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AN ABSTRACT OF THE THESIS OF

Brittany N. Owensby for the degree of Master of Science in Radiation Health Physics presented on March 2, 2020.

Title: Atmospheric Radon Modeling for Aerial Measurements

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Abstract

The Ariel measuring system (AMS) is a national asset in responding to radiological or nuclear events. The AMS operates out of several aerial platforms, such as the BK-117 helicopter and the P3 Long Range Tracker, under many equipment configurations. Measurements can be telemetered real time to reach back for evaluation and processing to minimize time between data acquisition and the hazards assessment. One of the corrections applied to the raw data set is the removal of atmospheric radon influences prior to activity calculations. This correction is characterized by a one-time water line measurement where terrestrial influences are minimal. This work proposes an alternate method utilizing linearizing functional fit modeling to establish an atmospheric radon equilibrium factor that incorporates fluctuations of radon concentration due to climatic changes. Modeling the photopeak count rate change from the 1765 keV survey data set provides a more representative radon contribution correction over the time of the acquisition to achieve a higher fidelity in the accuracy of the results.

Atmospheric Radon Modeling for Aerial Measurements

By

Brittany N. Owensby

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APPROVED:

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Head of the Department of Nuclear Engineering and Radiation Health Physics

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Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Brittany N. Owensby, Author

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1 Introduction

The Federal Radiological Monitoring and Assessment Center (FRMAC) is a federal asset that is responsible for coordinating offsite monitoring and assessment to nuclear and radiological incidents within the United States. FRMAC is an interagency organization with representatives from various federal, state and local radiological response organizations. This Assessment Division serves as the technical lead of all government response organizations by integrating all radiological data collected by responders. Under the National Response Plan (NRP), The Department of Energy (DOE) and the National Nuclear Security Administration (NNSA) are two of the many agencies to maintain this operational readiness. NNSA's mission is to protect the health and wellbeing of their citizens by providing verified radiation measurements, interpretations of radiation distributions and characterization of overall radiological conditions.[1] Trained personnel and mobile equipment are provided in executing this mission.

This work summarizes one of the consequence management agencies administered by the DOE and NNSA, The Aerial Measuring System (AMS) and the associated technical data manipulations. The AMS is based and operated out of Nellis Air Force Base in Las Vegas, NV with additional operational capability at Andrews Air Force Base near Washington, DC.

Additionally, NNSA headquarters requested the DOE Region 3 Radiological Assistance Program (RAP 3) to pilot and implement a regional AMS capability (AMS 3).[2] Since this expansion became operational in 2009, other RAP teams have implemented the regional AMS capability throughout the United States. The AMS consists of helicopters and fixed-wing aircraft outfitted with gamma radiation detection systems for rapid response to nuclear and/or radiological emergencies. These airborne platforms are supported by a team of scientist, technicians and pilots to detect, measure and track radioactive materials deposited on the ground and to search for lost or stolen radioactive sources.

Aircraft selected to conduct an aerial radiation detection mission is based on availability, mission requirements, geographic location and expectations of response time. Fixed-wing aerial platforms operate at a higher velocity for quick response and mapping of the deposition. Helicopters operate at a lower altitude and at a decreased velocity to provide a better estimate of the contamination in the affected area. Typical parameters of the AMS 3 flights is provided below.[2]

- The typical parameters for a helicopter survey are 70 knots ground speed, an altitude of 150 feet above ground level (AGL) and line spacing of 300 feet.
- The typical parameters for a fixed-wing aircraft survey are 160 knots ground speed, an altitude of 1000 feet AGL and line

spacing of 2000 feet (Customs and Border Protection P-3 aircraft).

Potential radiological emergencies range from detonation of a nuclear device, accidental release of radioactive material from a nuclear power plant or stolen radioactive material from a potential terrorist. The AMS is also capable of natural radioelement mapping. The AMS deploys an array of aerial measuring equipment mounted on aircraft to acquire gamma radiation data with associated position data for ground deposition mapping and lost or stolen source recovery. Parameters that effect gamma measurements include[12]:

1. Inverse square attenuation of point source data;
2. Air mass attenuation from altitude to ground measurement;
3. Contribution from cosmic rays;
4. Contributions from atmospheric radon;
5. Naturally occurring radioisotopes, Potassium, Uranium and Thorium (K/U/Th);
6. Measurement contributions from aircraft materials and detection systems;
7. Ground surface anomalies due to changes in survey area.

Typical laboratory measurements for radionuclide identification or quantification contain fixed geometries under optimal conditions. The AMS is unique in that measurement conditions vary due to differences in source to

ground distance, terrestrial differences, air craft velocity and continuously changing atmospheric conditions.

The aerial measuring system is the primary asset for a rapid spectroscopy acquisition in assessing the contamination level due to an accident. Attaining and analyzing soil samples to characterize the contaminant deposition is time consuming and difficult to manage administratively. Aerial gamma spectroscopy is subject to many uncertainties due to radionuclide distribution in soils, application of conversion factors and variance in the background, terrain differences over an area of interest, and potential unidentified influences.

One significant influence on the measurements is outdoor radon (^{222}Rn), a noble gas concentration present in the atmospheric boundary layer from decay of radium in the uranium decay series. Radon is ubiquitous and easily travels over significant distances by advection and diffusion. The concentration varies not only on location but also due to weather related influences, including temperature vertical gradient, wind speed, air temperature, and seasonal variability.

Radon is a positively charged heavy metal decay product capable of reaching concentrations ranging from 1-100 Bq/m^3. This product can form small molecular clusters in the air with drift velocities dependent on the

atmospheric electric field. The temporal variability in the air near the ground fluctuates diurnally, where wind speed, temperature, stability and intensity of turbulence directly influence the variability in concentration. Studies have shown radon concentration is inversely proportional to the averaged windspeed and directly proportional to the temperature differences.[4]

In AMS applications, a large area may be covered during the time the aircraft remains in the air. Fixed wing aircraft are able fly for approximately 8 hours, where weather influences can change drastically throughout the flight. Radon increases can occur in the air and build up on the aircraft structure. Natural sources, ^{222}Rn, ^{220}Rn and ^{219}Rn, contribute to atmospheric radon concentration variability. Due to the short half-lives from the actinium (^{219}Rn) and thorium (^{220}Rn) series, the contribution to atmospheric radon is primarily from the uranium (^{222}Rn) series.

Non-Terrestrial background counts include cosmic, atmospheric radon and aircraft material influences. This is a one time, averaged measurement correction at the nominal survey altitude and is applied to each spectral data energy window. The correction does not account for changing climatic conditions for the total survey acquisition, where atmospheric radon influences vary up to 30 %.

The initial radon concentration is determined utilizing an upward detector method. Ideally, it would be optimal to monitor changes in atmospheric concentrations during the flight. Due to limitations of space in the aircraft and the need to maximize the detection sensitivity, it is not reasonable to dedicate a single detector in the sensor array to monitor potential changes during a survey.

The current aerial measurement data handling guidelines contains a onetime atmospheric correction that assumes environmental conditions are constant for the total survey acquisition. The objective of this work is to identify an alternative method in correcting for atmospheric radon fluctuations, utilizing linearizing transformation modeling to provide a more accurate correction relative to time and position.

2 Literature Review

2.1 Radioactivity

The mechanism of an unstable atom spontaneously undergoing a nuclear transformation results in the formation of a new element, called radioactive decay. Characterization of these transformations is dependent on the mechanism of transformation, including alpha-particle emission, beta-particle and positron emission and orbital electron capture. Radioactive properties of the element are independent of physical and chemical states of the radionuclide. Gamma radiation may be associated with all of the transformation mechanisms. This release of energy depends on two factors, neutron to proton ratio and the mass-energy relationship among the parent and daughter nucleus and emitted particle.

The amount of a specific radionuclide in a sample is expressed in disintegrations per second, or Becquerels (Bq). This amount is referred to as activity of the sample and will change over time dependent on the constant rate of decay (λ). The decay constant represents the rate of time the unpredictable process will decrease the number of atoms by half, where the half-life ($T_{1/2}$) is radionuclide specific. Therefore, the activity (A) is directly proportional to the number of atoms (N) in the sample at the time of

measurement. The decay process will produce radioactive daughters until the daughter product is a stable nuclide.[9]

Eq. 1: $A = \lambda N$

Eq. 2: $\lambda = \ln(2) / T_{1/2}$

2.2 Naturally Occurring Radioactivity

There are three sources of naturally occurring radiation. Cosmic radiation is the oldest source, which is believed to have originated approximately 14 billion years ago. The second source is from primordial radioactive elements, which were created approximately 4.5 billion years ago when the earth was formed. Naturally occurring radioactive materials with concentrations or quantities of concern from a radiological protection standpoint are known by the acronym NORM. A third source of natural radiation is cosmogenic radioactivity, where radionuclides are produced from cosmic radiations interacting with the atmosphere. More detail on these three sources of natural radiation are provided in the subsections below.[9]

2.2.1 Cosmic Radiation

Highly energetic cosmic rays from extraterrestrial sources are created from bombarding the earth. One of these sources is the sun, emitting alpha particles and protons. Another source originating beyond our solar system is galactic

radiation, which consists mainly of electrons and protons. These primary particles enter the earth's atmosphere and collide with the atmospheric molecules, producing secondary cosmic rays. The intensity of cosmic rays increases as the altitude above earth increases due to the decreased shielding effect of the atmosphere. The intensity also increases with increased latitude north and south of the equator due to the earth's magnetic field deflecting high-velocity charged particles across the magnetic force field.

2.2.2 Cosmogenic Radioactivity

Numerous cosmogenic radionuclides are produced by the interaction of cosmic rays with the atmosphere. Many are produced at low concentrations and have insignificant contributions to dose. The two radionuclides produced of interest are anthropogenic tritium (^{3}H) and radiocarbon (^{14}C), which must be considered when interpreting radioactive measurements. The production of these two radionuclides occurs at a steady state, where the production rate is equal to that of the decay rate.

2.2.3 Primordial Radioactivity

There are four decay chains, consisting of long series' of isotopes of various elements present in the earth's soil. Uranium is the most abundant of the radioactive elements and is ubiquitous in the natural environment, found in the soils at average concentrations of 3 ppm (parts per million). The Uranium Series is headed by ^{238}U while ^{235}U heads another series called the Actinium

Series. Extremely stable compounds are formed between uranium and phosphorus, therefore increasing U concentrations in soils where compounds exist.

^{232}Th heads another long chain of successive radionuclides (Thorium Series), and like U is an ubiquitous naturally occurring radiation at approximate four times the abundancy. The figures below provide the 3 decay series.

Figure 1: Uranium-238 Natural Decay Series (Reference 19)

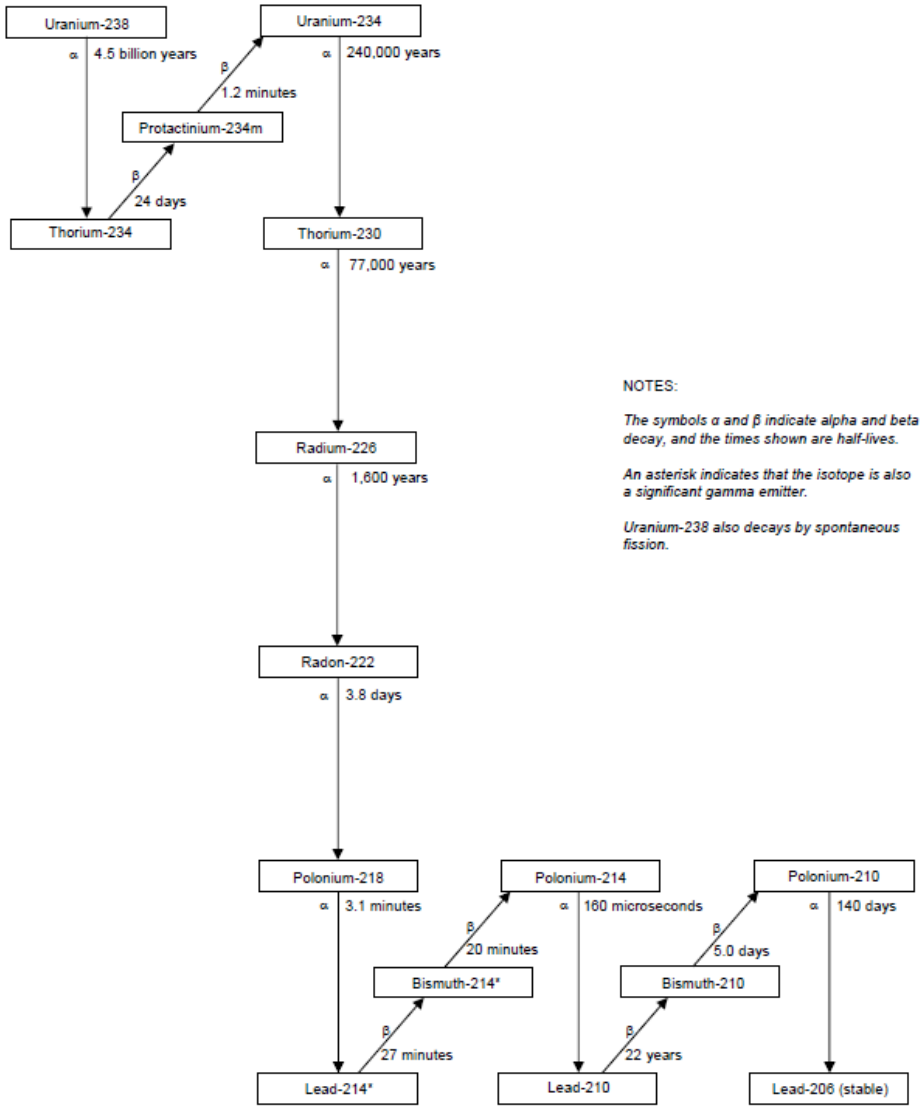


Figure 2: Uranium-235 Natural Decay Series (Reference 19)

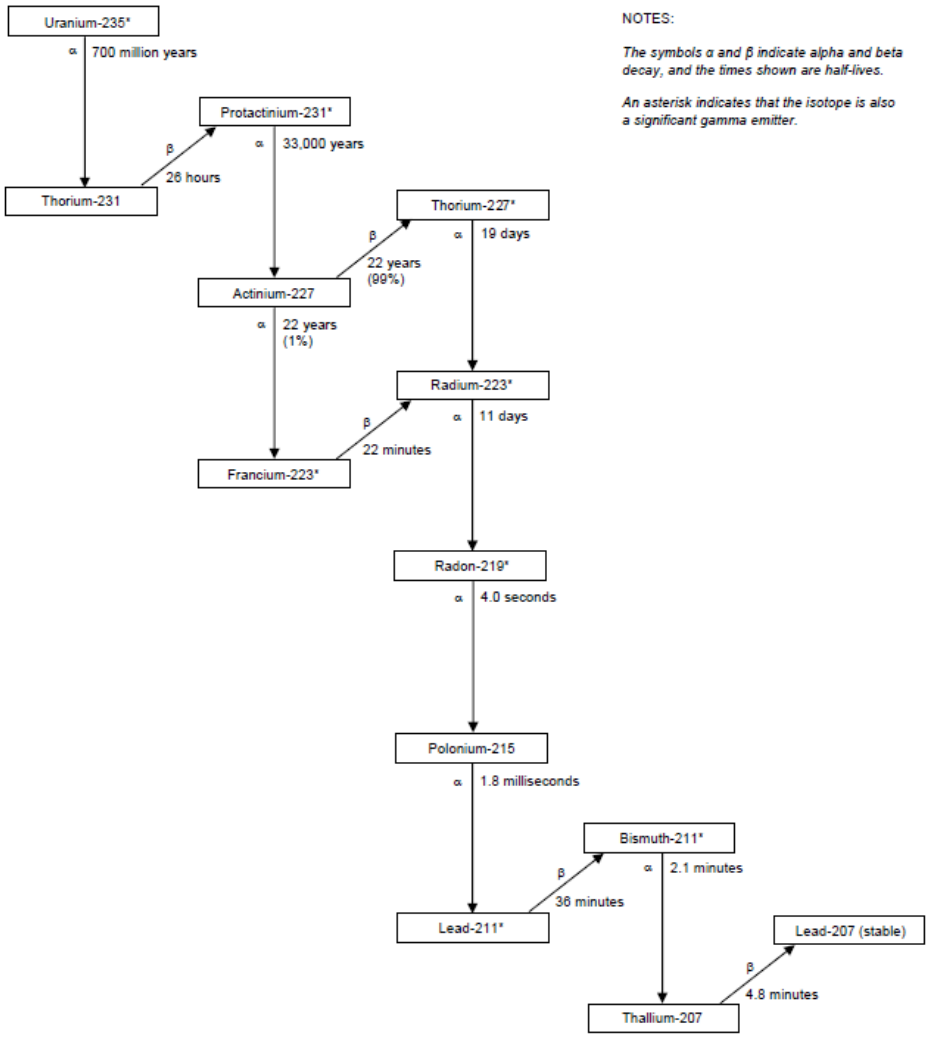
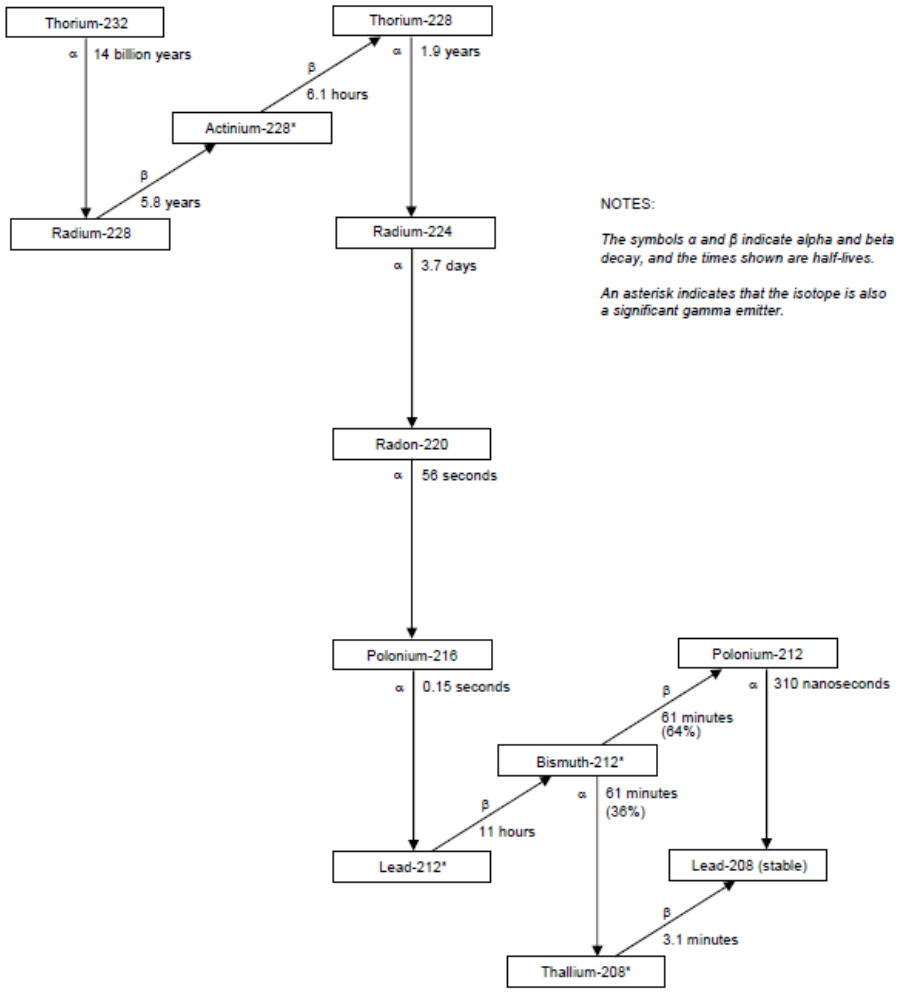


Figure 3: Thorium-232 Natural Decay Series (Reference 19)

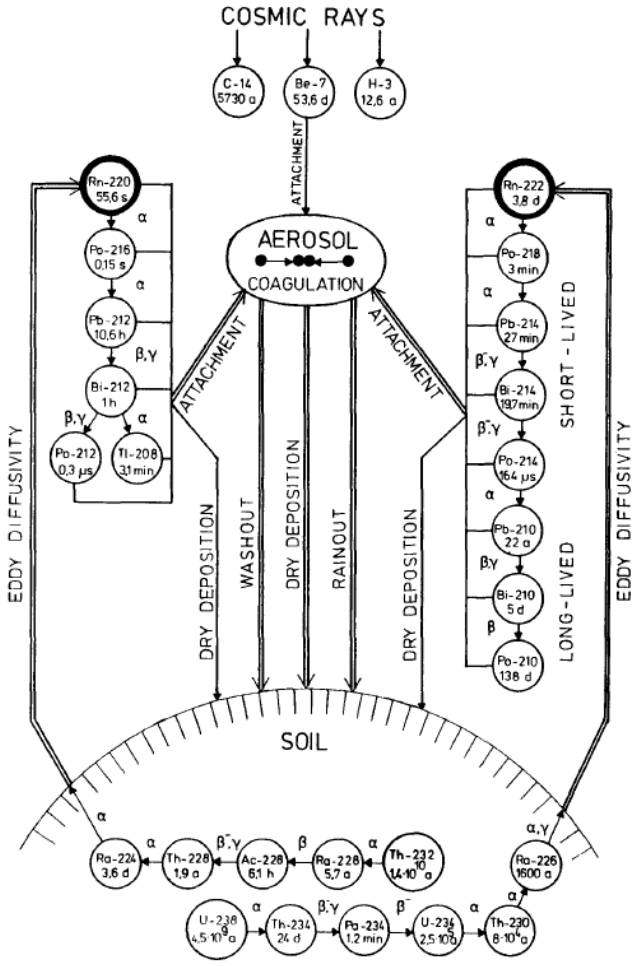


The three series mentioned above have certain commonalities, where the first member of each is very long-lived. The neptunium series has since decayed away due to the short half-life of ^{241}Pu (13.2 y), therefore a decay chain is not provided. A second commonality of the remaining decay chains is the presence of the radioactive gas radon (Rn), where each isotope of radon has a specific name dependent on the decay chain. For the Uranium Series, the

gaseous Rn is called radon, the gas is called thoron for the Thorium Series and called action in the Actinium Series. The third commonality is the end element in each case is lead.

Radon gas is significant due to public health concerns from naturally occurring environmental radioactivity. The gas is dispersed throughout the local atmosphere from diffusion out of the earth and into the air, where distribution occurs by meteorological processes. Radon gases decay and their radioactive daughters attach themselves to atmospheric dust, where the atmospheric concentrations vary widely around the world and depend on the local concentrations of uranium and thorium. Despite it's short half-life, radon gases travel long distances and is a contributor to changes in hydro-geological mixing and seismic activities in the ground. The gas travels through advection and diffusion to the surrounding air, reacting easily with aerosols in the air. The radioactive progenies of radon include lead, polonium, thallium and bismuth isotopes and are the main proponents of the reaction with air aersols, which highly depend on aerosol sizes, concentrations and transportations.[3] The removal of these radionuclides existing in the atmosphere occur by radioactive decay, or processes such as dry deposition, rainout, washout.[7] The figure below provides Radon, Thoron and their decay products in the open air for the both the Thorium (^{220}Rn) and Uranium (^{222}Rn) Series.[4]

Figure 4: Radon, Thoron and associated decay products in the open atmosphere (Reference 4)



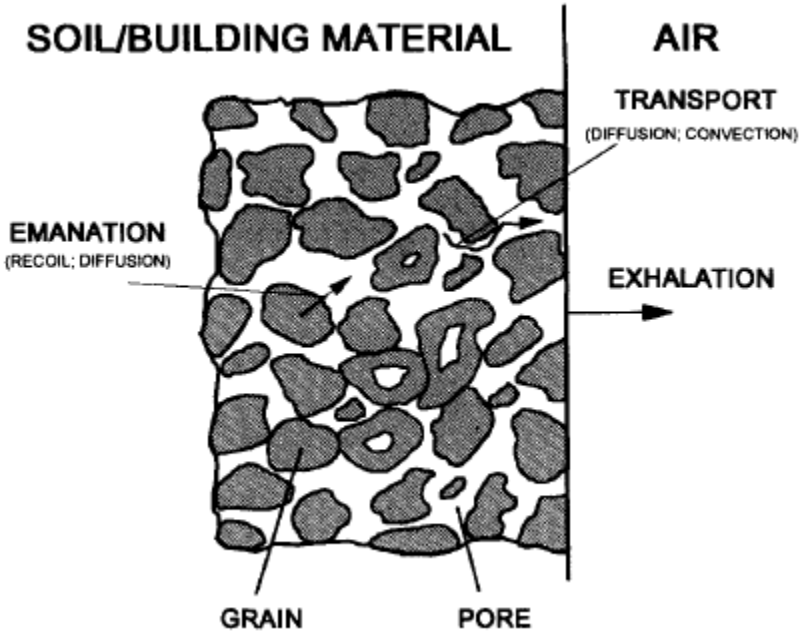
There are various mechanisms or pathways in which radon gas from NORM sources enter the atmosphere. These short-lived gases are then transported through the air medium and decay to their radioactive daughters. It is important to note the initial concentration is dependent on the radioactive parent in the NORM series, radium.

2.2.3.1 Radon Gas Emanation and Transport in Materials

The main transport of radon/thoron gases into the atmosphere is by crossing the interface between the air and soil or building material structures. Radon/thoron release into the air from water sources, such as the ocean or ground-water is relatively small in comparison to the gas introduction from other sources. The gas concentrations in soil and building materials is typically 10^3 and 10^4 times higher than the atmosphere, where the activity concentration released over a time period for a designated surface is known as the exhalation rate. Meteorological conditions affects the concentration of radon/thoron in the open atmosphere, which is characterized by the source term, exhalation rate and atmospheric dilution processes.[4]

Emanation power describes the process of radium decaying in the soil grains, where resulting atoms of radon isotopes must first escape from the mineral grains to air-filled pores (Figure 10).

Figure 5:Radon/Thoron mechanisms of exhalation from soil (Postendorfer 1993)



The amount released is known as the emanation fraction and is considered to have two components, recoil and diffusion. Solid grains have a low diffusion coefficient of gases, therefore it is assumed the main fraction of emanation power is from the recoil process. Studies have shown moisture content has a large impact on the emanation coefficient, where the introduction of water within a pore has a higher stopping power and ends the penetration of radon gas to another grain. Radon emanation power of soil ranges from 1 to 50 % and thoron is approximately 5 times smaller. Within building structures, the emanation power ranges from 0.2 to 30 % for radon and 0.2 to 6 % for thoron.[4]

In order for Radon/Thoron to reach the atmosphere, a fraction of the concentration must transport through the pores to the surface prior to decaying. These two basic transport mechanisms to the surface is diffusion and convective flow. Diffusion results in the flux density, where the concentration is proportional to the gas concentration and the specific mediums diffusion coefficient. Conventional movements are created by pressure differences that are dependent on meteorological conditions. Therefore, the exhalation rate of radon/thoron is dependent on the soil and material profile and many other external factors e.g weather, moisture content.

2.2.3.2 Radon daughter aerosol formation

There are two steps in generating radon/thoron daughter aerosols in the atmosphere. Once the decay products have been introduced into the atmosphere, they react quickly with trace gases and air vapors forming small particles called clusters or unattached radionuclides. Secondly, the radionuclides attach to the existing aerosol particles in the atmosphere to form radioactive aerosols. This attachment rate is a function of particle size and concentration. Turbulent mixing of the lower atmospheric air is the primary diffusion mechanism for radon/thoron and their associated decay products, where the distribution varies with altitude due to vertical variations of wind velocity and changing atmospheric stability.[4]

2.2.3.3 Influences on Radon/Thoron Transport in the Atmosphere

The atmosphere contains natural and man-made solids from many sources of origination. Mathematical models to predict exact behavior of aerosols introduced into the environment are not readily available, but the manner in which a contaminant diffuses into the atmosphere under a given set of meteorological conditions may be predicted.[7] This is helpful in determining the survey area of interest when there has been a contaminant released, but does not provide real-time data on those influences during data acquisitions. Variations in gaseous concentrations are dependent on location, time, altitude and environmental conditions.

During normal daytime conditions, the earth's surface absorbs solar radiation resulting in a warmer atmosphere. Typically, the temperature gradient decreases as the altitude profile increases. Under superadiabatic conditions, the temperature decreases at a higher rate than the adiabatic expansion rate of air. This causes an unstable atmosphere, where the rise rate of air is accelerated because it becomes less dense than the ambient atmosphere.[7]

The temperature gradient may also increase with altitude due to a highly stable condition called inversion. A temperature inversion is caused

when warm air runs over cold air due to advection of cooler air at sea level or by diurnal cooling of the lower atmosphere. This is typically seen when the earth's surface begins to cool more rapidly than the atmosphere, such as sunset.

2.2.4 Potassium

Potassium-40 (^{40}K) is the only unstable radioisotope of the 3 naturally occurring nuclides and present as 0.17 % of natural potassium. With a half-life of 1.3 x 10^9 years, it is long lived and found in soils, rocks and within the human body. Although it is not apart of the NORM series, it is considered natural radioactivity and presented to the soils as fertilizer.[7]

2.3 Nuclear Industry

Nuclear physics was founded and studied due to identification of naturally occurring radioactivity, specifically uranium and thorium due to their long half-lives. The long-lived primordial decay chains remain today, and without their existence the likelihood of scientific development of reactors or nuclear weapons may not have been discovered.[8] Radionuclides are also produced within a laboratory utilizing nuclear reactions. The use of radioactivity has proven valuable in scientific advancements, medical, and space applications.

With the utilization of radioactivity, containment and monitoring of effluents released in the environment is important in protecting the human population and the ecosystem from excessive exposure. Engineering and administrative controls are utilized to ensure an unknown spread of containments does not occur.

2.4 Biological Basis for Radiation Protection

Since 1942, research as been directed towards understanding the mechanisms of radiation injury and ecological relationships that exist due to a radioactively contaminated environment. Compiled research from many sources provide knowledge on the effects of radiation exposure, where the greatest volume of literature comes from research with experimental animals. The research provided significant findings on the dose-response relationships for various species, but does not directly correlate for humans. Radiation injury follows the same basic mechanisms, but there is a major difference in susceptibly among different species. Over the years, more data has been compiled to determine human biological effects from exposure to radiation. Data has been compiled from a variety of medical treatments, occupational workers, from radiation accidents and from the survivors of the Japanese atomic bombings in Hiroshima. Prompt, delayed, somatic, and genetic effects are undesirable effects due to excessive radiation exposure to an individual.

The effects are either seen immediately, or after a latent period where a person has symptom free time span. Many have died due to a form of radiation exposure, serving as an important resultant in monitoring and mitigating exposure.[20]

2.5 Nuclear Measurement Detection

The basis of measuring or quantifying radioactivity depends the nuclear transition and converting an instrumental detection of any particle or radiation produced from a charged secondary particle to an electrical signal. Charged particles (alpha/beta) produce a detector signal through ionization and excitation of the detector material directly. Since gamma rays are uncharged, they cannot be directly measured using this method. Instead, the detection is based on other types of photon interactions, by which gamma-ray energy is transferred to electrons within the detector material. The excited electrons have charge and lose their energy through ionization and excitation of the atoms through the detector medium. Practical gamma ray detectors depend upon interaction with a solid, where the number of electron hole pairs produced is directly proportional to the energy of the electrons produced by the primary interaction. To effectively measure the energy spectra, the type of particle or radiation type must be known to quantify the associated radioactivity.[8]

For scintillation detectors, the energy of the photons interacts with a scintillating medium, electrons released during ionization are converted into light photons. The light photons then reach a photocathode to undergo a photon-electron conversion, which then are multiplied utilizing a photomultiplier tube to create a current pulse that is proportional to the initial ionizing event. Scintillators not only quantify the intensity of radiation, but are used for radioisotope identification by obtaining an energy spectra over an acquisition time. Sodium iodide scintillating mediums have been in use for over 60 years and have good energy resolution, compact size and a broad energy response range, capable of measuring nearly all NORM and man-made gamma-ray emitting radionuclides.[10]

The shapes and features in spectra occur due to specific interactions of radiation with the detector. Some of the commonalities and a brief explanation are provided below.

Full Energy Peaks occurs when a gamma-ray energy deposits all of it's energy inside the detector medium;

Continuum is defined as the elevated count areas below and between peaks due to gamma-rays only depositing some of their energy in the detector;

Backscatter is a peak-like feature at a lower energy than the full energy peak due to scattering outside of the detector medium;

Compton Edge is a peak-like feature at a lower energy than the full energy peak due to scattering inside of the detector medium, followed by escape;

Annihilation is a 511 keV peak due to positron interactions within the detector medium;

Escape Peaks occur at 511 keV (single escape) or 1022 keV (double escape) below the full energy peak due to pair production and annihilation inside the detector;

Sum Peaks occur when simultaneous full energy peaks reach the detector medium at the same time;

Bremmstrahlung occurs from electrons slowing in matter and is associated with beta decay.

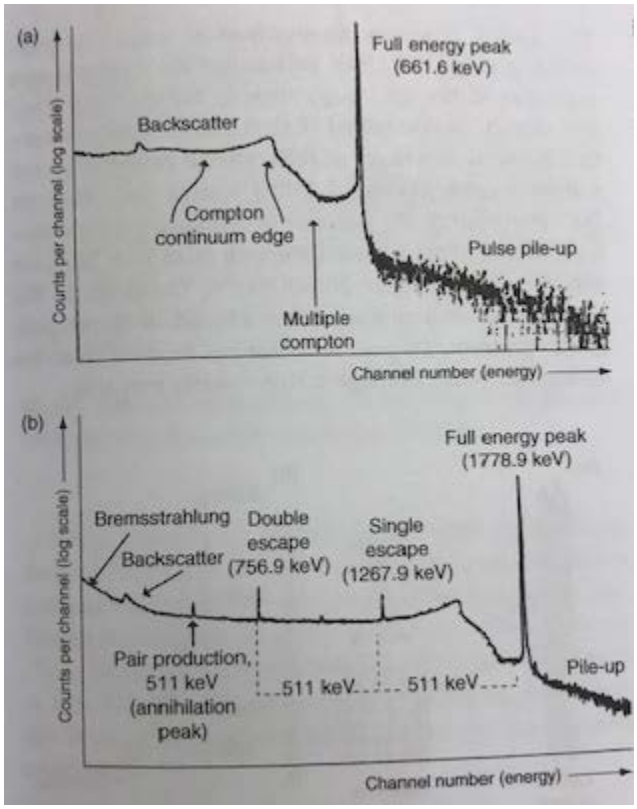


Figure 6: Various spectral features expected (Reference 10)

2.6 Facility Nuclear Measurements

Prior to start up and during facility operations, it is important to monitor the environment for anomalous increases of radioactivity and ensure significant amounts of effluents are not released. Knowledge on radiation levels around the facility is imperative since it is impractical to monitor dose to residents in the vicinity of the site. Documentation on the existing environmental levels prior to operations allow for the determination of the radiation impact from the facility. Measurements of external radiation levels in the region and quantification of the radioactivity in air, food and water will be included in the analysis before and after facility startup.

Environmental monitoring provides awareness of changes in population radiation exposure due to site specific nuclear facility operations and are responsible for detecting a release. The initial measurements will document the activity concentration from NORM sources and determine if an increase in concentrations exists due to site operations. Discriminating NORM, atmospheric variations and increases due to site operations challenging, where atmospheric fluctuations vary from several hundred to a thousand percent in a matter of hours.[15]

Aerial measurements are a practical method for mapping this data, as a large area is mapped a short amount of time. Additionally, anomalous concentrations are identified within the survey area for further adjudication

and inaccessible areas at the ground level can also be included in the survey area.

It is also important to document the average meteorological patterns and hydrological patterns to fully understand environmental changes. The atmospheric stability is measured by temperature change with altitude above the sampling site, where stability is distinguished by six classes[21].

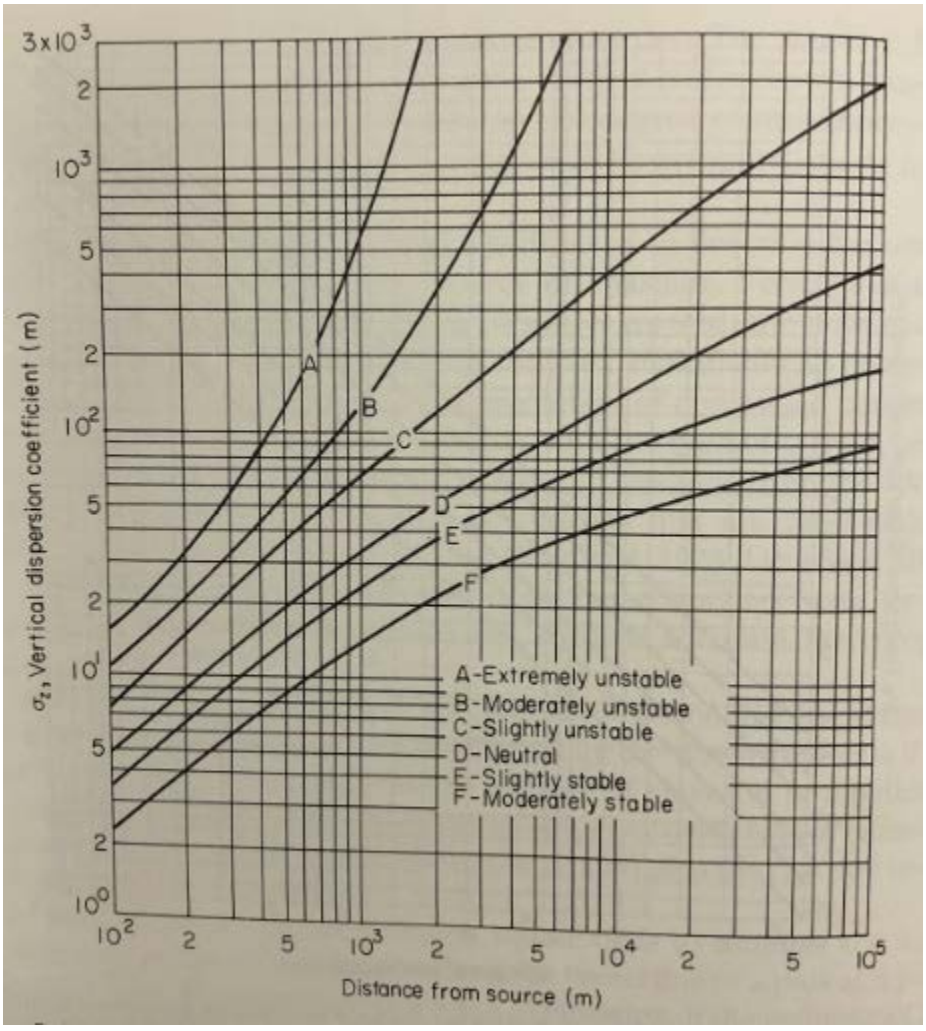


Figure 7: Vertical Diffusion vs downward distance from the source for various turbulence types (Reference 7)

Behavior of the radioactive release is predicted based on weather, where assumptions on the plumes dispersion patterns are made on the release into the environment. There are 5 types of plume dispersion patterns relative to vertical diffusion (Figure 6) and they are discussed below.[7, 15]

Looping – Indication of unstable air, where the release is unpredictably dispersed as the particulates are carried away from the site in the air

Coning – Likely due to high wind conditions, where particulates are carried away and span out as distance increases from the point of release.

Fanning – Occurs under inversion conditions

Lofting – is observed near sunset

Fumigation - is likely as the morning sun dissipates night time inversion conditions

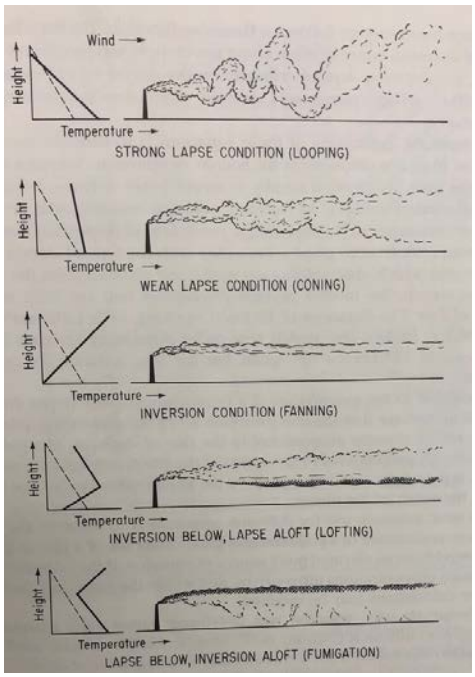


Figure 8: Stack-gas behaviors under various conditions of vertical stability (Reference 7)

Documenting weather conditions allows for predictions on particulate transport and emergency planning for characterization of the release.

3 Methods

Terrestrial radiation and radioelement concentration mapping is performed over a large survey area using aerial measurements. Aerial measurements are typically performed at the lowest capable altitude of the aircraft. At this significant distance from the ground, the only detection equipment feasible in assessing the contaminants on the ground are those capable of measuring

gamma emitting radionuclides. Gammas are more penetrating than charged particle emissions and are capable of traveling long distances in air. The detector response is a function of the photon energy measured and the angle of incidence for the measurement. The range of contaminants deposited on the ground will vary depending on the type of accident or legacy contamination that varies the isotopic distribution based on nearby facility operations. Information on the accident in conjunction with the aerial measurements is used to assess the hazards at ground level.[13]

3.1 Aerial Survey Planning

The National Atmospheric Advisory Center (NARAC) is a national support and resource center for emergency planning, real-time assessment, emergency response, and detailed studies of atmospheric releases of nuclear, radiological, chemical, biological, and hazardous natural materials. NARAC incorporates daily weather forecast into atmospheric transport predictions to model plume arrival times and dose levels for dispersed radioactivity.[5] Located at the Department of Energy/National Nuclear Security Administration's Lawrence Livermore National Laboratory (LLNL), NARAC provides timely and accurate plume predictions to aid emergency preparedness and response efforts in protecting the public and the environment.

Applying predictive plume models in aerial measurement planning is a valuable resource in determining appropriate response operations for nuclear

accidents and in developing initial protective action guidelines for responders and residents near the area of the accident. Prior to performing any data acquisition, the scope of the operation must be characterized with enough detail for effective flight planning and execution. Some information included within the characterization include the location of the release or lost source and environmental conditions at the time of the incident. Flight plans are generated with ARCMAP GIS datasets for the area of interest.[21]

3.2 Equipment

AMS deploys large volume NaI(Tl) detection sensor(s) with associated electronics and communication systems designed and built by the Remote Sensing Laboratory (RSL). Typical dimensions of the sensors consist of 2”x4”x16” and 4”x4”x16” sensor volumes. Dependent on the aircraft and equipment availability, 1 to 20 detectors can be flown at any given time as a virtual detector based on sensitivity needs and aircraft availability. At SRS, the systems are calibrated to 3 keV per channel, with a range up to 3 MeV. The system is installed, a communication check initiated, and a system check is performed prior to executing the flight plan.

All data for this work was acquired on DOE’s Bk-117 with 3-2”x 4”x 16” NaI(Tl) detection systems.

Figure 9: SRS BK-117

3.3 Data Acquisition

The software framework and associated modules used for real-time acquisition, data visualization and analysis of gamma spectroscopy data for AMS detection systems is AVID. The modular system records gamma radiation intensity, spectral data and Global Positioning System (GPS) position every second. Compatible flight plans are generated in the ArcMap

software for the GPS and AVID software for pilot navigation and plan visualization. The system reports gross gamma counts (GGC) per second relative to position. Aircraft velocity and altitude should be constant throughout the flight. Collected data is presented as “bread crumps” and returned in various colors to visualize the count rate on a geo-referenced map.[17] An example is provided below.

Figure 10: Example of AVID Survey Map

3.4 Height Attenuation Coefficients

Airborne surveys attempt to fly at a constant altitude in order to apply a valid attenuation coefficient for flight line acquisitions. Due to the topographical changes in terrain for a large area survey, the height flown at altitude above ground level must be corrected to height above ellipsoid (HAE) to determine nominal survey height. Positioning for each spectral second is recorded, where

Digital Elevation Mapping (DEM) corrects each data point based on geographic location.

Any material between the source and detector diminishes the photopeak due to photon interactions per unit distance traveled. It is expected the window count rates decrease exponentially as height increases for the range of altitudes typically flown for a normal survey.[12] A portion of the system calibration includes obtaining an averaged gross count rate at multiple elevations, such as 100, 300, 500, 750 and 1000 feet. The following least squares function is used to fit the average data relative to height. This provides a model of the systems linear attenuation coefficient (u), where an input of the HAE for the survey yields the linear attenuation coefficient (ft^{-1}) at the altitude flown for the desired energy window.

Eq.3: $$u=B_o e^{Bx}$$

B_o = Intercept, modeled constant

B = Slope, modeled constant specific to energy window

x = HAE (ft)

3.5 Background Characterization and Equipment Verification

Radiation not originating from the earth's surface must be characterized to quantify exposure levels 3 meters (m) above ground surface. In order to correct for cosmic, atmospheric radon, and trace amounts of NORM from

aircraft materials, a “water line” was flown outside of the area of interest over a large body of water.

The radioactivity from aircraft materials is constant during the flight. The cosmic portion is determined by acquiring data at “high” incremental altitudes where atmospheric radon is minimal, typically from 1 km up to 4 km above sea level. The averaged count rate per altitude establishes a profile of the cosmic sensitivity. The count rate from the high energy prompt gammas (3-6 MeV cosmic window) is linearly related to the increasing count rate of the energy window data. Aircraft and cosmic background spectra are subtracted for the energy calibrated observed spectra for the region of interest.[12]

Atmospheric radon is the main source of background accumulation in the lower atmosphere due to radon loss from terrestrial sources. The concentration is determined by a flight line at survey altitude over a body of water. This method utilizes upward-looking detectors, which provides directional sensitivity in distinguishing the atmospheric concentration in relation to radioelement mapping of NORM nuclides at the ground level. The water line acquisition should be flown center of the water body. Additionally, the body chosen must have a surface area greater than the field of view of the detector to minimize terrestrial influences from the water bank. The horizontal

field of view for the detection system is approximately twice the altitude (Figure 7).

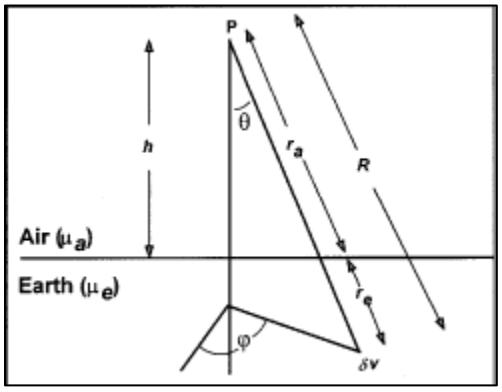


Figure 11: Source-detector geometry for a two layer earth-air model (Reference 12)

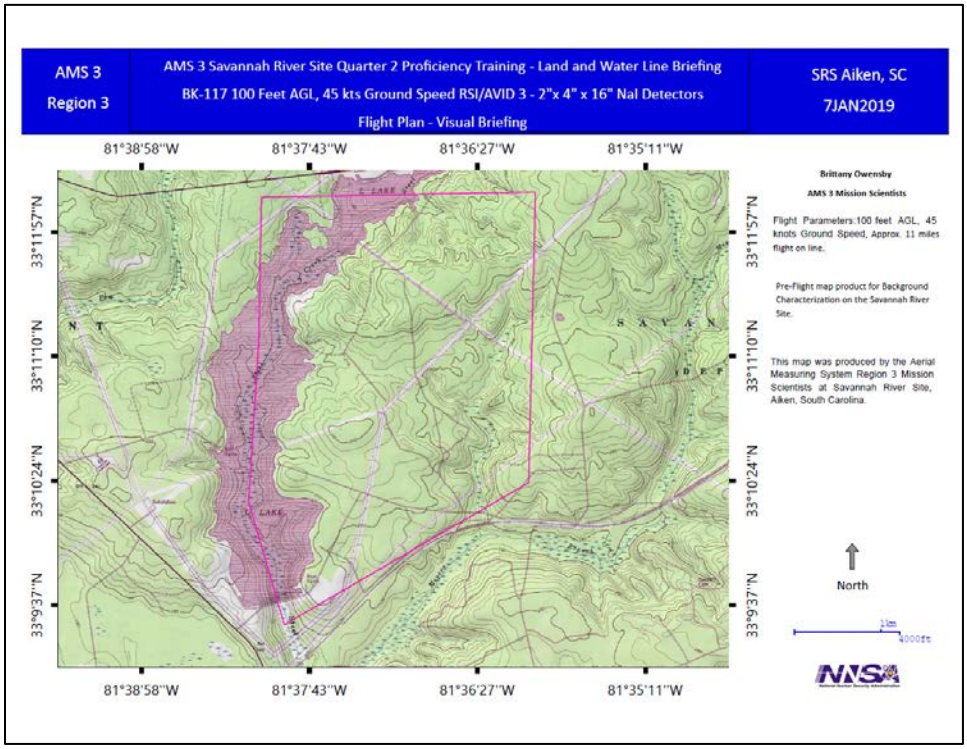
A "land line" was flown over similar terrain with uniform geologic features outside of the area of interest prior to the data acquisition. The line utilizes terrestrial gammas emitted from NORM sources as a final energy check prior to acquisition. An additional measurement of the land line post survey acquisition verifies no changes have occurred in the detection system during data collection. When the survey involves a contamination area, the verification line must contain uniform radioactivity of NORM concentrations and located up wind of the area of interest to ensure the contamination area is not impacting the results.

The characteristic background photopeak's found in gamma ray measurements include[10]:

1. Primordial nuclides: ^{235}U, ^{238}U, ^{232}Th and their associated daughters;
2. ^{40}K from the environment and personnel in close proximity to the detection system;
3. Anthropogenic nuclides: ^{137}Cs fall-out from nuclear weapons testing and facility accidents. ^{60}Co can be found in steel from manufactures and other fission products could be detected based on the location;
4. Activation Products: specific nuclides created by natural sources of neutrons activating the detector itself;
5. Prompt gammas radiation from neutron capture of detector and surroundings;
6. Excitation of stable nuclides within detector medium and surroundings;
7. Cosmic-ray generated nuclide: ^{7}Be;
8. Annihilation peak at 511 keV from pair production events within the detector environment and cosmic ray events.

The figure below is an example of a water and land spiral flight plan over L-area at SRS.

Figure 12: Example of a Water/Land line flight plan mapped at Savannah River Site in Aiken, SC by a mission scientist.



3.6 Gross Gamma Counts

The data of interest is extracted from AVID. Each count measured per second is integrated for the full spectral range, producing the total gross gamma counts. The background characterization acquired prior to flight execution is assumed to be constant for a complete flight and is removed from the raw data. The net count rate is also adjusted to the nominal flight altitude above ground level to height above ellipsoid. The energy specific air attenuation coefficient is applied for a window of interest to determine the true count rate

at the ground level. The relationship below in Equation 4 represents the corrections mentioned above.[12]

Eq. 4: $$GGC = \frac{1}{t_{Live}} \sum_{38}^{3028} (C_E - C_N) * e^{u*(x-x_0)}$$

GGC = Corrected Gross Gamma Counts per second (cps)

t_{Live} = Live Time during acquisition of gamma spectrum

C_E = Counts in gamma spectrum at Energy, E

C_N = Non-Terrestrial background counts from cosmic, radon and aircraft materials

u = gamma ray air attenuation coefficient (ft^{-1})

x = Altitude above ground level

x_0 = AGL to HAE from DEM corrections

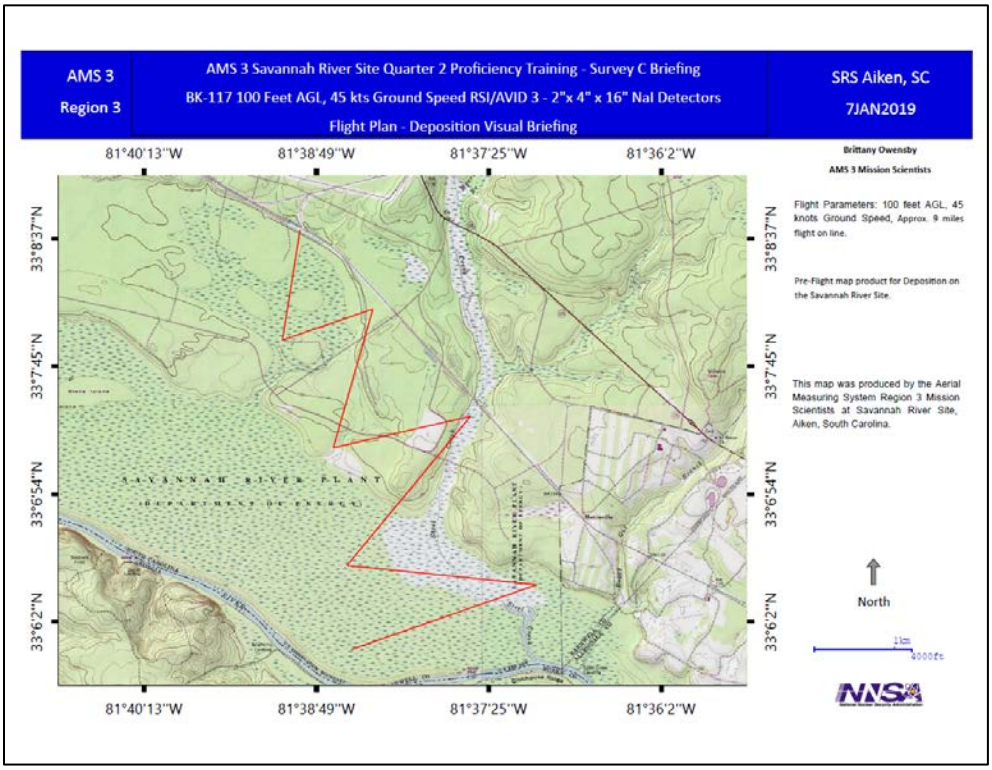
In order to calculate the exposure rate (R/hr), a derived conversion factor (cps/R hr^{-1}) is calculated using the average GGC and ionization chamber reading at ground level. Dividing the GGC by this factor allows for derivation of an exposure rate 3 meters above ground level for the energy window of interest.

3.7 Deposition mapping

The AMS aircraft has the capability of tracking dispersed radioactive plumes and ground deposition mapping. Plume tracking includes establishing an outer boundary count rate and isolating the radioactive cloud. Deposition mapping

occurs once the plume has fallen to the ground, then initiating a serpentine flight pattern over the contaminated field. Flight plans are generated using NARAC modeling but they are not fixed. Necessary alterations in the flight plan based on measurement results. Flight parameters are determined based on the total release concentration. Deposition mapping is a quick method in assessing contaminant levels to plan proper survey and sampling locations. The figure below is an example of a deposition flight plan.

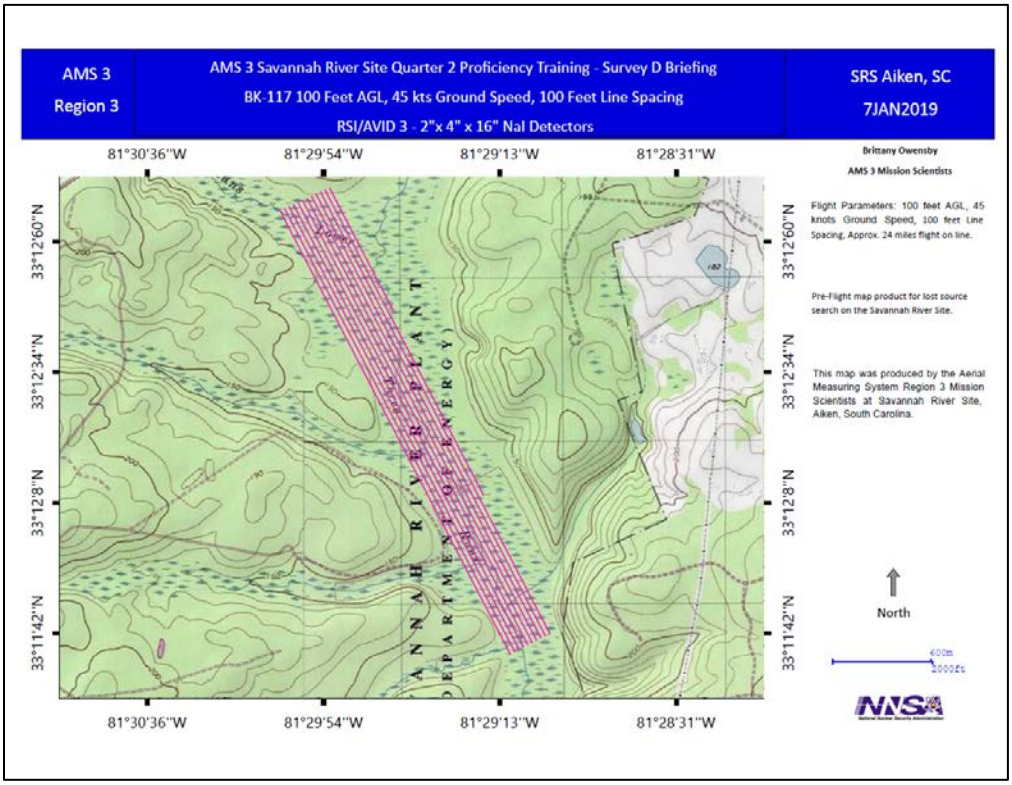
Figure 13:Example of a Deposition flight plan mapped at Savannah River Site in Aiken, SC by a mission scientist.



3.8 Lost/Stolen Source

To locate a lost/stolen source, adequate intel must be provided to determine flight area, radionuclide of concern, and activity levels to determine if aerial search operations provide necessary sensitivity in executing the search mission. Lost source flight plans follow road-ways or consist of parallel lines at a set interval over the projected area of interest for adequate coverage. Flight parameters are established on the sensitivity of the system in relation to the source term. If the source of interest is detected, localizing the position is estimated using trigonometric functions and flight line spacing. This grid pattern flight is also used for radioelement mapping of NORM nuclides for an area of interest. The figure below is an example of a lost source flight plan over an area of interest.

Figure 14: Example of a Lost Source flight plan mapped at Savannah River Site in Aiken, SC by a mission scientist.



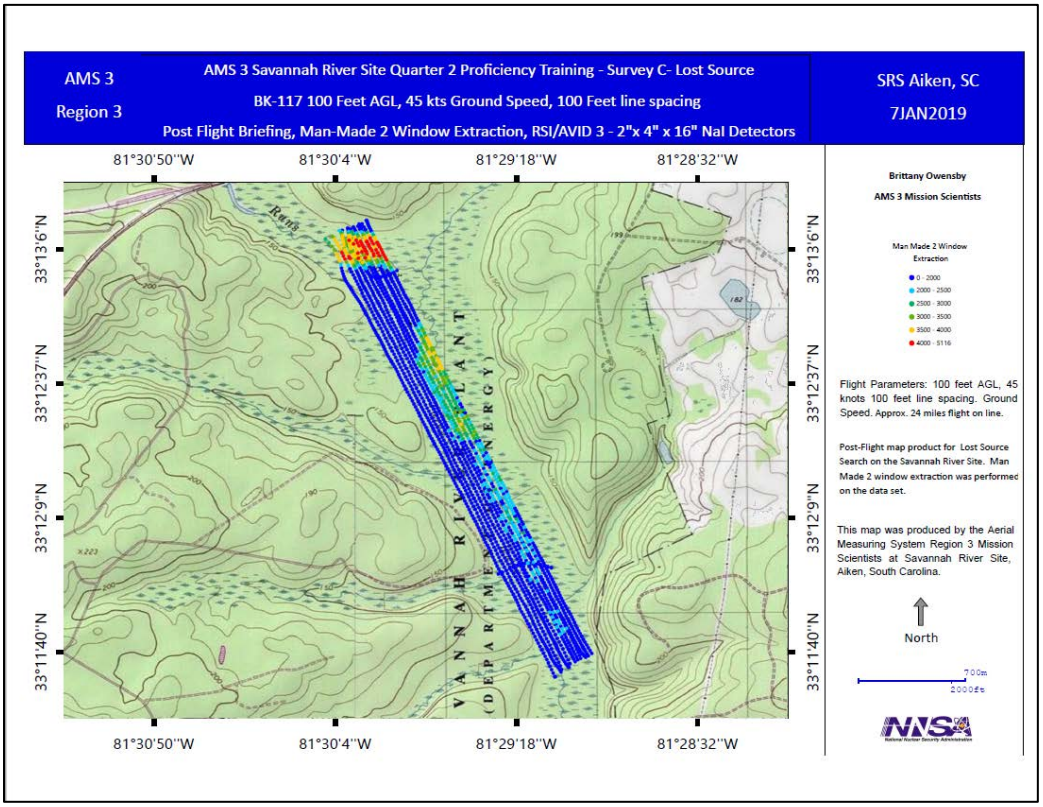
3.9 Data Processing

Extraction techniques are used to identify man-made radionuclides and its associated activity dispersed over the survey area. Aerial coverage is dependent on the aircraft speed and detector view. Terrestrial and geological fluctuations in the survey area can vary significantly for each spectral acquisition. The extraction techniques identify anomalies within the data set when an increase in counts is not obvious and extracts energy specific photopeak data for the radioisotope of interest.[17]

3.9.1 Man-Made Gross Count Extraction (2 Window Extraction)

A 2 Window (2W) Extraction utilizes spectral energy extraction techniques to minimize natural variations in spectral output and identify and improve the calculation of man-made activity. Spectral shapes of natural radioactivity remain fairly constant, but may vary in count rate. Typically, it is understood the low energy sum for the man-made energy region is within the range of 38 - 1394 keV and all counts in the high energy sum (1394 – 3026 keV) reflects emitted radiation from naturally occurring radionuclides. A change in the low and high energy ratio of natural components pinpoints an increase in counts.[12] The figure below is an example of a 2W extraction showing legacy man-made contaminants at the Savannah River Site (SRS). This calculated attribute of the data extracts NORM nuclides and provides a visualization where man made nuclides are present.

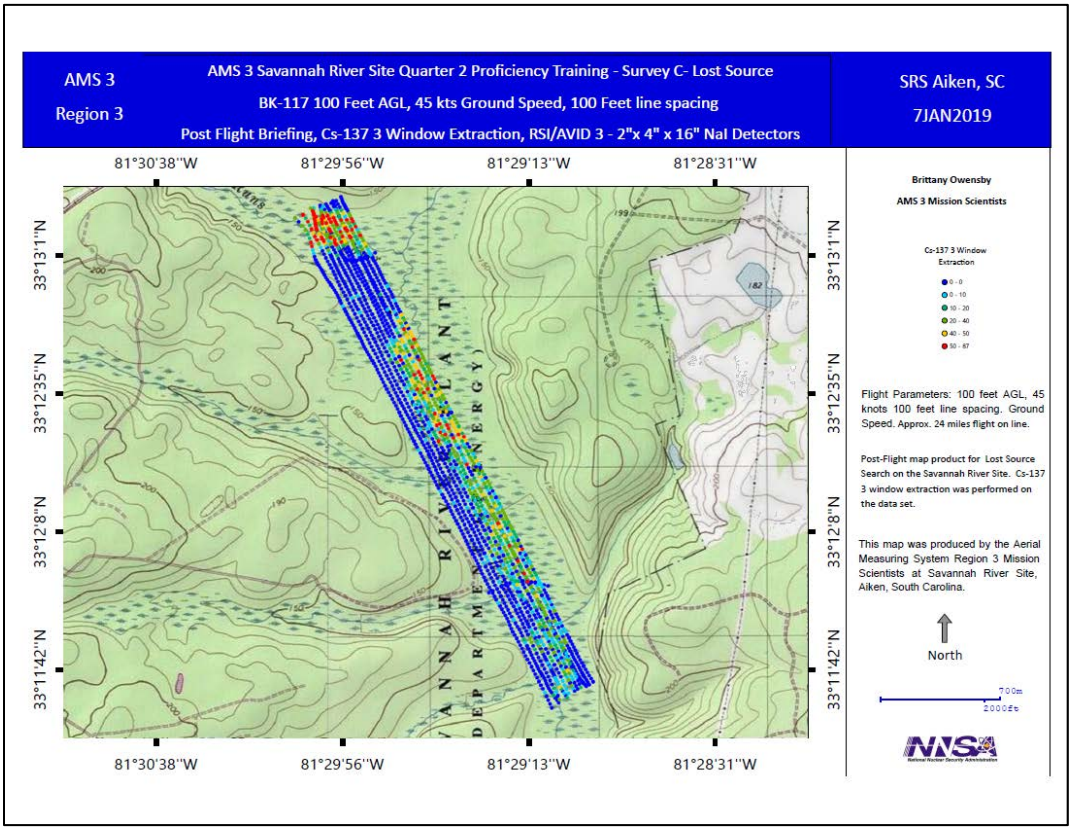
Figure 15: Lost Source flight executed at Savannah River Site in Aiken, SC by a mission scientist (2W Extraction).



3.9.2 Isotope Extraction (3 Window Extraction)

A 3 Window (3W) Extraction uses 2 narrow windows on each side of the photopeak of interest to remove the Compton contribution under the photopeak area. This algorithm is used to calculate the distributed isotopic activity and presented as a contour plot. The figure below is an example of a 3 window extraction of ^{137}Cs.

Figure 16:Lost Source flight executed at Savannah River Site in Aiken, SC by a mission scientist (3W Extraction 137 Cs).



3.10 Utilization of Results

FRMAC is responsible for handling all data and providing the most accurate environmental results regarding radiological conditions. The information provided is used for decision making, establishing radiological situational awareness and post-incident planning. Hazards are assessed to determine public exposure from a radioactive plume and ground deposition results. Derived Response Levels (DRLs) are developed from modeled atmospheric dispersion results in order to establish Protective Action Guides (PAGs). The AMS is one of many assets available in providing measurements to

characterize the environmental results of contaminants and naturally occurring materials.

3.11 Characteristic Gamma-Ray Energy's for ^{222}Rn

There are many gamma ray energies associated with NORM nuclides. The gamma energies associated to the ^{222}Rn decay with a significant abundance are limited. Peak energies identified in Table 1 are the characteristic gamma signatures associated with the daughter products of ^{222}Rn. These energies will be included in the spectral acquisition of the water line, where the atmospheric radon concentration at the time of measurement is segregated from terrestrial influences. Compton scattering from high energy gammas emitted from the terrestrial nuclides interfere with the low energies emitted from ^{214}Pb over terrain. There are many other energies associated with the decay of ^{222}Rn, but are not of interest in spectral analysis due to low yield. The gamma energies available for an analysis to evaluate potential ^{222}Rn concentration drift within the survey area is 609 and 1764 keV.

Table 1: Rn-222 characteristic gamma-ray energies (Peakeasy 4.97)

Rn-222 Age = Equilibrium			
Energy(keV)	Phot/Decay	Nuclide	Decay_Mode
609.312	4.61E-01	Bi-214	Beta-
351.932	3.76E-01	Pb-214	Beta-
295.224	1.93E-01	Pb-214	Beta-
1764.494	1.54E-01	Bi-214	Beta-

To identify a change in the concentration, establishing a baseline ($R_{Baseline}$) of the radon contribution acquired over land (GGC_{Land}) versus the measured contribution over water ($GGC_{Water\ 3W}$) is required to discriminate atmospheric radon from radon trapped and diffused at the ground level. Averaged data from the water and land line are used to establish this baseline value.

Eq. 5: $$R_{Baseline} = GGC_{Land\ 3W} / GGC_{Water\ 3W}$$

For a direct comparison of the contribution during the survey, an additional 3W extraction analysis of the 609 or 1765 keV energy window is needed post flight ($GGC_{Survey\ 3W}$). The correlation is analyzed through a ratio ($R(t)_{Survey}$), where no influences observed result in a constant ratio for each second of data.

Eq. 6: $$R(t)_{Survey} = GGC_{Land\ 3W} / GGC_{Survey\ 3W}$$

If influences are identified from $R(t)_{Survey}$ results, the appropriate corrections are modeled. Due to the proportionality relationship between environmental changes and radon concentrations, functional fitting is applied to model the rate of change in the radon concentration for a noted time period. Graphing a 3W extraction for either the 609 or 1764 keV energy displays distinctive characteristics relative to time and the relationship is characterized using the best data fitting transformation. The potential linearizing transformations for functional fitting are provided below.

Linearizing Transformations	
Y(t) =	$B_o + (B_1 / x_t)$
	$B_o + B_1 x_t$
	$1 / (B_o + B_1 x_t)$
	$x_t / (B_o + B_1 x_t)$
	$B_o B_1 x_t$
	$B_o e^{B1xt}$
	$B_o x_t^{B1}$

Table 2: Linearizing Transformations for Data Fitting

Y(t) = 3W GGC from 609 or 1765 keV (^{214}Bi) model value

B_o = Fitted constant

B_1 = Fitted constant

x_t = Time in seconds

Identifying the best transformation for the dataset is dependent on the rate of change and data correlation over time. An equilibrium factor related to position and time is established to provide a better representation of the changing atmospheric background.

4 Results

The charts below provide the spectral data for the water line, and peak fitting results of the 609 keV and 1765 keV regions of the daughter product, ^{214}Bi. The 609 keV peak is subject to interference from coincidence summing from other energies and ^{214}Pb energies are masked by gamma-ray interactions from the thorium decay series over terrain. Therefore, these energies are not candidates for evaluating atmospheric radon fluctuations. The 1765 keV peak energy is the only applicable indicator a change has occurred during the survey.

Figure 17: Peak Area for ^{214}Bi Water Line

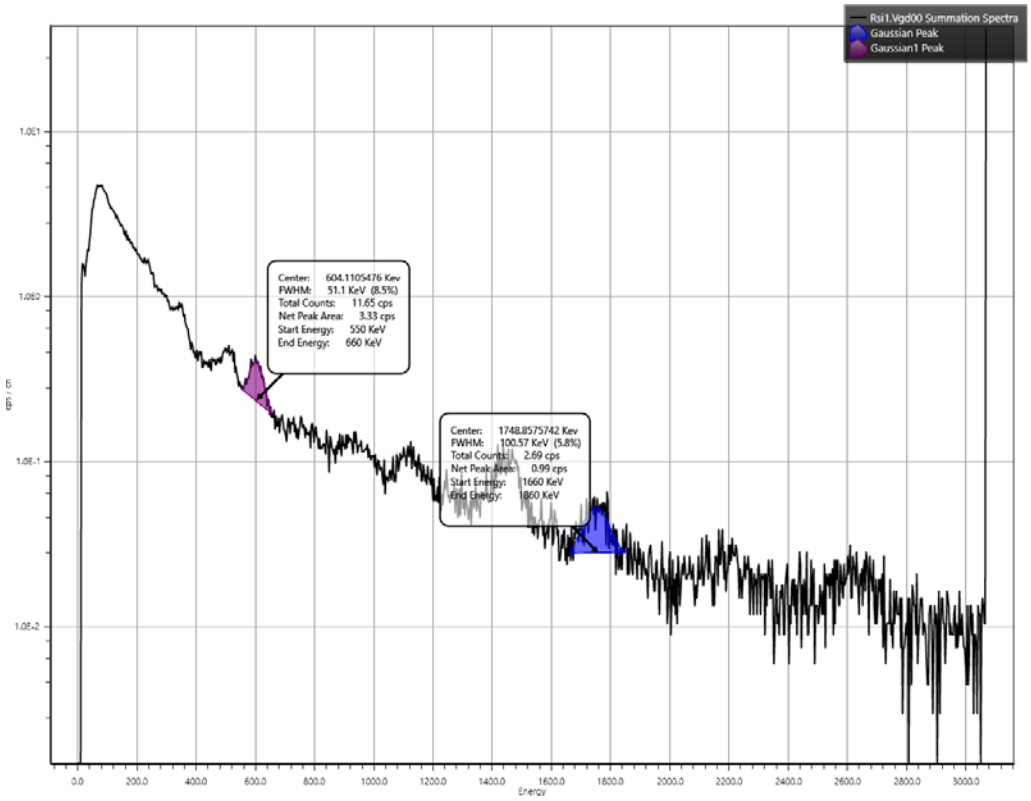


Figure 18: Peak Area for ^{214}Bi Land Line

The land line is flown over a uniform geological region representative to the survey area of interest. There are several mutual spectral interferences between many of the NORM nuclides. The 2614 keV energy from the thorium decay series interferes with lower energy peaks for acquisitions over land.[10] The x-y plotter in AVID plots data for the scaler attribute selected (e.g. 3W extraction). The scatterplot displays the strength, direction and relationship between the two parameters selected as variables and a visual representation of the data characteristic. The charts below are x-y plotter scatter plots of 1765 keV 3W extractions in relation to time for both the land and water lines. The water line resulted in an average integrated extraction of 2 GGC per second

and the land line resulted in 7 GGC per second. The difference is attributed to terrestrial NORM sources, specifically from 2614 keV. The data presented in both charts did not indicate a positive or negative correlation within the data sets, resulting in a fairly constant atmospheric radon contribution at the time of data collection ($R_{Baseline}$). The evaluated dataset did not require further modeling and the characteristic radon correction established from the water line is sufficient.

Chart 1: Water Line Acquisition (Cosmic, Aircraft and Atmospheric Radon), AVID

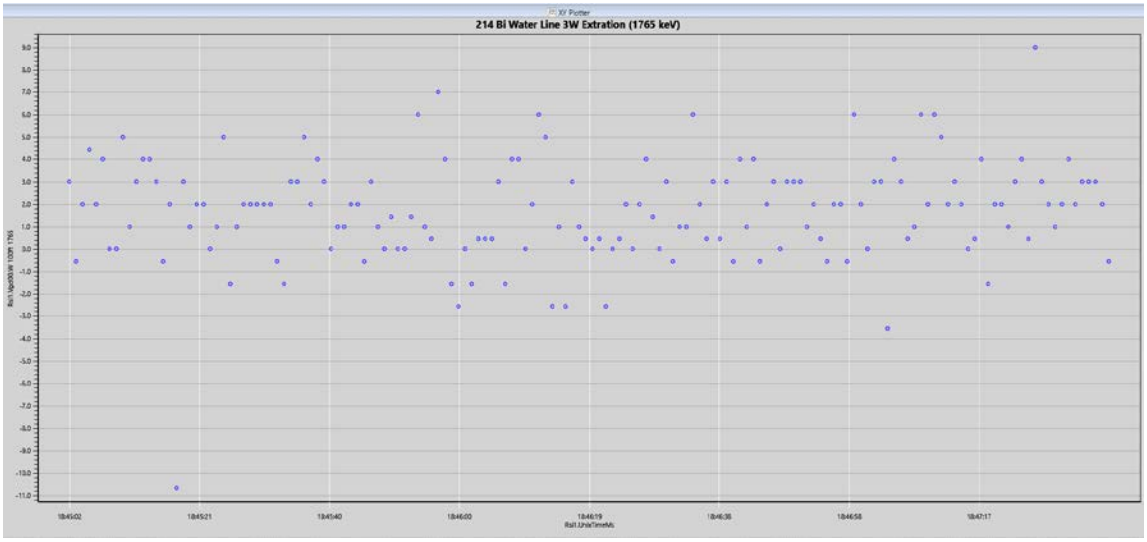


Chart 2: Land Line Acquisition (Cosmic, Aircraft and Atmospheric Radon), AVID

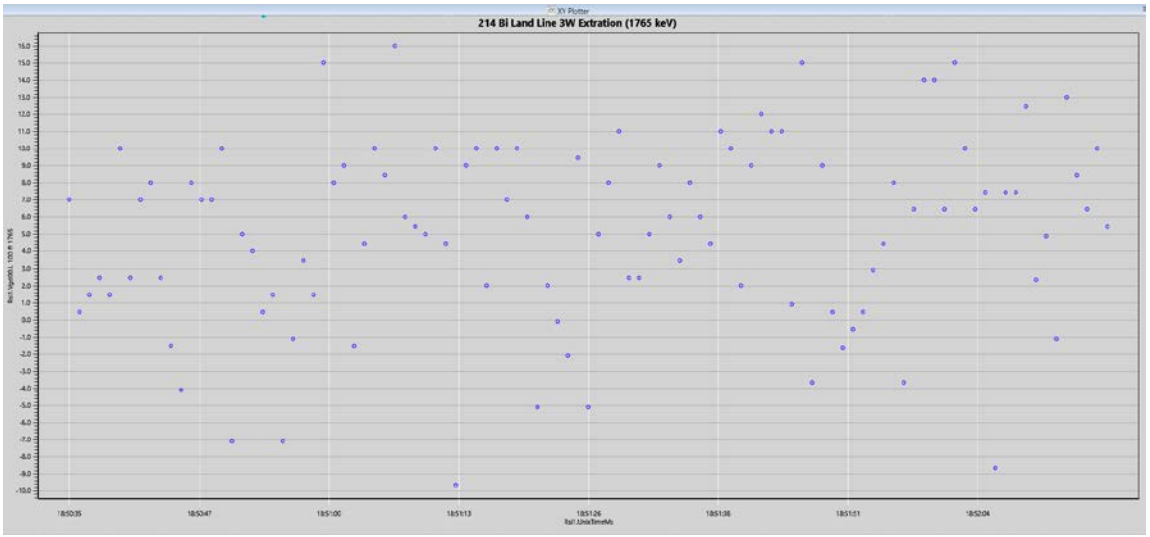
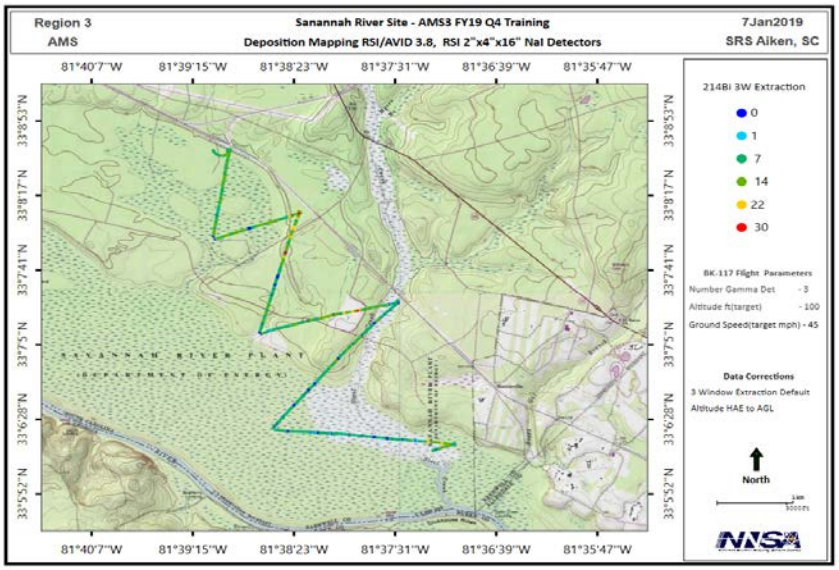


Figure 13 provides a deposition acquisition performed at the Savannah River Site, where the extracted 1765 keV peak area generally remained constant throughout the survey.

Figure 18:Deposition performed at SRS, Aiken SC



5 Discussion

The 3W extraction method (^{214}Bi) of the survey area over time is used to compare the full energy peak of radon to the land line data. This established method provides a tool to determine if there were meteorological influences, where distinctive characteristics evolve during the survey acquisition over time. This association is defined by functional fitting the form of the relationship for the ^{214}Bi 1765 keV 3W extraction within the survey for the data range significantly impacted.

The method surpasses the one time characterization in systematically applying a valid radon background correction. The strength of the relationship is defined by the slope of the fit. The type of fit will depend on rate of distribution change and must be modeled on a case by case basis.[18]

Environmental changes impact the vertical distribution of atmospheric radon. Unfortunately, the aircraft only has means of temperature output at the survey altitude, therefore cannot detect additional parameter changes at various heights above the ground. Photon interaction theory predicts the beam intensity will decrease exponentially over travel distance for a given photon energy. Due to the lack of data observing this positive or negative correlation, an example could not be provided validating the proposed model. Application of the proportionality relationship and attenuation theory, the data should exhibit exponential growth or decay as the rate of change. With this

assumption, the relevant model function for radon characterization is the exponential transformation.

The assumptions required to use the model include:

1. The cosmic interference is linear and dependent on the energy window of interest and does not fluctuate significantly during the time of survey acquisition.
2. The NORM concentration is generally constant over a survey area and the moisture content is uniform during the acquisition. This method cannot be utilized for radioelement mapping of uranium ore deposits.
3. The aircraft contributions are constant and do not change during survey acquisition.
4. There is a constant factor of proportionality between the atmospheric radon concentration and environmental conditions.
5. The topography surveyed should be relatively consistent.

6 Conclusion

The AMS data is used in assessing the threat to the public. Estimated activity concentrations are used to protect first responders and assist decision makers in determining a proper response to ensure the public health is protected following an incident including a nuclear or radiological release. Simple radioactivity counting is subject to many uncertainties, and specialty counting via aerial measurements introduce additional systematic variations.

The generalized procedures provided for raw data correction identify an upward looking detector to monitor atmospheric contributions within the spectral data. Isolating a sensor for this purpose decreases the overall detection sensitivity. The functional fitting method extracts information from the acquired spectrum and establishes an appropriate correction with respect to time and position. Accounting for climatic variations in the background is one correction in achieving accurate results.

The data used in this work did not require an exponential transformation for radon drift and the model could not be validated. Environmental flights are costly and are performed strictly on a requested basis. If the resources were available, I'd establish a test plan to obtain data in various climatic conditions to determine the overall concentration fluctuations observed at the Savannah River Site. These results would aid in determining if a derived correction is needed to normalize results and minimize variation in

response. Work on the proposed model will continue to progress until sufficient data is obtained to either prove or discredit the model.

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