present the gamma-ray exposure rates (ER) attributable to natural radioactive nuclides and any man-made radiological anomalies expressed in terms of standard deviations above background.

The data were collected by the RSL Aerial Measuring Systems (AMS) using a radiation data acquisition system built by Radiation Solution Inc. which employed an array of twelve 2" × 4" × 16" sodium iodide thallium-activated NaI(*Tl*) detectors flown onboard a twin-engine Bell 412 helicopter and were geo-referenced using a differential Global Positioning System (DGPS). Gamma energy spectra were collected continuously each second during the survey. This spectral data provides the capability to distinguish ordinary fluctuations in the natural background radiation levels and radiological signatures produced by man-made radioactive sources. Spectral data can also be used to identify specific radioisotopes and produce isotope-specific contour maps.

2.0 SURVEY SITE DESCRIPTION

The two survey areas in King and Pierce Counties, with the planned survey flight lines, are shown in Figures 1 and 2.

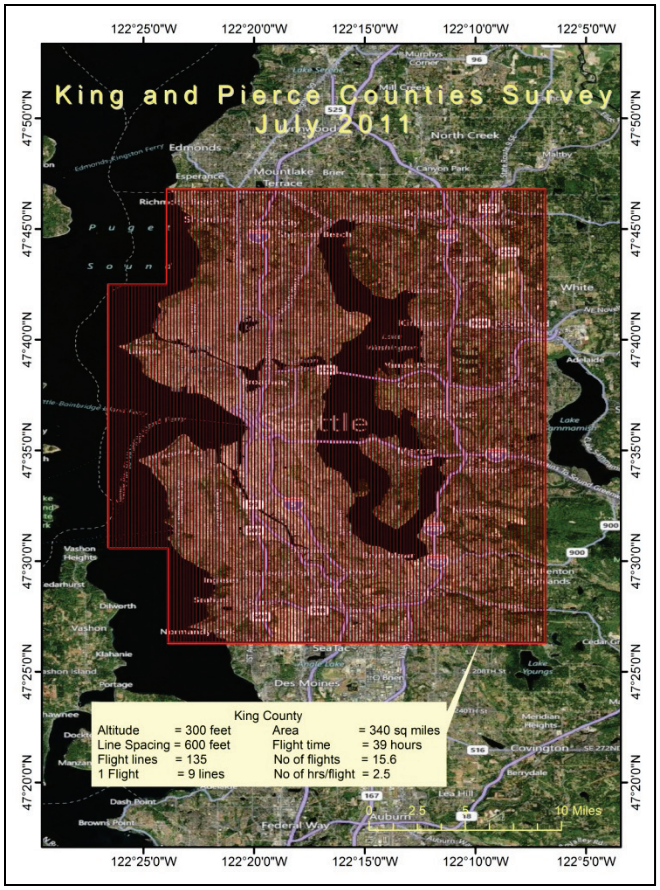


Figure 1. ***King County survey area and planned flight lines.***

The King County survey area covered approximately 345 square miles and included the Seattle metropolitan area. The area was roughly bounded by Puget Sound to the west, the city of Redmond to the east, SeaTac Airport to the south, and the I-5/104 intersection to the north. This area includes the densely populated urban centers of Seattle, as well as several of the adjacent suburbs, with a metropolitan population of about 3.5 million. A small portion of the survey lines was flown over the waters of Puget Sound. To reduce the flight time over water, the first 18 lines on the west side were shortened. Seattle is located at mean-sea-level (MSL) elevation that varies from 0 ft to 520 ft.

The Pierce County survey area was bounded by Commencement Bay on the north, South 56th Street on the south, Union Avenue on the west, and South 1st Avenue on the east. The rectangular survey area covered approximately 60 square miles. The city elevation is about 240 ft MSL.

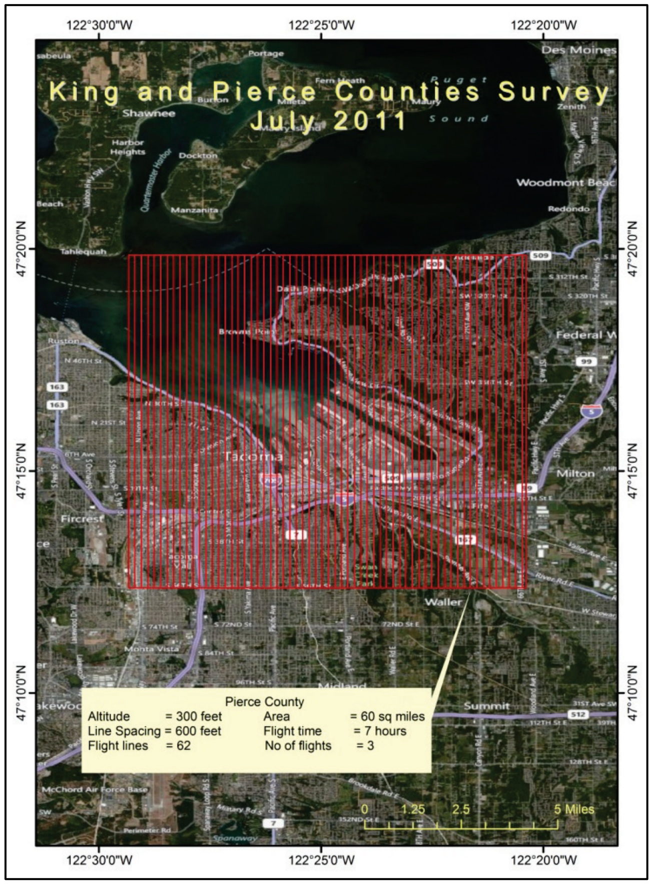


Figure 2. ***Pierce County survey area and planned flight lines.***

To assure data integrity and to monitor/correct for variations in the detectors' background count rate due to aircraft, radon and cosmic rays; two additional geographical features were selected. The first one, called the fixed land test line was a 3710 ft long runway located at the King County International Airport/Boeing Field. The runway is at an elevation of 21 ft MSL. The second, a fixed water line, was located in the middle of the southern portion of the Lake Washington. Locations of the fixed and water test lines are presented in Figures 3 and 4 respectively.

Figure 3. ***Land Test Line at the King County International Airport.***

Figure 4. ***Water Test Line at Lake Washington.***

3.0 SURVEY PROCEDURE

3.1 Aerial Measurements

The aerial survey was planned to provide one-hundred percent coverage of the designated survey area with the aerial detector footprint. This task was accomplished by flying sets of parallel flight lines with the spacing twice the flight altitude. In the case of the King and Pierce Counties survey, with the flight altitude selected as 300 ft AGL, the flight lines were spaced 600 ft apart. The areas were surveyed at a nominal ground speed of 70 knots (~120 ft/sec.)

The basic methodology of the aerial radiological survey is presented in Figure 5.

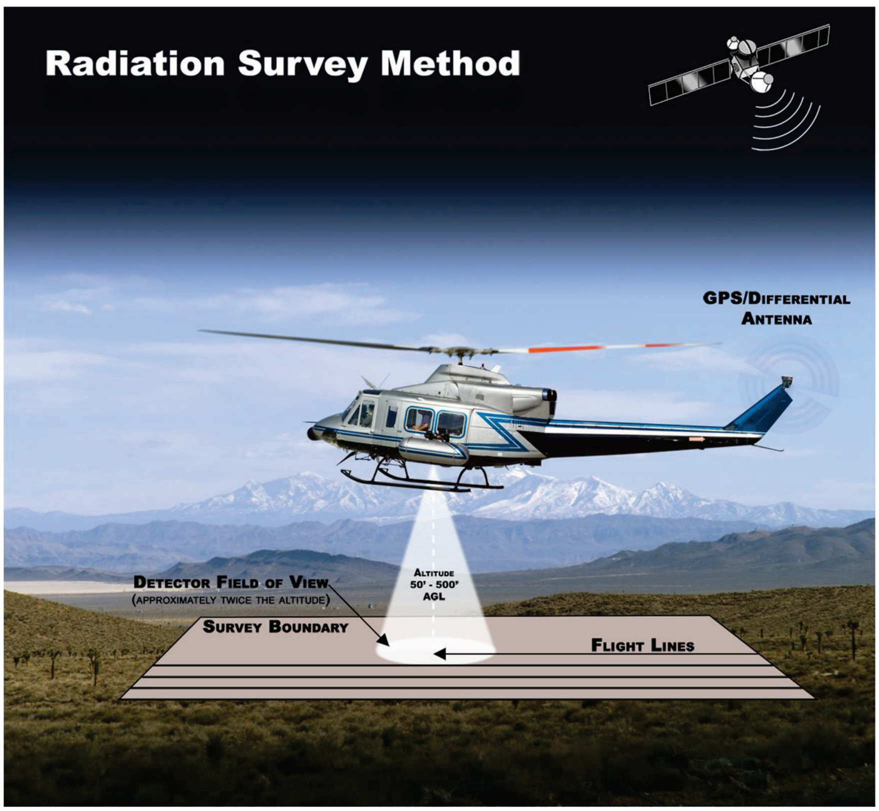


Figure 5. ***Methodology of the aerial radiation survey.***

Completing the King County survey area required establishing 135 flight lines, and as the helicopter's fuel capacity restricted the flight time to approximately 2.5 hrs, nine lines were flown during each flight, resulting in a total of 23 flights to completely cover the survey area.

As the Pierce County survey area was significantly smaller in surface area, it required only 62 flight lines and five 2.5-hr flights to complete the survey. In both cases the lines were arranged in a north-south direction and were flown starting with the lines on the western edge of the survey area progressing east.

At the beginning of each flight, the fixed land-test line and water-test-line were flown at the nominal survey altitude of 300 ft AGL. The same over flight was repeated after completion of the survey flight-lines, just before landing for refueling. The refueling was done at the King County International Airport/Boeing Field, Tukwila, Washington in the Clay Lacy Forward Base of Operation (FBO).

3.2 Ground-Based Measurements

The AMS aerial acquisition system is calibrated in terms of exposure rate at the Lake Mohave Test Line (LMTL) located approximately 50 miles south of Las Vegas, Nevada. The LMTL has been used since 1995 when a detailed characterization was performed [Colton and Hendricks, 1995]. A total of 100 in situ measurements were taken at the LMTL using a high purity germanium (HPGe) spectrometer and a pressurized ionization chamber (PIC). Based on those measurements, the exposure rate conversion factors for terrestrial radioactivity were derived from the past and current AMS aerial data acquisition systems.

To validate the local calibration at the survey site, a set of ground-based HPGe and PIC measurements were acquired at four locations along the fixed land test line. The PIC directly measures gamma ray exposure rate from all sources: terrestrial, cosmic and radon. As the aerial survey results are typically expressed as a terrestrial-only gamma-ray exposure rate (with the radon and cosmic component treated as background), the comparison with the PIC values can be done by adding the radon and cosmic contribution to exposure rate values derived from the aerial data.

For more direct measurements of the terrestrial-only component of exposure rate, a calibrated gamma-ray spectroscopic system was used. The methodology of deriving the exposure rate from the gamma spectra is described in the scientific literature [Beck, 1980; IAEA, 1990; Quindos, 2004]. For this project the approach based on Novak [Novak, 1988] was used. If the peak areas (cps) corresponding to Ra-226, Th-232, and K-40 in a spectrum, collected with a high resolution gamma spectroscopic system are converted to soil-specific activity in picocuries per gram (pCi/g), then the relationship shown in Equation 1 can be used to derive the terrestrial component of gamma ray exposure rate (*ER)* in micro-roentgens per hour (µR/h) at 1 m AGL.

$$ER\left[\frac{\mu R}{h}\right] = 1.82\left[\frac{\left(\frac{\mu R}{h}\right)}{\left(\frac{pCi}{g}\right)}\right] \times A(Ra)\left[\frac{pCi}{g}\right] + 2.82\left[\frac{\left(\frac{\mu R}{h}\right)}{\left(\frac{pCi}{g}\right)}\right] \times A(Th) + 0.179 \times A(K)\left[\frac{pCi}{g}\right] \qquad (1)$$

where, *A(Ra), A(Th), and A(K)* are the estimated activities of Ra-226, Th-232, and K-40.

During this survey, the measurements were averaged over a period of 10 min (600 sec) for the HPGe. For the PIC, ten 1-min integrated readings were taken at a height of 1 meter AGL. The locations of the ground-based measurements locations are presented in Figure 6.

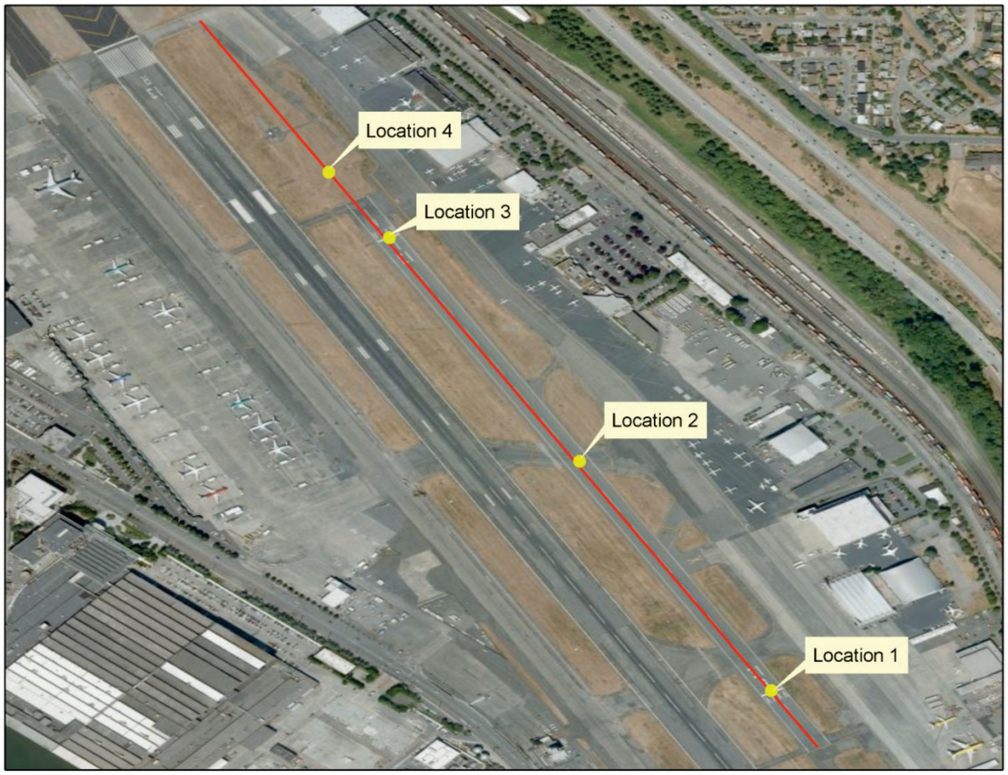


Figure 6. ***Ground-based measurement locations at the runway test line.***

4.0 SURVEY EQUIPMENT

4.1 Rotary Wing Bell 412 and RSI Data Acquisition System

AMS utilized a Bell-412 helicopter (Figure 7) and a detection system developed by Radiation Solutions Inc. for AMS applications (Figure 8). The Bell-412 is a twin engine utility helicopter that has been manufactured by Bell Helicopter since 1981. With a standard fuel capacity of 330 gallons, it is capable of flying for up to 3.7 hours, with a maximum range of 356 nautical miles and a cruising speed of 122 knots. However, with the AMS radiation survey configuration of 12 detectors, four crew members (two pilots, a mission scientist and an equipment operator), the AMS Bell 412 was capable of 2.5 hours of flight time with a survey speed of 70 knots (120 feet/sec) at survey altitude of 300 ft AGL.

Figure 7. ***AMS Bell 412 helicopter with externally mounted radiation detector pods.***

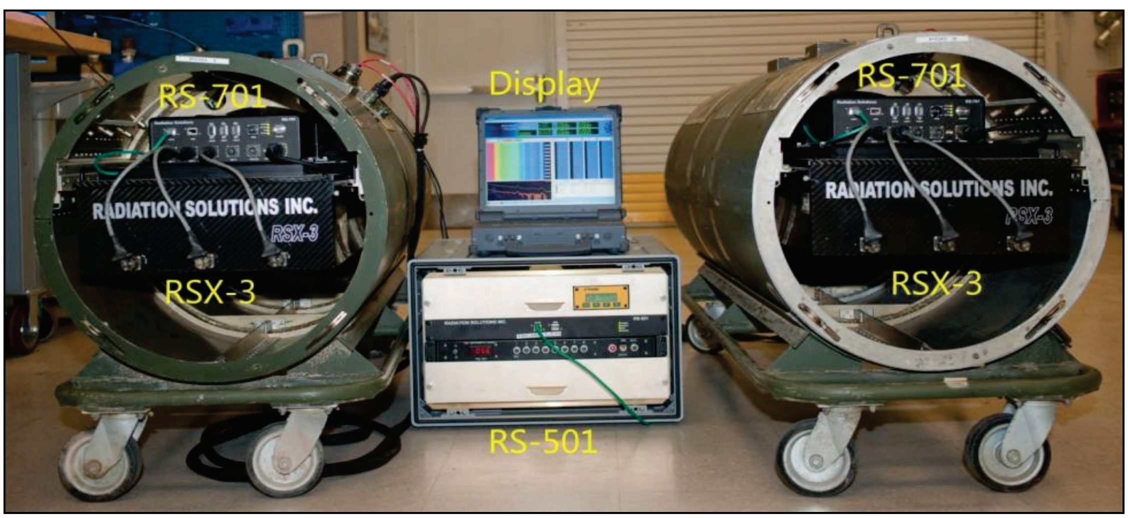


Figure 8. ***Components of the AMS RSI Aerial Radiation Data Acquisition System.***

The RSI system, built for AMS, employs a total of twelve sodium iodide thallium-activated NaI(*Tl*) crystals, fabricated as log-type detectors with dimensions of 2" × 4" × 16". These detectors are packaged in four RSX-3 units. Each RSX-3 unit is a carbon fiber box containing three 2" × 4" × 16" (128 cu in≈ 2 liter) sodium iodide thallium-activated NaI(*TlI*) crystals. The logs are coupled to a photomultiplier tube system that produces analog signals for digital analysis by the Advanced Digital Spectrometer (ADS) module (Figure 9).

Data from each of the three ADS modules are sent to one of four RS-701 consoles. An RS-501 aggregator box combines the outputs of the RSX-3/RS-701 units together, provides a power distribution unit, and houses the Trimble differential GPS receiver. Four RSX-3 boxes and four RS-701 consoles are fitted into the externally-mounted aluminum pods (two RSX-3s and two RS-701s per pod) on the left and right sides of the Bell 412 helicopter.

Figure 9. ***RSX-3 box with three 2”×4”×16”* sodium iodide thallium-activated *Na(Tl) crystals, three PMTs, and ADS modules.***

Each individual sodium iodide thallium-activated NaI(*Tl*) crystal detector has its own high-speed (60 MHz) analog-to-digital converter and a digital signal processor/field programmable gate array (DSP/FPGA) assembly. This module converts the analog signal from the detector to a digital spectrum with a 10^6 channel resolution. Using a unique detector energy calibration curve stored in each ADS module, the spectrum is linearized with a nominal value of 3 keV per channel and is compressed to the system’s native 1024 channels. The high-speed adaptive DSP processing allows each pulse to be corrected, if necessary, without distortion at very high data throughput rates, up to 250,000 counts per second (cps)/crystal, and up to 10 Hz data sampling. The combination of zero dead time, , individual crystal linearization, and accurate detector summation results in exceptionally clean spectra. These spectra are fed by 1Mbps RS-485 data connections to the system RS-701 console. The Detector Processing Unit (DPU) continuously monitors the state of health of the individual crystals and the system. Each crystal is individually gain stabilized using a multi-peak approach effectively eliminating the need for any pre-stabilization with external sources. This makes the unit capable of handling the wide dynamic range of radiation data seen in airborne applications.

4.1.1 Integrated Console (RS-701 Console)

Each of the four RSX-3 units is controlled by an RS-701 console mounted on top of the RSX-3 box (Figure 10). The console uses RSI proprietary analysis techniques to automatically adjust the gain of the detectors to compensate for changing temperature and aging drift effects. The system uses spectra of natural radioactive isotopes of uranium (U), potassium (K), and thorium (Th) present in all ground material to stabilize the system at startup and maintain this gain automatically during system use with no user input required. The RS-701 console has a built-in GPS receiver; however, as the AMS RSI system integrates multiple RS-701 consoles into a RS-501 aggregator, the built-in GPS receivers were used only as synchronizing timers and not for positioning. An additional modification to all RS-701 units was the power management option. All the RS-701 units power up when the helicopter main power is applied; versus the standard option of using the individual power up switches.

Figure 10. ***The RS-701 console on top of the RSX-3 detector box.***

4.1.2 Integrating Console (RS-501 Aggregator)

Four RS-701 consoles were integrated into a single RS-501 aggregator, shown in Figure 11. The RS-501 aggregator combines the outputs of the RSX-3/RS-701 units together, and provides a power distribution unit and differential GPS. The RS-501 unit retains ninety-six 15 minute files representing the last 24 hours of data acquisition recorded to a solid-state disk in a 24-hour circular buffer. The RS-501 is interfaced with the laptop computer running the RadAssist software used for system monitoring and real-time data display in flight.

Figure 11. ***RS-501 aggregator console with the Trimble GPS receiver.***

4.1.3 RadAssist Software

RadAssist is a software used to communicate with the RS-501 aggregator console to receive and interpret data and monitor detectors performance. It runs on a laptop computer connected to the RS-501 via an Ethernet link. RadAssist software allows user real-time control over the device and allows for monitoring and recording data. The Live Data View main screen and the optional GIS View are shown in Figure 12 and 13.

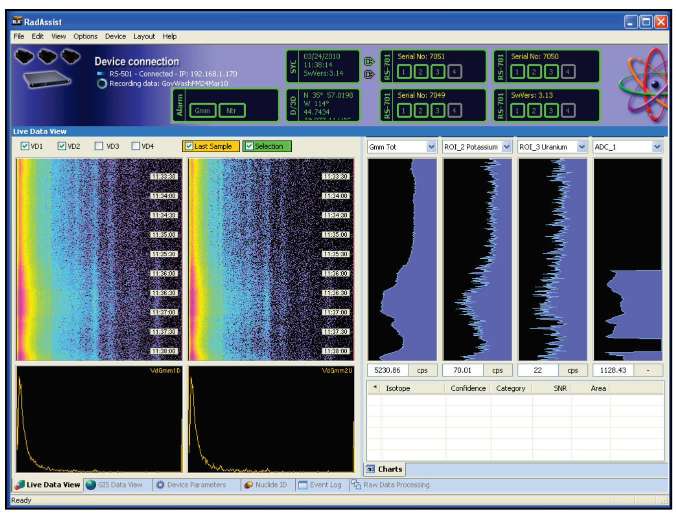


Figure 12. ***RadAssist Live Data View screen***

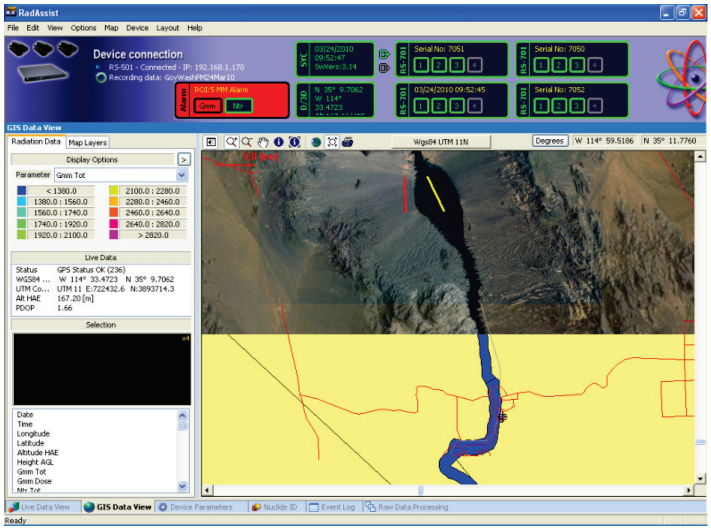


Figure 13. ***RadAssist GIS screen.***

4.2 HPGe and PIC

The ground-based verification measurements were made with the calibrated high-resolution gamma-ray spectroscopic system and the pressurized ionization chamber (Figure 14).

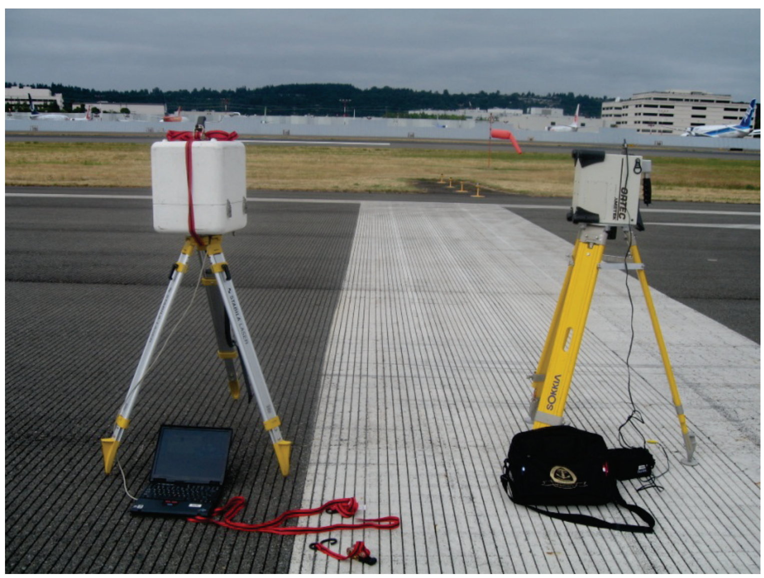


Figure 14. ***The PIC (left) and HPGe (right) used for measurements at the land test line.***

The gamma-ray spectroscopic system utilized a mechanically cooled, 15% efficient high-purity germanium detector (ORTEC Detective-EX), mounted on a dedicated tripod one meter above the ground. The gamma spectra were collected for 600 live time (t_{Live}) seconds. The ORTEC Gamma Vision 6.01 software was used to collect and analyze the spectra.

The high-pressure ion ionization chamber is a highly sensitive and stable detector for gamma radiation. Gamma-ray photons travel through the pressurized argon gas (25 atm), ionizing the gas. A high-voltage power supply biases the detector cathode sweeping the ions out of the gas and generating the current, which is measured by the electrometer and converted to output voltage, a direct measure of the exposure rate. The PIC used for this project was the GE Energy Reuter-Stokes, Inc Model RSS 131. Average of ten 1-min-integrated measurements was collected per location.

5.0 ANALYSIS PROCEDURES

AMS uses a dedicated in-house developed data processing methodology and software, the PC-based Radiation and Environmental Data Analysis Computer (PC-REDAC). The collected spectral data are processed in several steps, starting with the correction of the gross-counts to the nominal flight altitude, correcting for all background components (radon, cosmic, helicopter), deriving terrestrial exposure rate, extract man-made activity, and finally activity from individual isotopes. All data are then presented as contour maps using commercial GIS software (ESRI ArcGIS Desktop 10.0).

5.1 Gross Count

The gross count (GC) extraction method utilizes the integral counting rate in a single spectral window covering the relevant energy range. Typical background in that window (assumed constant for a complete flight) is removed and the net count rate is adjusted to the nominal flight altitude by the following relationship:

$$C_{GC} = \left(\frac{1}{t_{Live}} \sum_{E=24}^{3027} C(E) - C_N \right) e^{\lambda (H - H_0)} \quad (2)$$

where,

C_{GC} = gross count rate at nominal survey altitude (cps)
t_{Live} = live time during collection of gamma spectrum (s)
$C(E)$ = counts in the spectrum channel of energy E (keV)
C_N = count rate attributable to nonterrestrial sources (cps)
H = actual aircraft (radar measured) altitude, (ft or m above ground level)
H_0 = nominal flight altitude, (ft or m)
λ = gamma-ray air attenuation coefficient (ft^{-1} or m^{-1}).

The non- terrestrial background count rate C_N, was determined from the test line altitude profile and adjusted on a flight-by-flight basis, with contributions from cosmic rays, the aircraft system, and airborne radon. The air attenuation coefficient λ is determined from the altitude spiral flown over the test line.

5.2 Terrestrial Exposure Rate

The terrestrial exposure rate is derived from the integrated counting rate in the gamma energy spectrum range between 24 keV and 3027 keV. Generally, this can only be performed by a detailed analysis of the gamma energy spectrum and by using models that relate exposure rate to each gamma energy photopeak in the spectrum. However, for the background surveys, when the primary isotopes of interest are naturally occurring radioactive materials (NORMs), the exposure rate calibration coefficients can be derived experimentally from the aerial data collected from flight over a calibrated test line. In that case, the count rate, measured in counts per second (cps) at survey altitude, is converted to exposure rate (*ER*) in μR/h at 1 meter AGL using the following equation:

$$ER = \frac{C_{GC}}{F} \tag{3}$$

where,

C_{GC} = gross count rate at survey altitude (cps)

F = experimentally derived conversion factor (cps/μR h^{-1}).

The conversion factor, *F*, is determined from the documented calibration test lines located at Lake Mohave in Clark County, Nevada [Colton and Hendricks, 1995]. The calibration range has been used to relate the count rate observed at different altitudes with different detector arrays to the exposure rate measured at 1 meter (3.3 feet) AGL using pressurized ionization chambers. The conversion factor assumes a uniformly distributed radiation source: 1) covering an area that is a large when compared to the field of view of the detector system (a circle with a diameter roughly twice the altitude of the aircraft), and 2) having a gamma-ray energy distribution similar to that of the natural background of the calibration test line. Because man-made activity generally does not conform to conditions described in 1) and 2), the conversion factor described may not accurately describe exposure rate from man-made activity detected in survey activities.

5.3 Man-Made Gross Count

The aerial data were also used to determine the location of man-made radionuclides. The man-made gross count (MMGC) is the portion of the gross count that is directly attributed to the gamma rays from the man-made radionuclides: industrial, medical, etc. Evidence of man-made radionuclides is sometimes indicated by obvious increases in the gross count rate. However, slight variations in the gross count do not always indicate the presence of a man-made anomaly, since significant variations can result from changes in the underlying geology or changes in the ground coverage (e.g., river, dense vegetation, buildings).

A MMGC algorithm has been developed that uses spectral energy extraction techniques to suppress natural variations and improve separation of man-made from natural radioactivity. This algorithm takes advantage of the fact that while background radiation levels often vary by a factor of two or more within a survey area, background spectral shapes remain essentially constant. More specifically, the ratio of natural components in any two regions (windows) of the energy spectrum is nearly constant.

Although this procedure can be applied to any region of the gamma-energy spectrum, for general man-made activity, common practice is to place all counts from 24 to 1394 keV into the man-made window (low energy sum), where most of the long-lived, man-made radionuclides emit radiation, and to place all counts from 1394 to 3027 keV into the natural window (high energy sum), where most of the naturally occurring radionuclides emit radiation. The MMGC rate can be expressed analytically in terms of the integrated count rates in specific gamma energy spectral windows (keV):

$$C_{MM} = \sum_{E=24}^{1394} C(E) - K_{MM} \sum_{E=1394}^{3027} C(E) \tag{4}$$

where,

C_{MM} = MMGC rate at the survey altitude (cps)

$C(E)$ = count rate in the gamma-ray energy spectrum at the energy E (cps)

$$K_{MM} = \frac{\sum_{E=24}^{1394} C_{ref}(E)}{\sum_{E=1394}^{3027} C_{ref}(E)} \tag{5}$$

The K_{MM} ratio is of the low-energy counts to high-energy counts in the background spectrum measured over an area that only contains gamma radiation from naturally occurring radionuclides. $C_{ref}(E)$ represents count rate in the reference gamma energy spectrum at the energy E.

This MMGC algorithm is sensitive to low levels of man-made radiation even in the presence of large variations in the natural background. When man-made radioactivity has been identified, a detailed analysis of the gamma energy spectrum is conducted to ascertain which radionuclides are present.

5.4 Isotope Extraction, General Three Window

The three-window extraction algorithm is a linear Compton tail removal technique. The algorithm uses two relatively narrow windows on each side of the photo peak of interest (third window). The Compton contribution, assumed to be in the central window, is interpolated from the outside window contributions. The actual ratio of background central counts to the sum of the outside counts is derived from measured flight data as with other extractions. AMS uses a three-window algorithm to extract specific isotopes when looking at an unknown survey or suspect area. The three window algorithm methodology is presented in Figure 15 and the following equation:

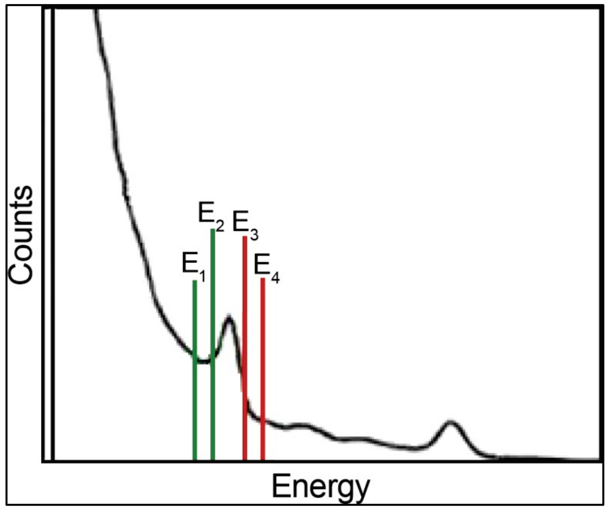


Figure 15. ***3-window algorithm applied to a typical spectrum.***

$$C_{3-window} = \sum_{E=E_2}^{E_3} C(E) - K_3 \left[\sum_{E=E_1}^{E_2} C(E) + \sum_{E=E_3}^{E_4} C(E) \right] \quad (6)$$

where K_3 is defined as,

$$K_3 = \frac{\sum_{E=E_2}^{E_3} C_{ref}(E)}{\sum_{E=E_1}^{E_2} C_{ref}(E) + \sum_{E=E_3}^{E_4} C_{ref}(E)} \quad (7)$$

where,

$C_{3\text{-}window}$ = count rate from the 3-window algorithm

E_n = limiting energies of the windows ($E_1<E_2<E_3<E_4$)

K_3 = ratio of the counts in the primary window to the counts in the two background windows in a reference region of the survey area

The three-window algorithm is also very useful in extracting low-energy photopeak counts where the shape of the Compton-scatter contributions from other isotopes is changing significantly.

5.5 Anomalies

Radiological anomalies are defined as radiation readings that are significantly higher than local background. In terms of isotopes that are not part of natural background, the anomalies are identified using man-made extraction algorithm described in Section 5.3. The MMGC algorithm eliminates the natural background counts, and the remaining signal is assumed to be of man-made origins and requires further investigation.

However, if the radiological anomaly is caused by the strong signal of a naturally occurring isotope, the criterion of six standard deviations (6 σ) above local background is applied. The 6σ value is selected as a compromise between the sensitivity of the system and elimination of the statistical false positives.

An example of the time series with the radiation anomaly is shown in Figure 16.

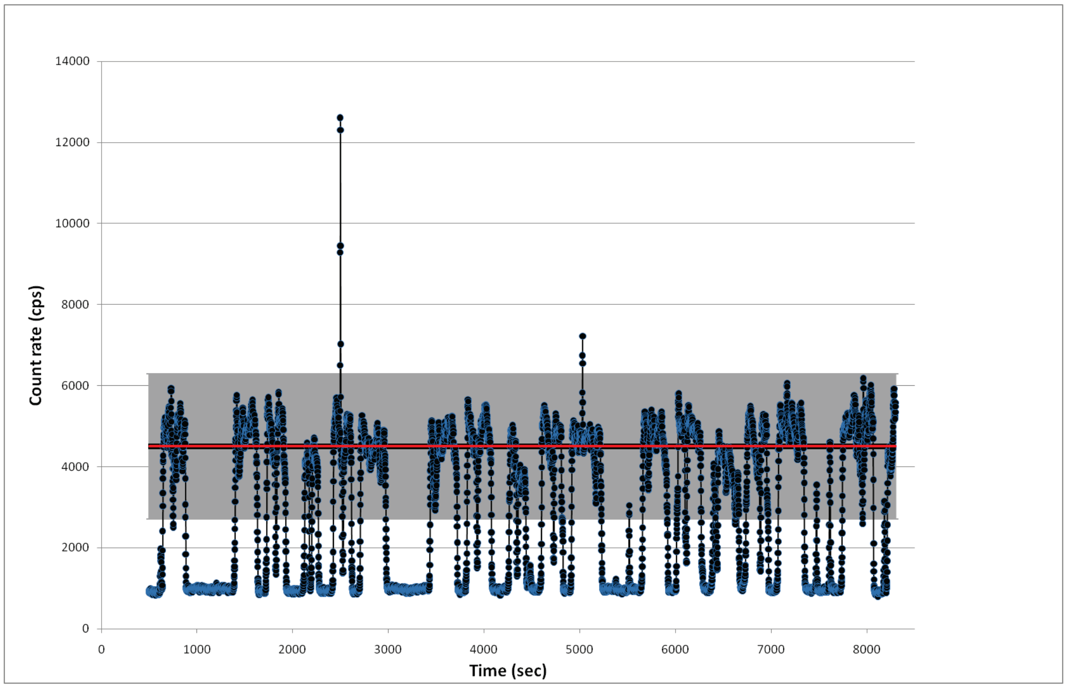


Figure 16. ***Example of time series of a flight with radiation anomaly (Flt#3, July 11, 2011).***

The red line represents the average count rate in the vicinity of the anomaly, and the grey band represents 6 standard deviations (6 σ) above and below the average. The two peaks represent the data collected on the two flight lines close to the radiation source.

5.6 Quality Controls

During radiation surveys, AMS applies several quality checks to monitor the performance and stability of the data acquisition system. They are:

Before takeoff, one minute of data are acquired with a 10 µCi Cs-137 calibration source placed at the specified location on the each of the pods containing radiation detectors.

Before takeoff, four minutes of background data are acquired at the helicopter parking location that remains constant during the survey.

Collected source and background data are used to perform a series of checks of detectors linearity, energy calibration, and efficiency. These actions are called the “pre-flight.”

The pre-flight is reviewed by the mission scientist for consistency.

During the survey, land-based and water-based test lines are established and they are over-flown before and after each survey flight. The test line data are used to verify the data acquisition system performance before and after each survey flight, and to derive the flight specific values of radon and system background. The test line length is selected to generate about 60 data points (one minute overfly duration).

After landing, one minute's worth of background data are collected at the helicopter parking location to verify once more that nothing has changed in the acquisition system.

The collected survey data are checked for consistency with the set of computer subroutines called "post-flight", to discover any dropouts in GPS signal, detector stabilization issues, increase in system electronic noise level, etc.

5.7 Attenuation and Sensitivity

To compensate for the variation of the flight altitude above terrain from the nominal survey altitude, the numerical correction is applied to the GC data using Equation 2. The altitude and background corrected GC values are used to derive the ground exposure rate.

The critical parameter for the altitude correction is an air attenuation coefficient λ. As the λ is dependent on the air density, the local λ is derived for the survey location. This process involves flying an altitude spiral over the land test line. The typical altitudes are 150, 300, 500, 750, 1000, 1500 and 3000 feet AGL. The lowest altitude is typically selected based on flight safety; the highest selected altitude is 3000 ft AGL where there is negligible contribution from terrestrial radiation. To derive the local air attenuation coefficient, the average count rate for each altitude is plotted on a log scale, and a liner equation is fit. Typical results are presented in Figure 17.

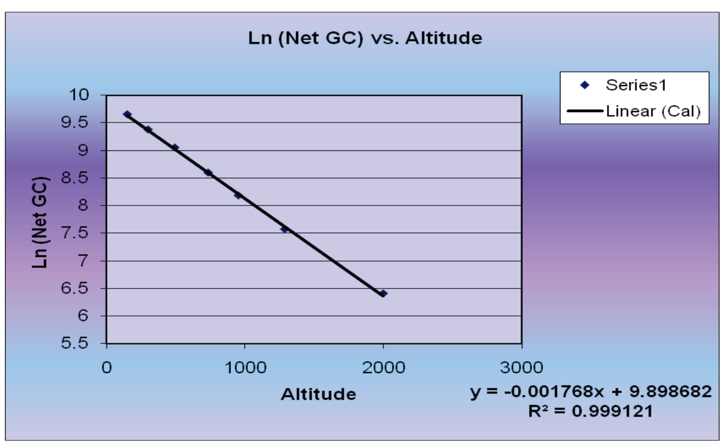


Figure 17. ***Example of plot used to derive local air attenuation coefficient.***

The fit equation parameter of 0.001768 is the linear air attenuation coefficient λ in $feet^{-1}$ for the location where the spiral was flown. This process was used to derive the λ for the King and Pierce Counties survey.

The AMS RSI system sensitivity was derived from calibration flights flown over the Lake Mohave Test Line (LMTL) in 2010 when the RSI was adopted as the primary AMS survey equipment. As a result of these calibration flights, a calibration coefficient converting the net counts at altitude to exposure rate at 1 m above ground level was derived and the results are presented in Figure 18.

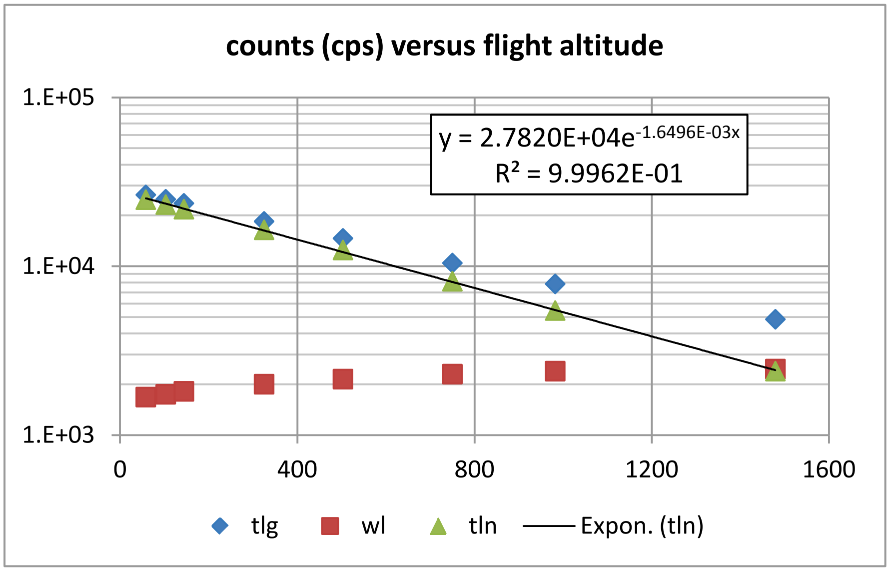


Figure 18. ***Example of results of sensitivity analysis for the RSI system using LMTL data (flight 08/09/2011-2).***

The graph in Fig 18 shows the count rate collected over land test line (tlg), water test line (wl), and net counts (tln) plotted on a logarithmic scale with the fitted regression line [Expon.(tln)].

The data from the LMTL were used to derive the exposure rate conversion coefficient for the King and Pierce Counties survey. The average values of three calibration flights flown in September of 2011 were used for these calculations (Table 1).

Table 1. Summary results of the LMTL calibration flights.

Flight	Net Average Count Rate (cps)	Average Air Attenuation Coefficient (feet^{-1})
09/08/2011-1	27350	0.0016624
09/08/2011-2	27820	0.0016496
09/08/2011-3	27780	0.0016060
Average	27650	0.0016393
Standard Deviation	261	0.0000296

The LMTL exposure rate ground truth was measured as 8.5 μR/h over the land portion of the LMTL [Colton et al, 1995]. Using the methodology described earlier, the conversion exposure rate conversion coefficient *ER(A)* based on the LMTL data (bold values in Table 1) for *A*= 300 feet altitude is:

$$ER(A) = \frac{27650\ cps}{8.5\ \mu R\ h^{-1}} \times e^{(-0.0016393\ ft^{-1} \times 300\ ft)} = 1989\ cps/(\mu R\ h^{-1}) \qquad (8)$$

This terrestrial exposure rate conversion coefficient is measured and calculated using the natural background gamma energy of the LMTL. In this form, the derived terrestrial exposure rate conversion factor is suitable for calculating the terrestrial exposure values within a background radiation baseline survey area; however, it may underestimate or overestimate the exposure rate values when applied to data from areas containing man-made radioisotopes.

6.0 SURVEY PROCEDURE

The airborne gamma survey consists of a series of individual flights defined as the flight time between take off and consequent landing, in the case of the Bell 412 with 12 detectors and 4 personnel onboard a flight of about 2.5 hours in duration. Each flight starts and ends with collecting data for one minute on the ground, followed by the start and later end overfly of the land test line and water test line, and finally flying the flight survey lines that had been pre-programmed into the helicopter steering system. An example of a single flight with all flight components labeled is presented in Figure 19.

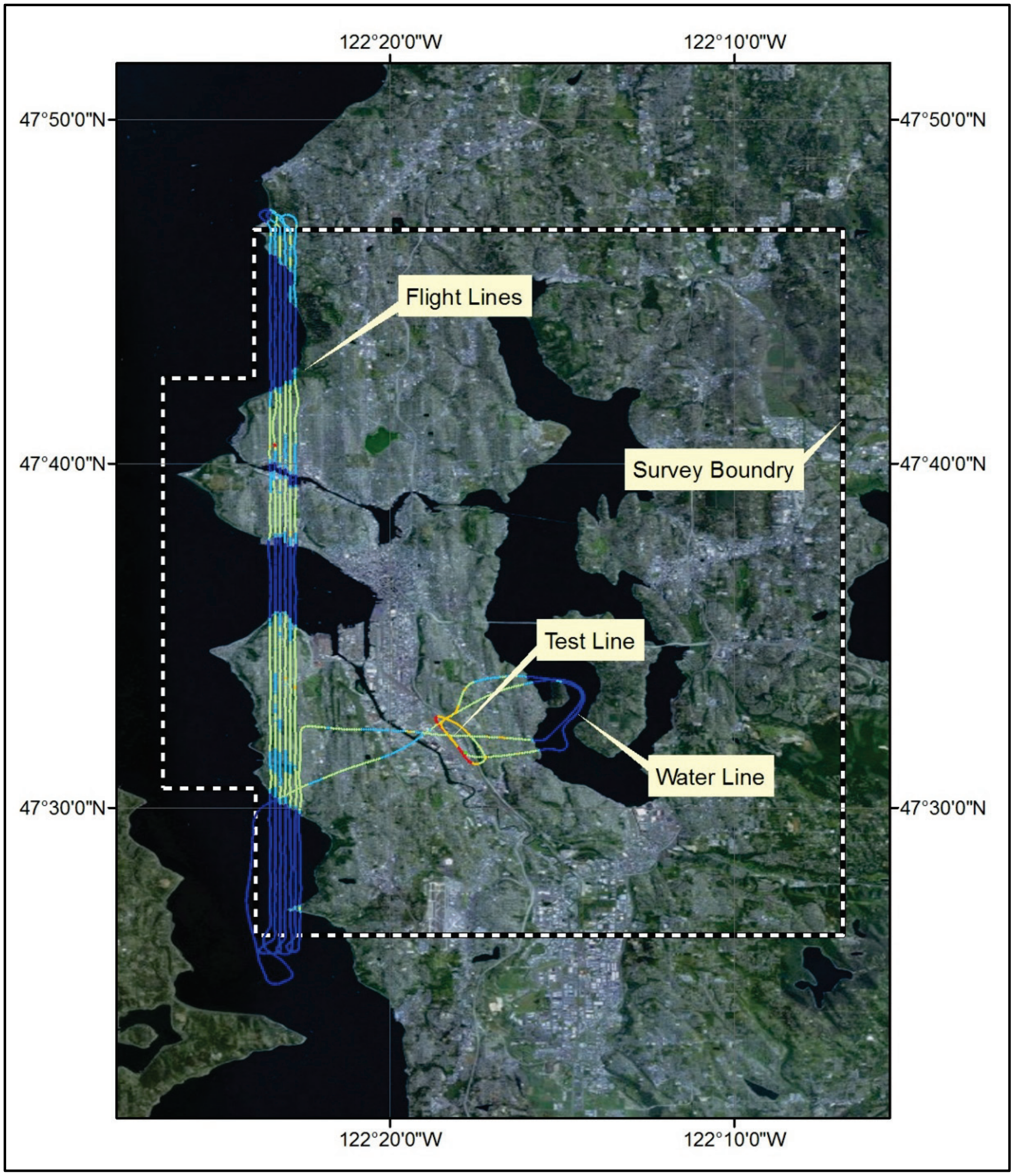


Figure 19. ***Survey flight components.***

7.0 RESULTS

7.1 King and Pierce Counties Survey Altitude Spiral

The altitude spiral flight was conducted on July 18, 2011, from 11:10 to 13:50 PDT over the land test line, which was established on the shorter runway at King County International Airport. For this survey, the nominal altitudes for the spiral were 150, 300, 600, 750, 1000, 1500 and 3000 feet AGL. Results of the spiral flight are presented in Figure 20. The fit to the background corrected net count rate versus nominal flight altitude is good (goodness of fit was R^2=0.99985). The resulting local air attenuation coefficient was **λ=0.00186 ft^{-1}**. This coefficient was used in the data processing to correct the count rate for the altitude variation for all King and Pierce Counties survey flights.

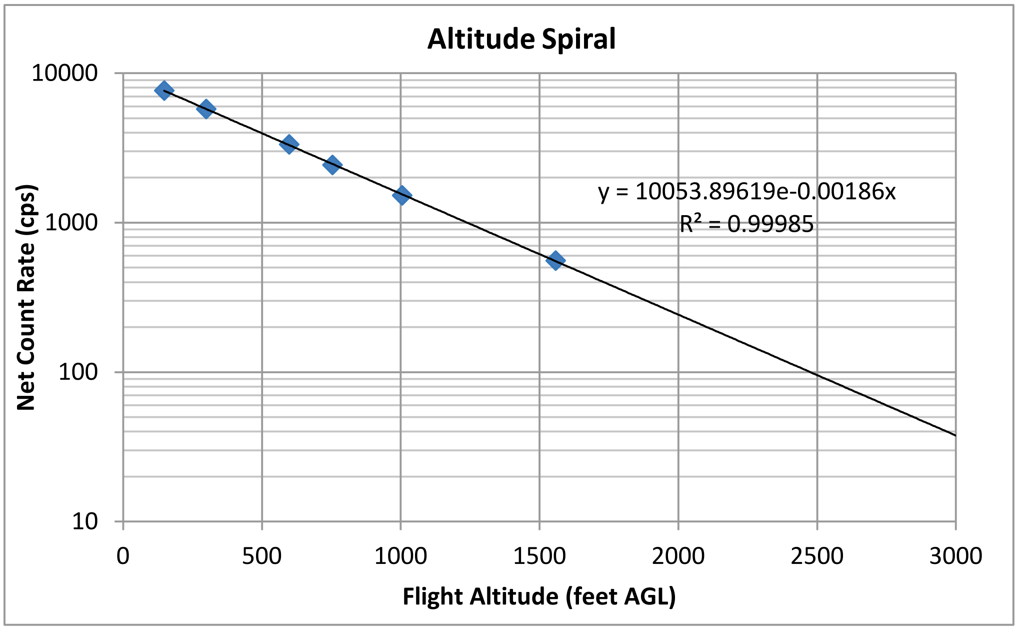


Figure 20. ***Results of altitude spiral flight during King and Pierce Counties survey.***

Using the combination of the calibration conversion coefficient at the LMTL of 3253 cps/(μR h^{-1}), and the local air attenuation coefficient from the test line at King County International Airport λ=0.00186 ft^{-1} , the exposure rate conversion coefficient used for producing the map data products for this survey was:

$$ER(A) = 3253\,\frac{cps}{\mu R\ h^{-1}} \times e^{(-0.00186 ft^{-1} \times 300\ ft)} = 1862\,\frac{cps}{\mu R\ h^{-1}} \tag{9}$$

7.2 Quality Control Checks

7.2.1 One Minute on the Ground

When planning the survey, AMS planners asked the FBO to provide a designated parking location for the helicopter that would be available throughout the duration of the survey. The purpose of this was to provide a consistent location for an additional consistency check. Before takeoff, but after the system is powered on for at least 30 minutes for stabilization, 60 seconds worth of data were recorded. A similar process was repeated after landing, but before shutting down the system. By performing this check on the ground, with a fixed distance from the detectors to the ground, the impact of variations in the flight altitude was eliminated. This particular quality check was one more way to verify that the system was operating correctly (e.g., summing counts from all 12 crystals) during the survey data gathering flight. Results of the 1-minute ground checks before and after survey flights are presented in Figures 21and 22, respectively. They show minimal variability in the count rates before and after flights, typically within statistical error, indicating correct system operation. The variability between individual flights was likely due to variable outdoor radon levels.

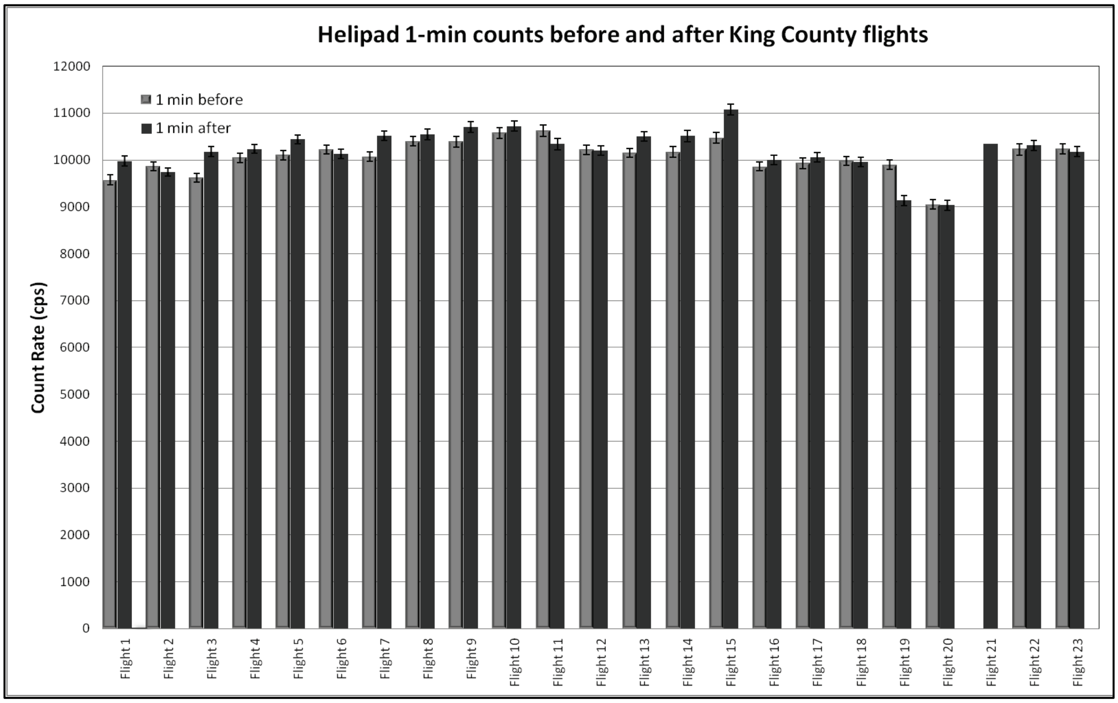


Figure 21. ***One minute count data at the helicopter parking location before and after King County flights.***

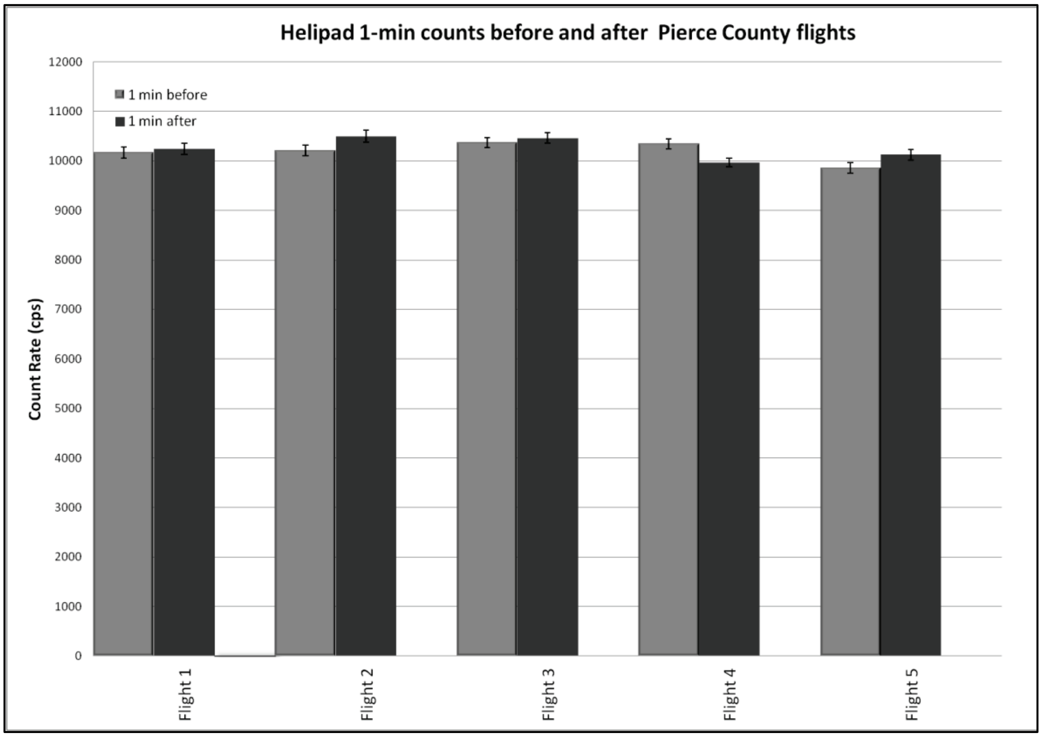
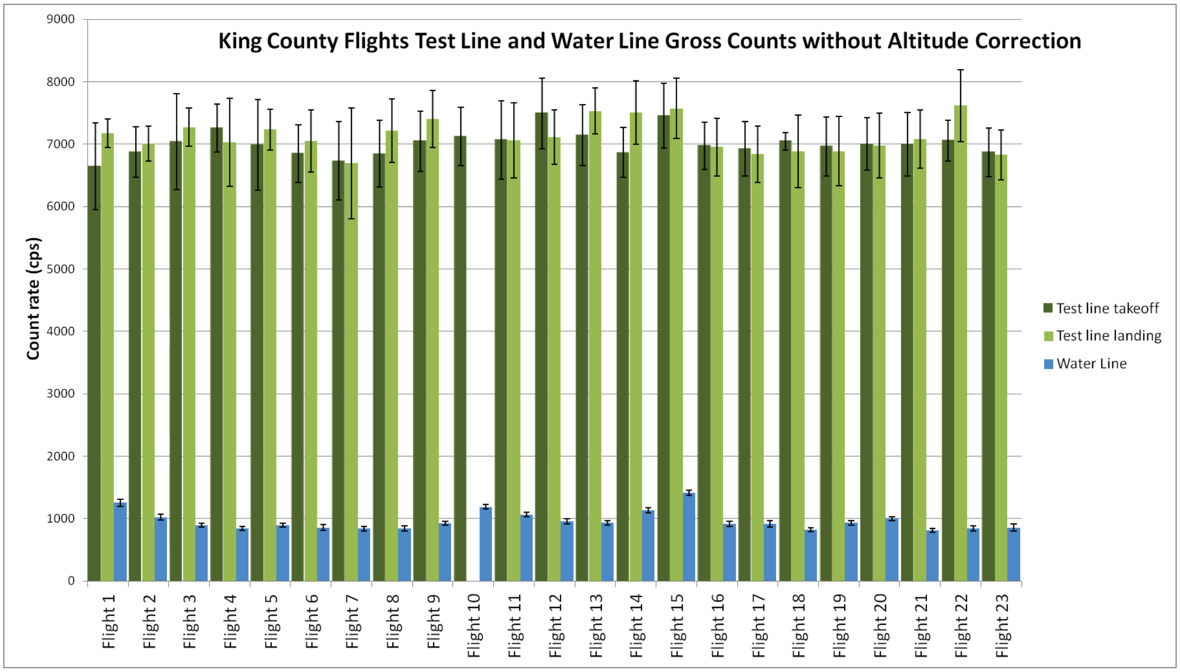


Figure 22. ***One minute count data at the helicopter parking location before and after Pierce County flights.***

7.2.2 Survey Test Line Overfly

Another performance verification check is to conduct a land test line overfly at survey altitude (300 ft AGL) at the beginning and at the end of each individual flight. In the case of the King and Pierce Counties survey, the land test line (King County airport short runway) was flown at the beginning of each survey flight, just after takeoff, and re-flown after completion of the survey flight, just before landing. Twenty-three flights were required to cover the King County survey area, so the test line was flown 46 times. However, the malfunctioning helicopter communication radio transmitter forced immediate landing towards the end of Flight #10 before completing the end-of-flight test line overfly and therefore only 45 test line data sets were collected. The resulting data for the King County survey flights are presented in Figures 23a and 23b, and results for the Pierce County survey flights are shown in Figures 24a and 24b. Figures 23a and 24a show counts not corrected for altitude, and in Figures 23b and 24b counts were corrected for altitude variations. Again, the variations between the counts before and after each survey flight are within statistical error, indicating consistent system performance. The correction for altitude did not significantly change the counts, indicating proper altitude maintenance by the pilots during the test line overfly.



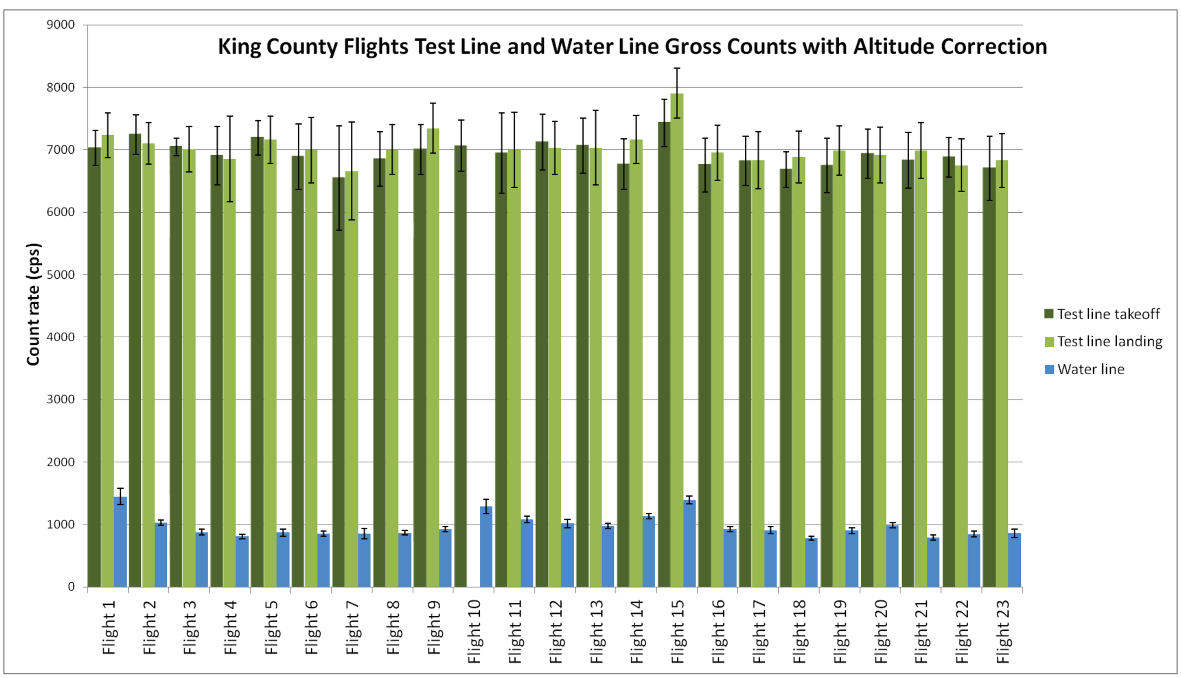
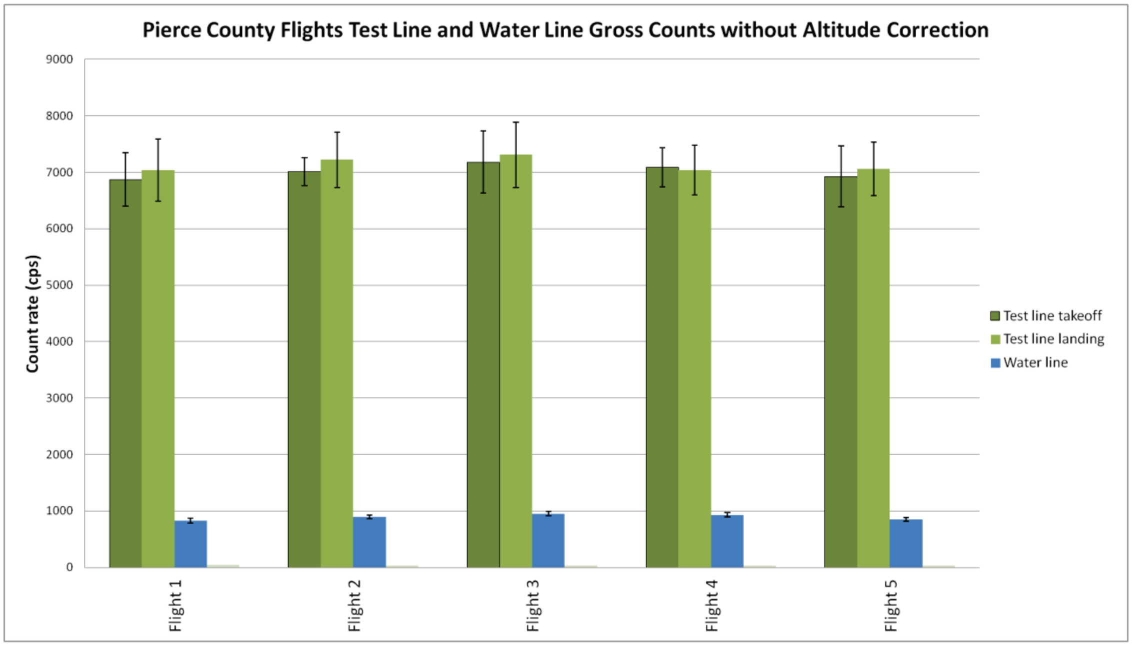


Figure 23. ***Test line counts during King County survey without (a) and with (b) altitude correction.***



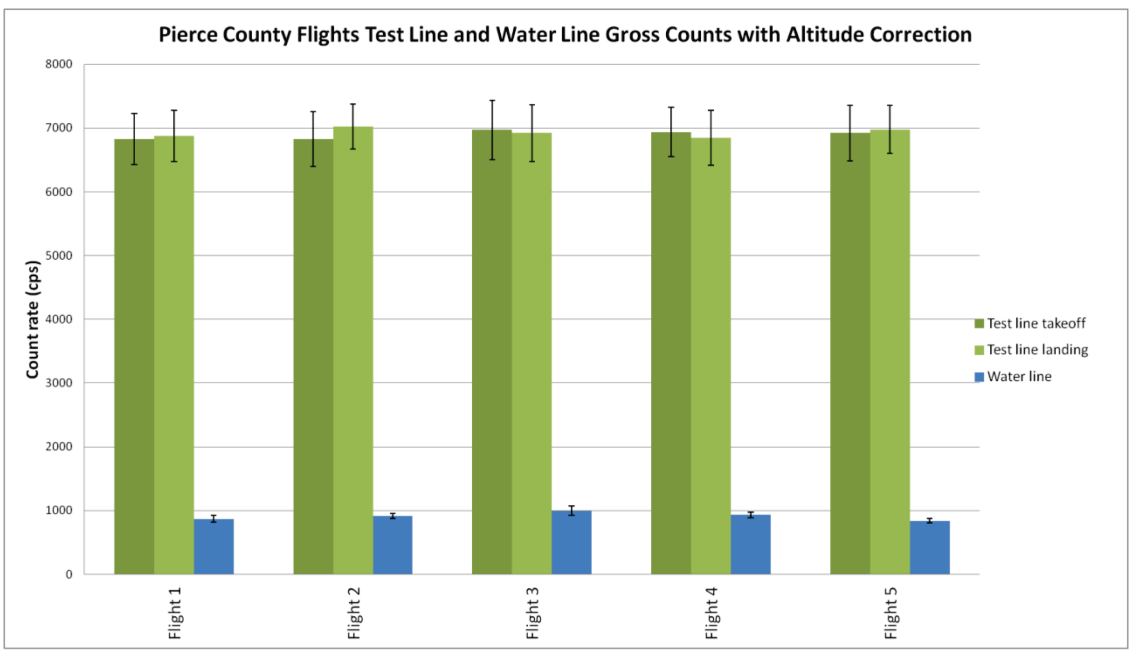
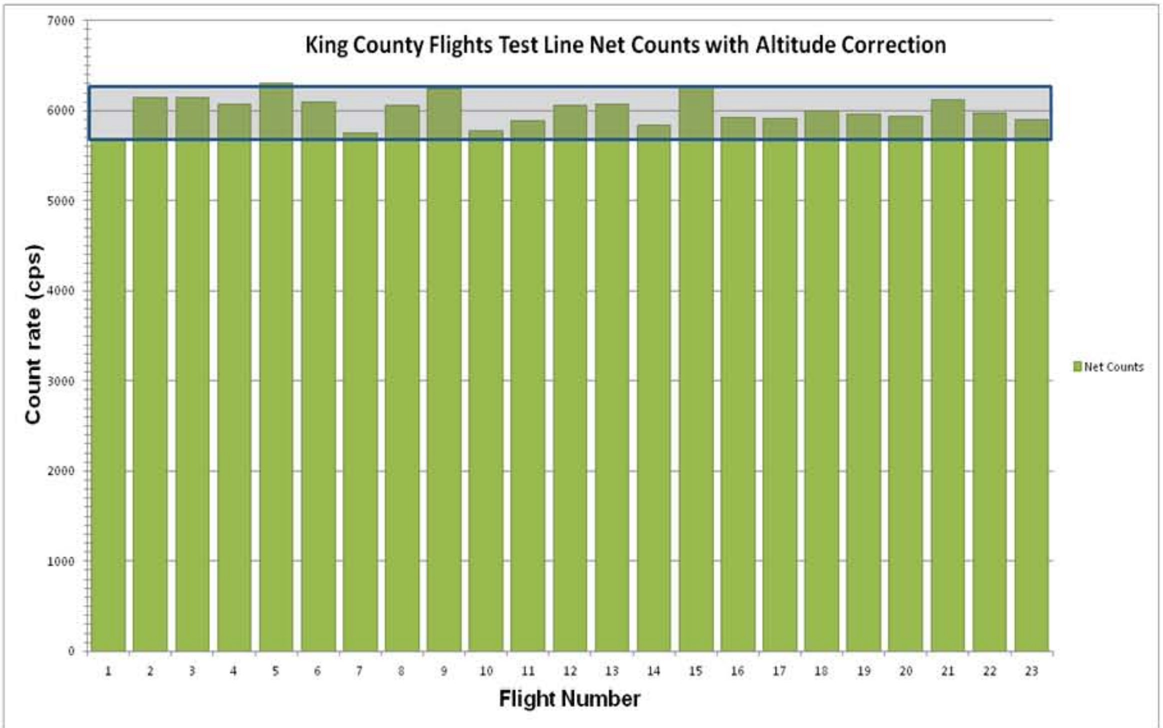


Figure 24. ***Test line counts during Pierce County survey without (a) and with (b) altitude correction.***

The survey test line overfly performed at the start and at the end of each flight serves two purposes. First, it is a final check on system sensitivity and background radiation of the aircraft, discussed above. Second, it monitors the effect of soil moisture in the survey area. The survey test line was selected to be easy to navigate, be of uniform radioactivity, and be typical of the survey area in terms of soil moisture content. The IAEA [IAEA 2003] recommends that after live time, background, and height correction, the average count rate over the test line should be within 10% of the mean count rate for all previous flights. Failure to meet this requirement may be because of equipment malfunction or a change in aircraft background. If the change in count rate is due to a uniform change in soil moisture in the survey area due to widespread precipitation, the IAEA recommends that flying should be temporarily suspended. This was not necessary during the King and Pierce Counties surveys as can be seen from Figures 25a and 25b, respectively.

7.2.3 Water Line Overfly

Overflying the water line during each survey flight serves two functions. The primary purpose is to monitor the ambient radon contribution to the signal detected by the radiation detectors. The secondary purpose allows for easy monitoring of the maintenance of altitude over a flat surface, and therefore increases overall pilots' precision. The results of the average altitude maintained over the water line for the 23 King County flights are presented in Figure 26a. A similar graph for the five Pierce County flights is presented in Figure 26b. Both graphs display a high quality of precision flying, as the altitude for the majority of flights was within ±30 ft of the target altitude of 300 ft AGL. However, it is important to notice some count rate variability due to changes in the ambient radon level.



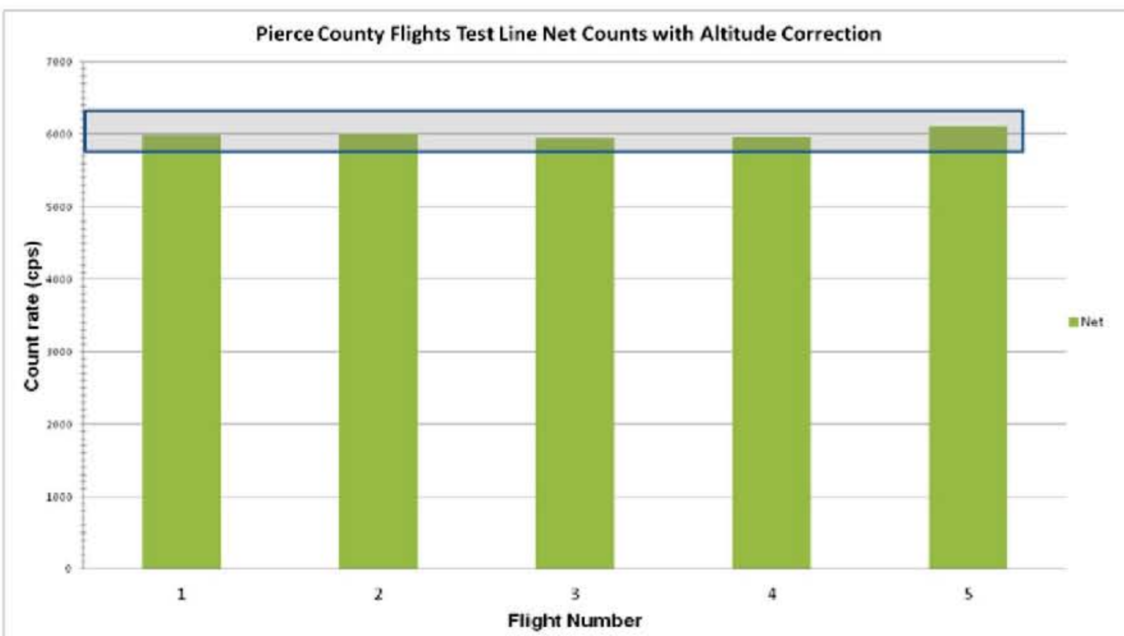
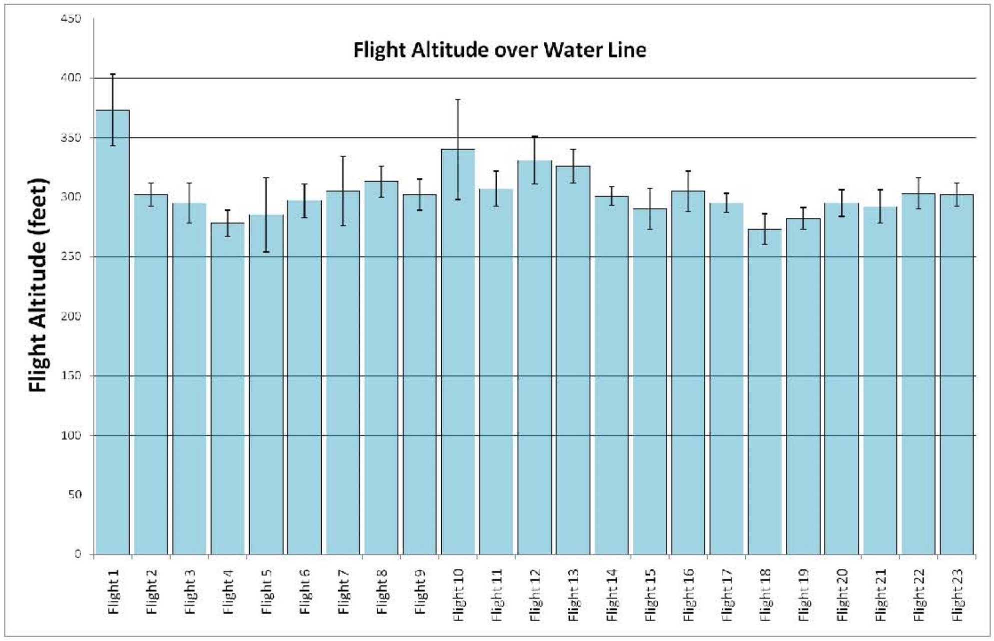


Figure 25. ***The Test Line net counts with the 10% of average criterion for the King (a) and Pierce (b) Counties flights.***



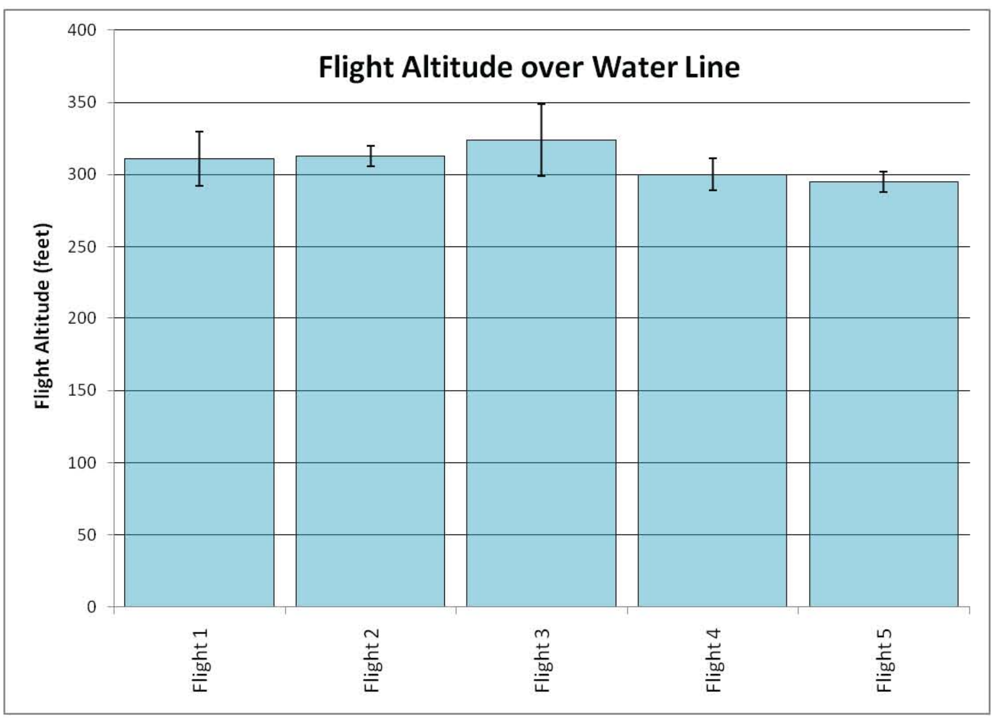


Figure 26. ***Distribution of flight altitude over water line for the King (a) and Pierce (b) Counties survey flights.***

7.2.4 Ground Truth Verification

To confirm the calibration (count rate to exposure rate conversion coefficient) used to express the results of the background radiological survey of King and Pierce Counties, a series of measurements using a calibrated Reuter-Stokes PIC and an HPGe gamma spectroscopy system were acquired along the land test line. The PIC measures the exposure rate directly in milli-roentgen per hour (mR/hr), but the HPGe spectral data needed to be converted to soil concentrations of Ra-226, Th-232, and K-40. The terrestrial exposure rates are then estimated indirectly from the gamma energy spectra recorded in flight using only information about the unscattered γ-ray flux density at 1m above the ground. Using the soil concentrations, the exposure rate at one meter AGL was estimated using the methodology described earlier in Equation 1 in Section 3.2.

Results of PIC measurements are presented in Table 2.

Table 2. Results of the PIC measurements along the test line.

Location	PIC (µR/hr)	PIC – Cosmic (µR/hr)
1 (runway)	5.2 ± 0.2	1.9
2 (runway)	5.3 ± 0.3	2.0
3 (runway)	5.3 ± 0.3	2.0
4 (grass)	6.2 ± 0.3	2.9

Results of the HPGe measurements are summarized in Table 3.

Table 3. Results of the HPGe measurements along the test line.

Location	Estimated Soil Concentration (pCi/g)			HPGe Exposure Rate (µR/hr)
	Ra-226	Th-232	K-40	
1 (runway)	0.504	0.143	6.1	2.4
2 (runway)	0.258	0.241	6.66	2.3
3 (runway)	0.359	0.287	5.89	2.5
4 (grass)	0.314	0.488	5.89	3.0

The PIC records the gamma signal from all components of natural background terrestrial, radon, and cosmic. In contrast, the HPGe estimates exposure rate only from terrestrial and the radon decay products component. The cosmic gamma rays are typically high-energy photons and are not registered by the HPGe crystal.

Therefore, to compare the PIC and HPGe results, the cosmic contribution needs to be added to HPGe results. The cosmic radiation contribution to the exposure rate at the earth's surface is a function of the elevation above sea level (i.e., barometric pressure) (Figure 27). Exposure rate cosmic component at the altitude of the test line (runway at 21 ft MSL) was estimated to be 3.3 µR/hr [Reuter-Stokes, 1983]. This value is very close to the 3.6 µR/hr at 760 mmHg (sea level) adopted by UNSCEAR (1977). The terrestrial exposure rates estimated from the HPGe spectrometer measurements seem reliable due to satisfactory comparison with the results of the corrected PIC measurements, for example both methods show higher ER on the grass than on the paved runway.

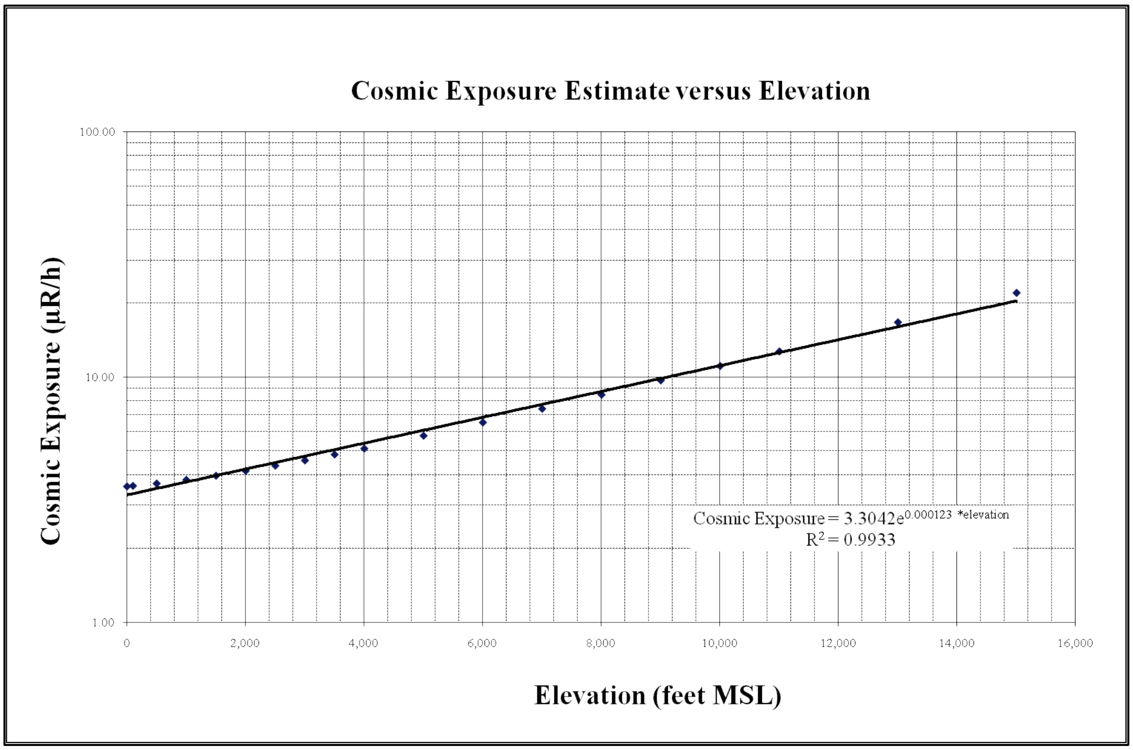


Figure 27. ***Cosmic exposure rate at different elevation [Reuter-Stokes, 1983].***

Results of the ground measurements were compared with the terrestrial exposure rate measured by the aerial system. The ground truth measurements were acquired on July 20, 2011, between 09:00 and 10:00 at the locations shown in Figure 6 at the beginning, middle, and end of the runway and at the grassy field adjacent to the runway. The test line overfly for Flight #16 (takeoff at 08:35 and before landing at 10:35) was used for comparison. The integration time was approximately 60 sec.

Average count rate after takeoff was 6972 cps, and 6952 cps before landing, suggesting no significant change in radon concentration. The average count rate between the two passes was 6962 cps. The corresponding water line count rate was 1106 cps resulting in net counts of 5856 cps. Converting the net counts rate of 5856 cps to exposure rate using conversion coefficient derived earlier of 1862 cps/(µR h^{-1}) yields the ground terrestrial exposure rate of 3.1 µR h^{-1}. Considering the three different methods used to derive the average terrestrial exposure rate at the land test line at the King County Airport, the agreement between aerial results of 3.1 μR h^{-1} and the results of the PIC and HPGe measurements method is within about 30% with a 50% variability within the ground measurements. These values are considered satisfactory for aerial measurements suggesting proper calibration of the aerial system.

7.2.5 Exposure Rate Contour Map

Using the methodology described earlier, the 1-second gross count data were converted to the terrestrial exposure rate values and then contoured using the PC REDAC software package.

Figures 28 and 29 are the resulting maps for King and Pierce Counties. The maps present contours of terrestrial exposure rates. The values for both cities show extremely low values ranging from 2 to 6 μR/h. For comparison, the terrestrial exposure rates derived from aerial radiometric data in the United States reported by the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s [Phillips et al, 1993] are presented in Figure 32, showing the King and Pierce Counties in the range 2.5-4.5 μR/h. Despite such low exposure rate values, the aerial measurements data easily distinguished the terrain features including the two bridges over Lake Washington: Highway 520 Bridge and I-90 Bridge, differentiating the higher radioactivity (NORMs) in the bridge construction materials over the water.

7.2.6 Man-Made Gross Counts Map

To locate any radiological anomalies in the survey areas, the man-made (MMGC) algorithm is applied to the 1-sec spectral data and resulting count rates are plotted as contour maps. The resulting map shows only the gross counts produced by man-made sources typically with energies bellow 1400 keV. The man-made count rate contours maps for King and Pierce Counties are presented in Figures 30 and 31. The map of King County (Fig. 30) shows several small areas of slightly elevated man-made activity (count rates). These anomalies were investigated during the survey, and the results of the investigation are presented in the next Section. The map of Pierce County (Fig. 31) shows no elevated man-made activity.

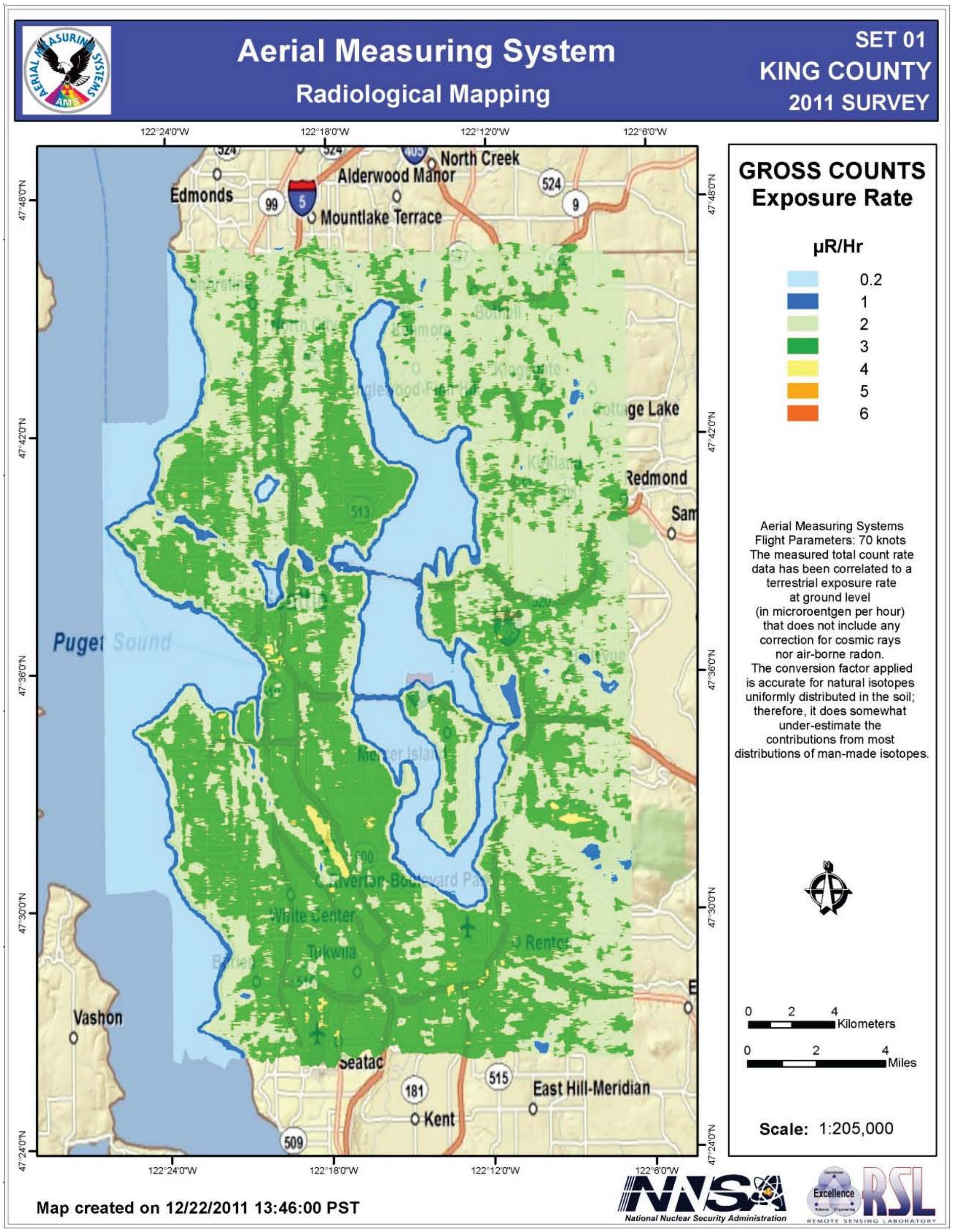


Figure 28. The terrestrial exposure rate map for the King County area based on the helicopter survey data.

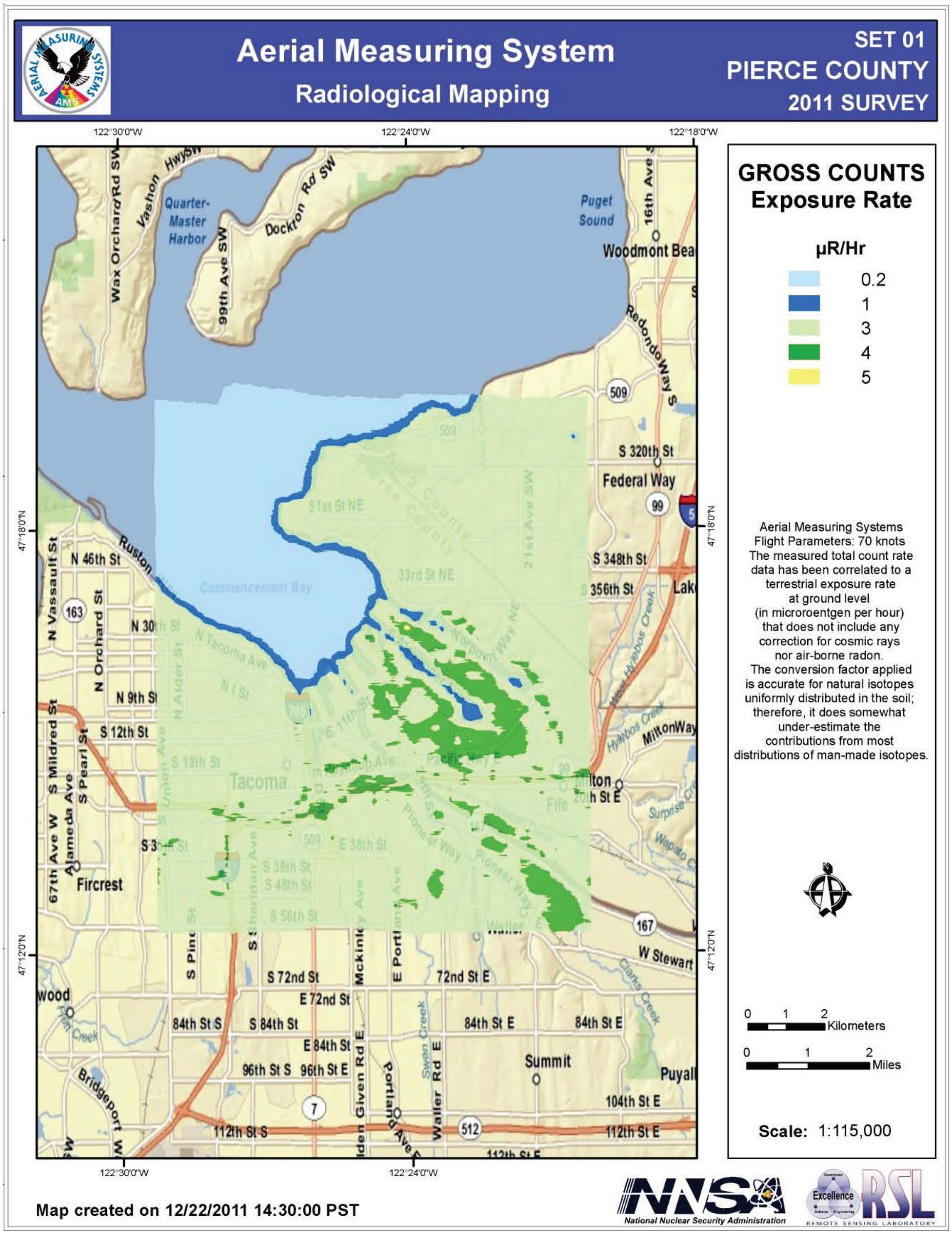


Figure 29. ***The terrestrial exposure rate map for the Pierce County area based on helicopter survey data.***

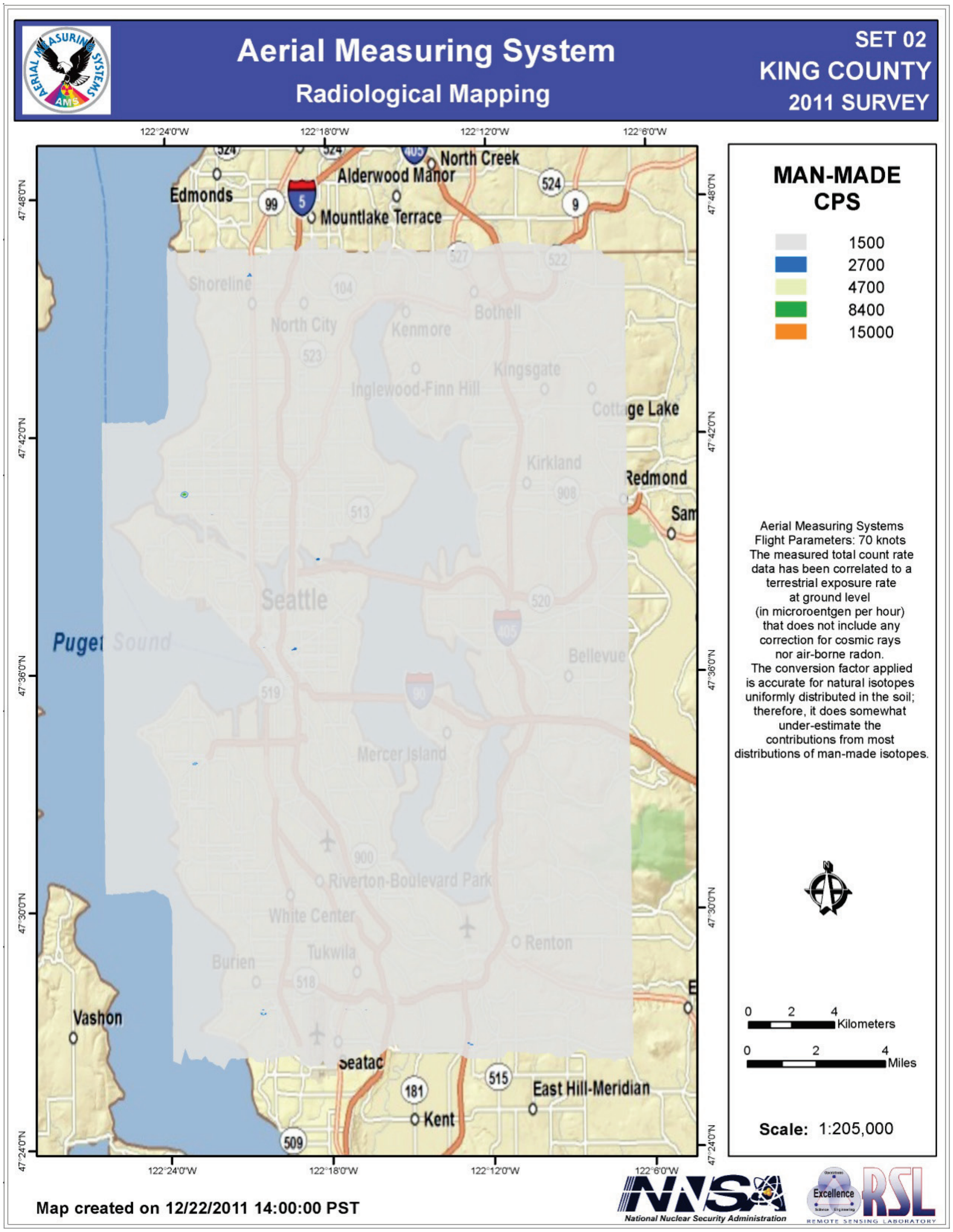


Figure 30. ***The man-made (artificial) radioactivity levels map for the King County area based on helicopter survey data.***

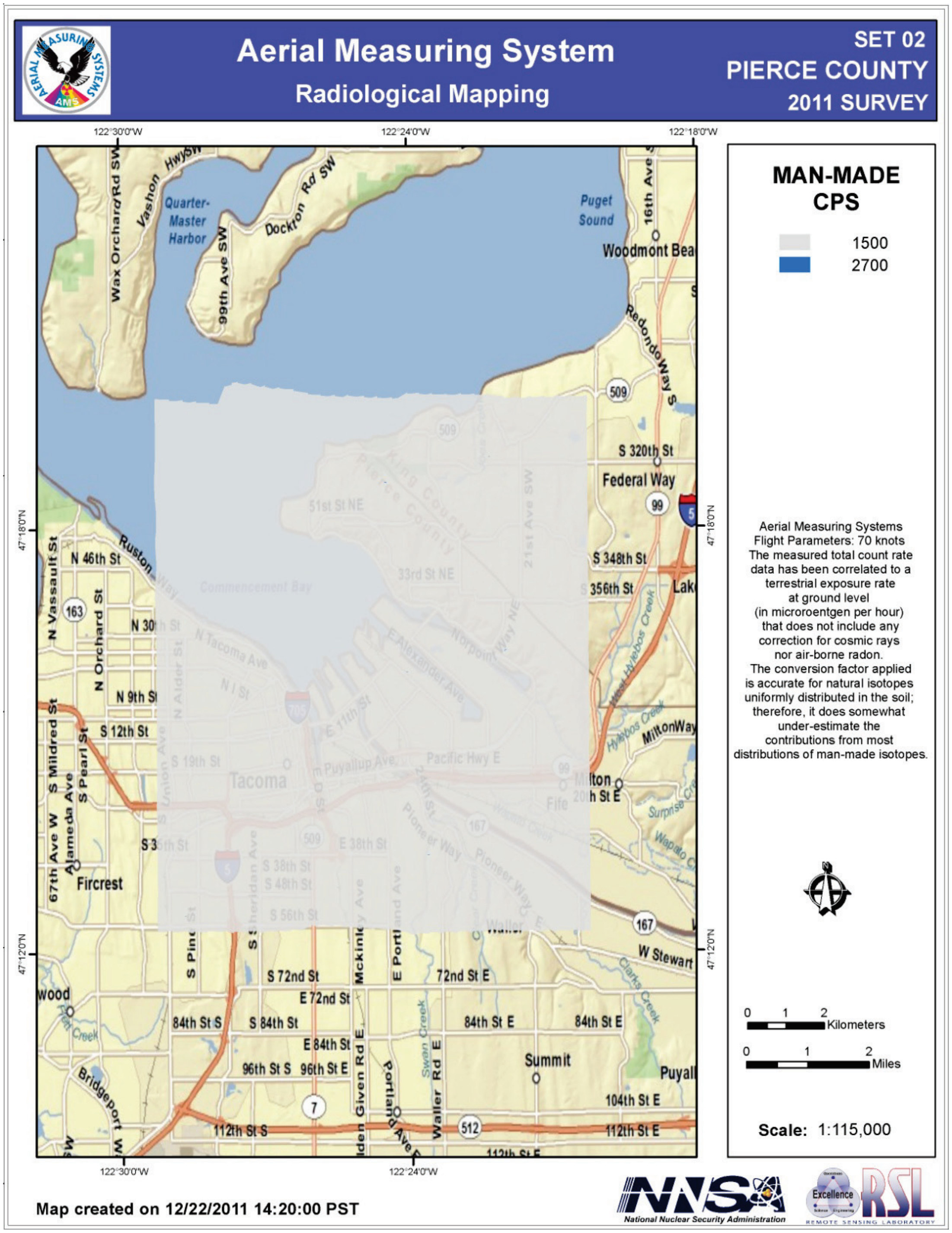


Figure 31. ***The man-made (artificial) radioactivity levels map for the Pierce County area based on helicopter survey data***

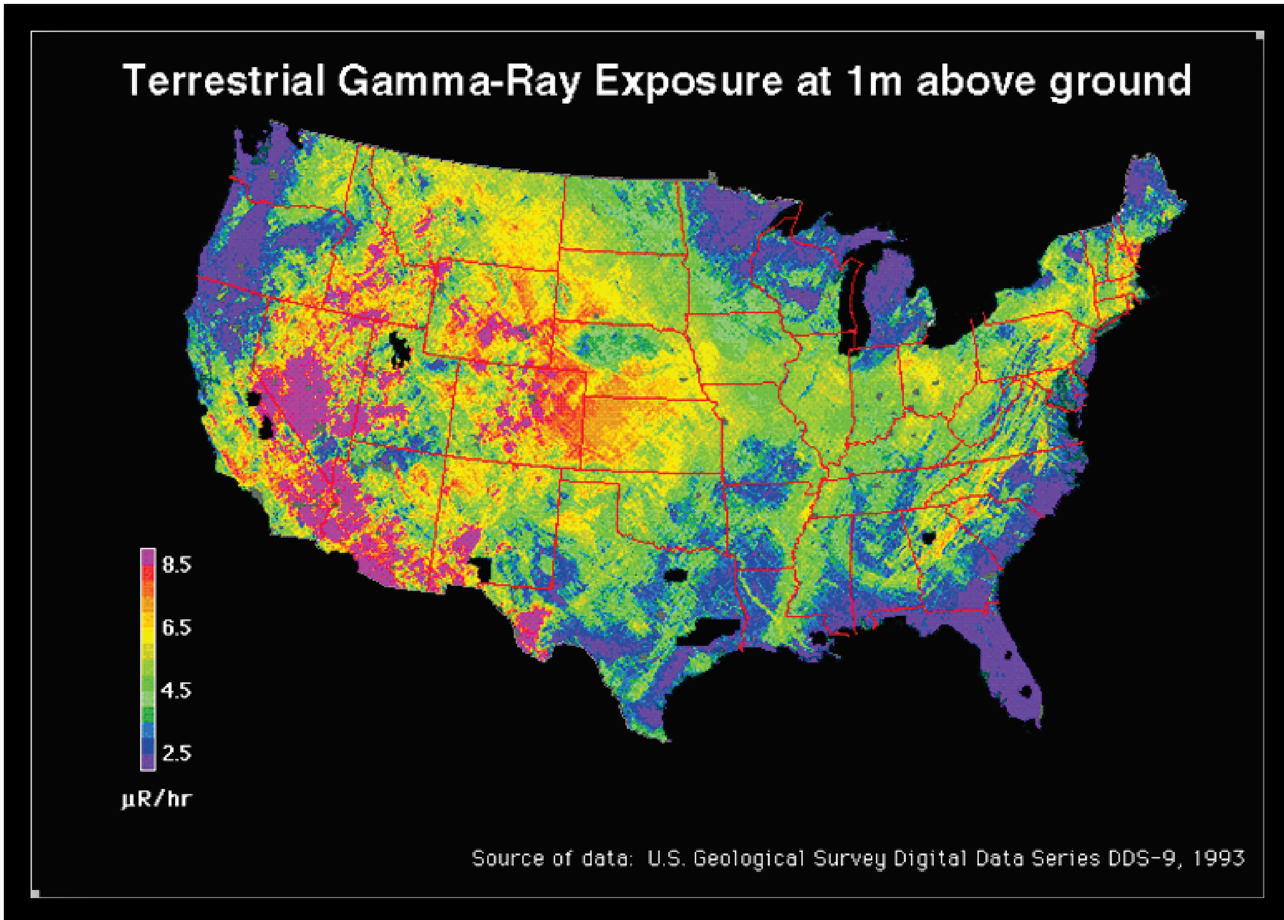


Figure 32. ***The terrestrial gamma-ray exposure in the US derived from geological data***

(URL: http://energy.cr.usgs.gov/radon/DDS-9.html).

7.2.7 Anomalies

Three radiological anomalies were recorded and investigated during survey.

7.2.7.1 I-131

The first anomaly was recorded during Flight # 3 on July 11, 2011. The system and subsequent analysis of the recorded radiation data (events: 2495-2500) shown maximum count rate of 12610 cps at event 2497 at the location in northern part of Seattle (see map in Figure 33).

Spectral analysis indicated iodine-131 (I-131) (see Figure 34). The anomaly was recorded while flying over a residential neighborhood. The presence of I-131 indicated the possible presence of a thyroid ablation patient. Iodine ablation therapy is used to treat residual thyroid cancer and metastatic disease after partial or complete thyroidectomy, and requires administering up 200 mCi of I-131[Silberstein *et al* 2005]. . A patient is required by the NRC to remain in the hospital if any individual member of the public is likely to exceed a radiation dose of 5 mSv (500 mrem) from that patient. Licensees may authorize patient release from the treating facility according to the relevant NRC Guideline [Current guidance is NUREG – 1556, Vol. 9, Rev 2, January 2008. Appendix U. Model Procedure for Release of Patients or Human Research Subjects Administered Radioactive Materials. Table U.1 Activities and Dose Rates for Authorizing Patient Release (p. U-5).For I-131: 7 mrem/hr (0.07 mSv/hr) at one meter, and/or at or below activity of 33 mCi (1.2 GBq)] when the survey meter reading is less than 48.5 mrem/h (or the equivalent unit mR/h) at one meter or when the oral I-131 dosage is 221 mCi or less Using standard AMS sensitivity conversion coefficients, the highest recorded net count rate of 11610 cps was converted to I-131 point source activity and yielded 50 mCi, with AMS acquisition system minimum detectable activity of 9.3 mCi when flying directly over the unshielded I-131 source.

These values are well within range of the typical activities of I-131 delivered to patients undergoing ablation therapy. According to Silberstein *et al* 2005: " for postoperative ablation of thyroid bed remnants, activity in the range of 2.75–5.5 GBq (75–150 mCi) is typically administered, depending on the RAIU and amount of residual functioning tissue present. ii. For treatment of presumed thyroid cancer in the neck or mediastinal lymph nodes, activity in the range of 5.55–7.4 GBq (150–200 mCi) is typically administered…"

Figure 33. ***Radiation anomaly recorded during the flight on July 11, 2011***

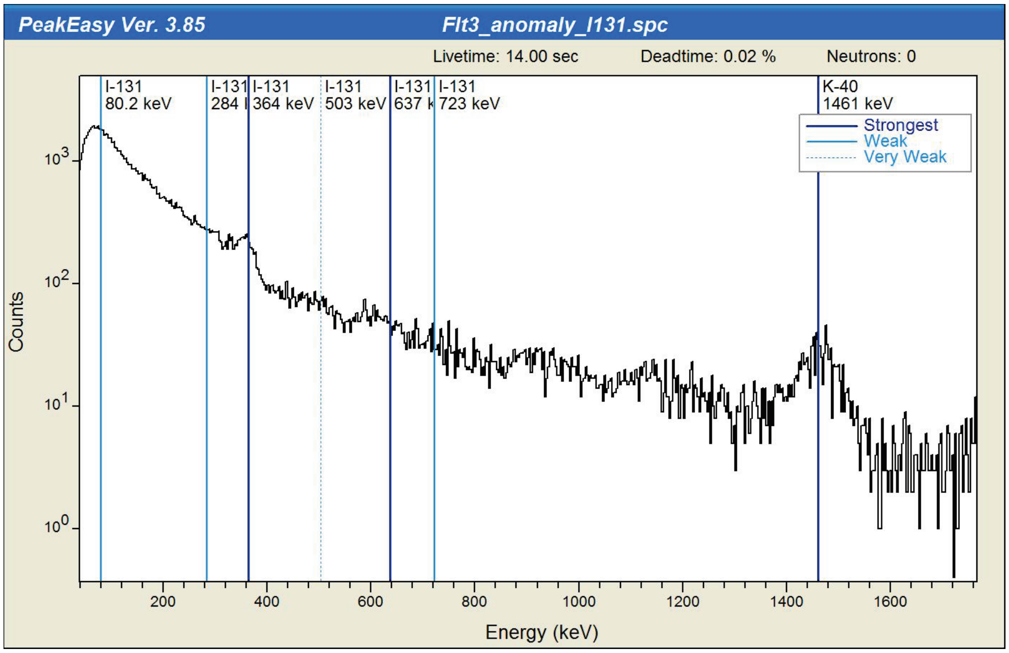


Figure 34. ***Gamma ray spectrum of radiation anomaly detected during the flight on July 11, 2011***

7.2.7.2 Annihilation Peak

The next anomaly was detected during Flight # 6 on July 13, 2011. The system and subsequent analysis of the recorded radiation data (events: 3589-3590) showed a maximum count rate of 9343 cps at event 3590 at the location of (122.342556W, 47.457381N) (see map in Figure 35).

Spectral analysis has shown a peak at 511 keV consistent with annihilation radiation (see Fig 36).

Location of the anomaly was over Highline Medical Center in Seattle that according to their web page has a diagnostic PET scanner which due to production of positron radiation emits annihilation gamma rays with energy of 511 keV.

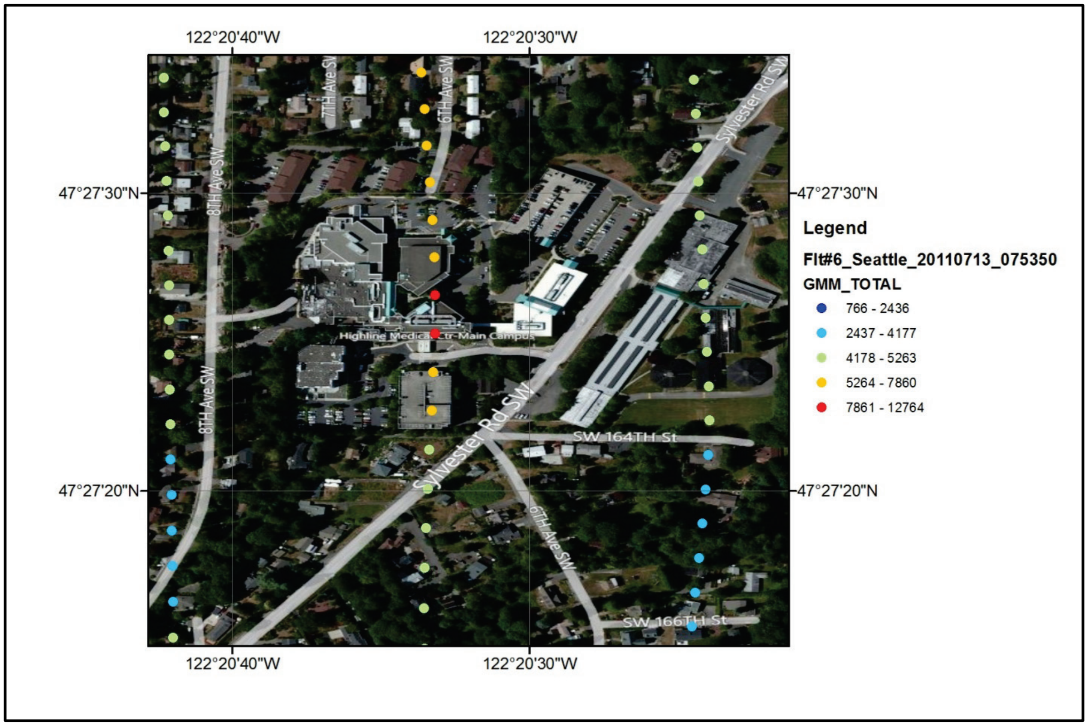


Figure 35. ***Radiation anomaly recorded during the flight on July 13, 2011.***

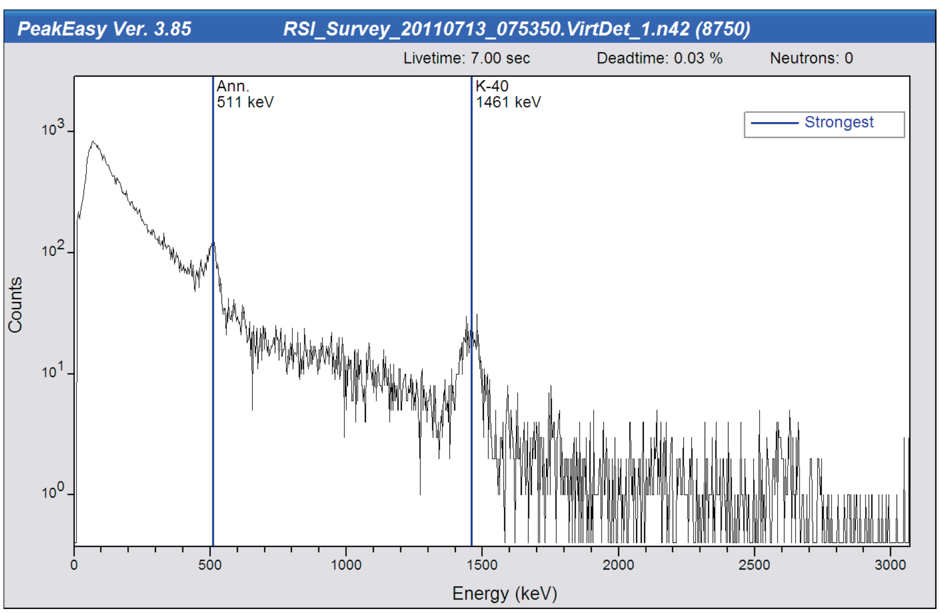


Figure 36. ***Gamma ray spectrum of radiation anomaly detected during the flight on July 13, 2011***

7.2.7.3 Elevated NORMs

The remaining detected anomalies (see Figure 30) were elevated NORMs. Even if the MMGC algorithm is optimized for extracting anomalies in the energy range of man-made isotopes, sometimes the elevated counts produced by natural occurring radioactive elements result in elevated counts in man-made energy window ("leaking"). A typical NORM anomaly was detected during Flight # 7 on July 13, 2011. An elevated count rate was observed at events: 5880-5883 with the maximum count rate of 15608 cps at event 5882 and location (122.323088W, 47.537538N) (Figure 37). The area was an industrial park with large storage pads. The subsequent spectral analysis (Figure 38) shows only gamma peaks associated with naturally occurring radioactive materials (NORMs), or elevated natural background caused by, for example, the type of gravel material used to construct the storage pads.

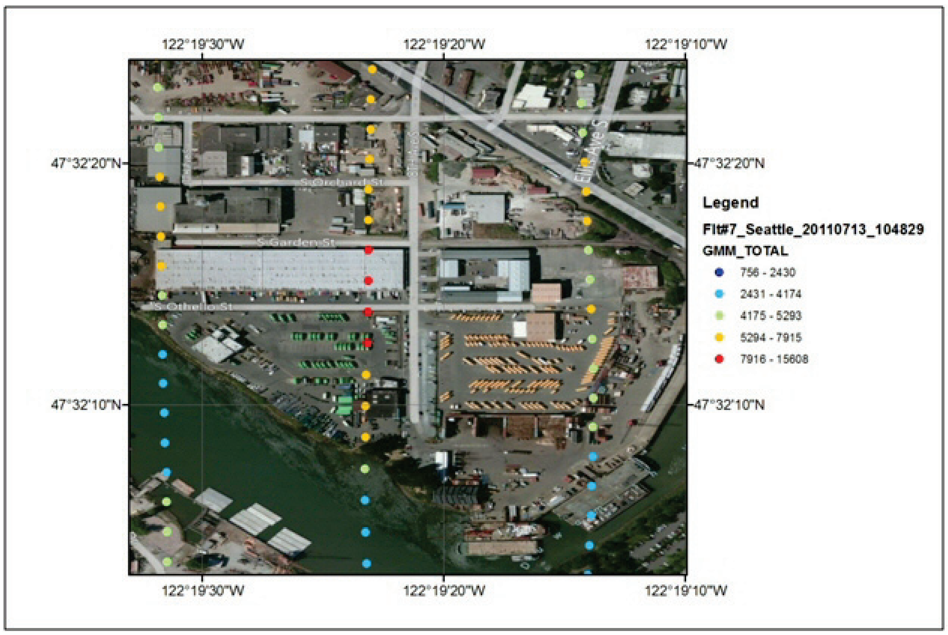


Figure 37. ***Radiation anomaly recorded during the flight on July 13, 2011.***

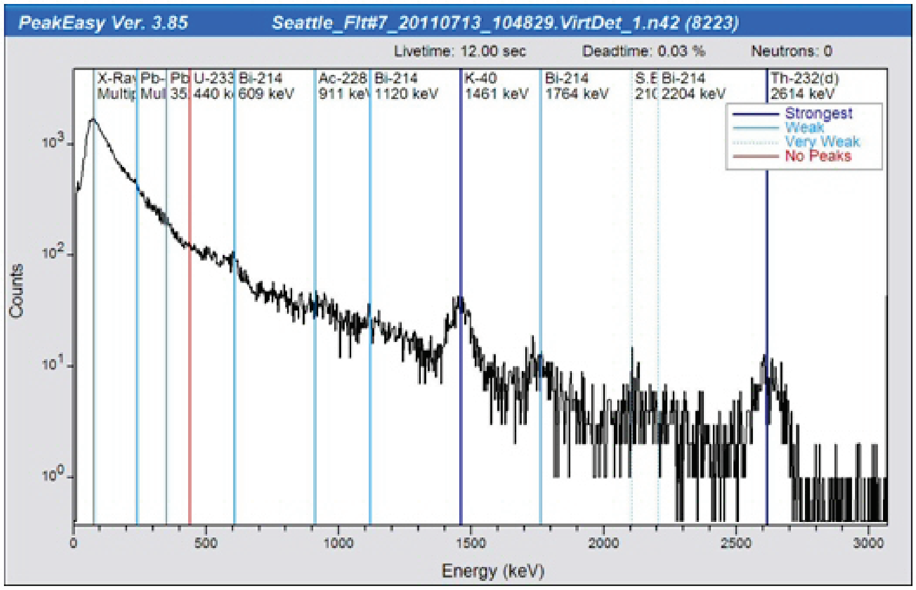


Figure 38. ***Gamma ray spectrum of radiation anomaly detected during the flight on July 13, 2011***

8.0 SUMMARY

An aerial radiological survey of the King and Pierce Counties in the state of Washington was conducted between July 11-22, 2011. The terrestrial gamma exposure rate and man-made activity for the King and Pierce Counties were documented. The aerial data were benchmarked to existing ground exposure rate measurements and shown to agree with the ground results. No significant man-made gamma activity was detected in the survey areas except the medical I-131 anomaly attributed to the thyroid ablation therapy patient and positron gamma emission from medical diagnostic facility. The extensive survey quality, consistency control checks, and calibration were carried out during the survey and are documented in this report. The unpredictable area weather, which could potentially affect the flight operations, was the only constantly unknown factor, resulting in the necessity to carry out three flights per day. This effort was required to complete the survey on time and on budget.

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APPENDIX A
SURVEY PARAMETERS

Survey Site:	King and Pierce Counties, Washington
Survey Coverage:	405 square miles (1049 square kilometers)
Survey Date:	July 11 – 22, 2011
Survey Altitude:	300 feet (~91 meters)
Aircraft Speed:	70 knots (~36 meters per second)
Line Spacing:	600 feet (~183 meters)
Navigation System:	Trimble DGPS (WAAS corrections)
Line Direction:	North-South
Detector Configuration:	Twelve 2″ × 4″ × 16″ sodium iodide thallium-activated NaI(Tl) detectors (4 RSX-3 units)
Acquisition System:	RSI RS-501 and 4 RS-701 units
Conversion Factor:	1862 cts per μR/h
Air Attenuation Coefficient:	0.00186 feet^{-1} (0.00610 meters^{-1})
Aircraft:	Bell-412 Helicopter
Survey Team:	Emanuele Avaro, Sonia Bonilla, Joe Cummings, William Duncan, Johnny Grimes, Elaine Hawkins, Katie Hildermann, Nick Lamar, Karen McCall, Tom McKissack, Timothy Rourke, Tom Selfridge Tom Stampahar, Johanna Turk, Piotr Wasiolek

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