Multi-Sensor Radiation Detection, Imaging, and Fusion

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Abstract

Glenn Knoll was one of the leaders in the field of radiation detection and measurements and shaped this field through his outstanding scientific and technical contributions, as a teacher, his personality, and his textbook. His Radiation Detection and Measurement book guided me in my studies and is now the textbook in my classes in the Department of Nuclear Engineering at UC Berkeley. In the spirit of Glenn, I will provide an overview of our activities at the Berkeley Applied Nuclear Physics Program reflecting some of the breadth of radiation detection technologies and their applications ranging from fundamental studies in physics to biomedical imaging and to nuclear security. I will conclude with a discussion of our Berkeley Radwatch and Resilient Communities activities as a result of the events at the Dai-ichi Nuclear Power Plant in Fukushima, Japan more than 4 years ago.

Keywords: Glenn Knoll; Gamma-ray detection; Gamma-ray imaging; Multi-mode data fusion; Nuclear Street View; Radiological resilience

1. Introduction

Since the discovery of X-rays by Wilhelm Röntgen in November 1895, technologies to detect directly or indirectly ionizing radiation has made revolutionary advances. The study and development of new and improved

radiation detection concepts remains a very active field of research with ever-growing number of applications. Since the 1960's, Glenn F. Knoll played an important role in these developments due to his contributions in research, as a teacher and mentor, and due to his textbook, sometimes called the “Bible” of radiation detection and measurements. The fact that similar concepts and technologies in radiation detection can impact so many applications and fields has been and remains fascinating. Applications range from answering fundamental scientific questions in physics to questions in biology and chemistry, to diagnostics and therapy in medicine, and more recently gained importance in national and global security. Our Berkeley Applied Nuclear Physics program is capturing some this research and - in the spirit of Glenn Knoll - is embedding education of the next-generation of scientists as well as the more and more important component of outreach to communities locally and globally.

In the following, I will discuss a few of our recent highlights in research and outreach: Electron-tracking based gamma-ray reconstruction, 3D volumetric or scene-fusion gamma-ray imaging, large-scale detection systems, and finally our Berkeley Radwatch program which led to the recent establishment of the Institute for Resilient Communities. The detection and imaging concepts range from $\sim \mu\text{m}$ to meter-scale and resolution instruments and include the development to integrate complementary information to enhance the sensitivity to detect weak or shielded radiation sources in complex radiation fields that are dominated by background.

2. Advanced detection and estimation concepts

As mentioned above, the ability to detect radiation emanating from atomic nuclei or nuclear processes has applications ranging from basic research to medicine and security. Some of the objectives in these diverse fields are similar as the goal is to detect or estimate weak specific nuclear signatures in the midst of potentially dominating and temporary- and spatially varying background. Conceptually, we can differentiate between detection and estimation. In detection, a binary decision matrix can be defined capturing all possible outcomes in being right or wrong about a detection or non-detection. In estimation, a non-binary function is to be measured, either as a quantity or shape or any other property of interest. Simple radiation counters, more advanced spectrometers, or imagers can be operated for both purposes, just for detection or for estimation. In any domain and implementation, the challenge is to discriminate between relevant and non-relevant information and to distinguish the signal of interest and background or the signal and noise with high sensitivity and specificity.

Particularly after the events and major releases of radioactive materials from the Dai-ichi nuclear power plant in Fukushima in March 2011, the use of Geiger counters increased substantially resulting in many wrong claims of contamination due to Fukushima globally. Except in the area close to the nuclear power plant and in the evacuated area, the specificity of a Geiger counter is not sufficient to discriminate natural background radiation from radioactivity that can be associated with the releases in Fukushima. In contrast, gamma-ray spectrometers such as high-purity Ge detectors are easily able to distinguish for example the Fukushima-related nuclear fingerprints of Cs-134 and Cs-137 from background caused by naturally occurring radioisotopes. Finding ways to enhance the understanding and estimating background variations enhances the ability to unambiguously detect and identify sources of interest, whether in environmental or security-related measurements. Complementary to spectroscopy, imaging concepts can be used to discriminate point-like threat sources over extended backgrounds or by correlating spectral signatures with specific locations. A gamma ray whose energy is measured is worth more than just the registration of its existence. The incident direction and the location of the source provide additional value. However, both, the spectroscopy and imaging are associated with decreased efficiency as not all gamma rays deposit their full energy in a detector and only a fraction of the incident gamma rays can be imaged. The gain in specificity due to spectroscopy, imaging, or a combination of both needs to be balanced with the loss in efficiency and the additional costs and complexity of the deployed systems. This is particularly true for detection tasks. Estimation tasks such as identification, localization, or determining shapes do require corresponding measurements of energy (for identification) and direction (localization and shape).

In the following, I will discuss a new concept in gamma-ray imaging that can potentially enable more specific and efficient gamma-ray imaging and the concept of three-dimensional volumetric imaging reflecting the ability to produce or use three-dimensional models for gamma-ray reconstruction in three dimensions. While the first concept is still in its early phase of development, the 3D volumetric imaging is much closer for deployment. As a matter of fact, we developed the idea and had the first conceptual demonstration about 7 years ago already [1,2].

2.1. Electron-tracking based Compton imaging

Conventional means of imaging individual gamma rays as widely used in nuclear medicine rely on collimators to determine the incident angle or the so-called line-of-response. They work satisfactorily at gamma-ray energies of

140 keV or up to 400 keV, at higher energies with significantly reduced efficiency due to the limited attenuation of gamma rays in the collimator. Coded aperture based imaging provides higher efficiency, up to 50%, however, is limited to simple source configurations. In addition, passive collimators and apertures are heavy, preventing easy portability.

An alternative approach for gamma-ray imaging relies on the ability to measure energies and three-dimensional positions of individual gamma rays interactions that are induced by the Compton scattering process [3,4]. These can be used to reconstruct the direction of the incident gamma ray to a surface of a cone. As shown in Fig. 1, the two first interactions provide the symmetry axis of the cone, the opening angle is determined by the energy of the first interaction and the total energy of the incident gamma ray. Since this concept relies on the Compton scattering process as its first interaction, it is called Compton imaging. The advantage of Compton imaging is the fact that no heavy collimator is needed limiting the field-of-view and efficiency resulting in reduced weight, specifically for high gamma-ray energies. The drawback is the requirement of position-sensitive detectors and the Compton scattering process. Because of the latter, Compton imaging does not work or has limited imaging performance at low energies, typically below 200 keV. Another disadvantage of Compton imaging is the ability to only reconstruct a cone for each event, reflecting the symmetry of the Compton scattering process. This symmetry can be broken if one can measure the initial direction of the Compton-scattered electron. This so-called electron-tracking based Compton imaging allows us to reconstruct an arc instead of a full cone on event-by-event basis, as shown in Fig. 1.

Figure 1 Illustration of electron-tracking based Compton imaging. Without the knowledge of the electron scatter direction, the direction of the incident gamma ray can only be restricted to a cone surface. By measuring the initial electron trajectory the cone can be reduced to an arc reducing the background in the reconstructed gamma-ray image. The resolution, i.e. the extension of the arc depends on the resolution of the electron track reconstruction. The intrinsic width of the cone and arc depends on the energy and position resolution for individual gamma-ray interaction of the instrument and ultimately, the uncertainty due to the intrinsic momentum of the Compton-scattered electron.

We were able, for the first time, to demonstrate electron-tracking based Compton-imaging in a solid-state detector [5,6]. While this concept has been shown before in gas-based instruments, these detectors are characterized by very low interaction efficiency and low energy resolution, significantly limiting the achievable gamma-ray imaging sensitivity [7]. The scientific CCDs we are using are fully depleted Si devices with a thickness of 650 μm and a pixel pitch of 10.5 μm [8]. These characteristics are well suited for tracking electrons above about 150 keV. We have demonstrated the ability to reconstruct gamma rays with an arc opening angle of about 30-60 deg., depending on incident angle and deposited energy [9].

In addition to the challenges associated with the accurate and efficient measurement of the initial direction of the scattered electron, the conversion of the measured electron energy and scatter direction into an energy and direction of the incident gamma rays requires sophisticated and new algorithms. As prerequisite, we have developed algorithms to extract the initial three-dimensional scatter direction of the electron by only observing the two-dimensional energy loss distributions provided by the intrinsically two-dimensional CCD [10]. We demonstrated the conventional electron-tracking based Compton imaging concept requiring at least two interactions to be detected by reconstructing coincidences between the scientific CCD and a three-dimensional position sensitive Ge detector. A new algorithm was derived to analytically reconstruct the incident gamma-ray energy and angle by just using the initial electron scatter direction and the energy deposited by the Compton scattered electron, i.e. by only

measuring the partial energy of the incident gamma ray [11]. This realization potentially allows us to reconsider inherently inefficient gas detectors, as only one interaction is required. Fig. 2 illustrates the results of the reconstruction of a Cs-137 source characterized by a gamma-ray energy of 662 keV.

Figure 2 Reconstruction of gamma-ray momentum, i.e. energy and incident direction by using the measured initial electron scatter direction and electron energy in a CCD system. Top left is the measured electron energy in the CCD reflecting the energy deposited by the Compton scattered electron. Note that the full energy of the gamma ray is not visible as only the energy of the Compton-scattered electron is deposited. Top right: Reconstructed gamma-ray momentum. Bottom left: Projection of momentum on energy axis illustrating the reconstruction of the incident, full gamma-ray energy. Bottom right: Reconstructed incident direction of gamma rays.

2.2. 3D Volumetric gamma-ray imaging

Complementary to μm -resolution and small-scale instruments used to develop a new generation of gamma-ray imaging instruments as discussed above, we are pursuing the development of medium-sized and hand-portable gamma-ray detection and imaging systems in combination with contextual sensors. These combined 3D volumetric imaging systems enable the simultaneous reconstruction of the 3D environment and the fusion of gamma-ray images with this 3D scene. This 3D fusion goes beyond the previously developed overlay of visual images and gamma-ray images in two-dimension by fully integrating multi-sensor information in three dimensions. The advantages are the significantly increased efficiency, accuracy, and contrast in the measurement and reconstruction of the gamma-ray information, the possibility for quantification of gamma-ray source activities, and the increased speed in the gamma-ray reconstruction. As development platform, we are using the second generation Compact

Compton Imager (CCI-2) and the High-Efficiency Multimode Imager (HEMI) [12-14]. Both systems are shown in Fig. 3.

Figure 3 Left: Second generation Compact Compton Imager consisting of 2 DSSD HPGe detectors mounted in a cryostat with contextual sensors, two panoramic video cameras and a Lidar scanner. Right: The hand-portable High-Efficiency Multimode Imager consisting of arrays of CPG CZT detectors to enable coded aperture and Compton imaging, simultaneously.

CCI-2 consists of two high-purity Ge (HPGe) detectors implemented in a double-sided strip detector (DSSD) configuration. Each detector has a thickness of 15 mm and 38 orthogonal strips with a strip pitch of 2 mm. Digital signal processing is used to obtain the position of individual gamma-ray interactions to about 1 mm in all three dimensions. This position resolution combined with the energy resolution of about 2 keV for each strip can provide an angular resolution down to about 4 deg at 662 keV when operated in Compton imaging mode. The angular resolution depends on the energy and data cuts implemented reflecting the trade-off between efficiency and angular resolution. The system is mounted on a cart providing support for the fully digital data acquisition system to read out the 152 strips, the power supplies, and the liquid nitrogen dewar to provide the necessary cooling for the HPGe detectors. While this system is too heavy for easy deployment, it represents an efficient platform to develop advanced detection and data fusion concepts. A more compact and hand-portable, DSSD HPGe based system is commercially available, albeit with worse position resolution [15]. In contrast to HPGe detectors that require cooling to about 100 K, CdZnTe (CZT) based instruments do not need cooling and can therefore be built inherently more compact and with less weight per detection volume. The CZT based HEMI instrument consists of 96 detectors implemented in a coplanar grid (CPG) configuration [16]. The individual, 1 cm³ big detectors are arranged in two parallel planes with 32 detectors in the front plane and a fully populated plane of 64 detectors arranged in an 8x8 array. The front plane of active detectors serves as coded aperture for low gamma-ray energies and as scatter plane

for Compton imaging for higher gamma-ray energies. The total active detector mass is 1.2 lbs with the whole instrument weighing about 8 lbs and is therefore easily portable. In comparison to the DSSD HPGe, the energy resolution is degraded and the position resolution is limited to 1 cm^3 resulting in an angular resolution of about 10 deg. at 662 keV. Both gamma-ray imaging instruments have been combined with contextual sensors such as high-resolution Ladybug video cameras and 32 beam rotating Lidar systems or Microsoft Kinect[®] sensors.

Fig. 4 illustrates the reconstruction and fusion of objects and images in 3D. By moving the cart or walking with HEMI through the scene, it is possible to reconstruct a point cloud representing surfaces of objects in 3D and to use these point clouds to increment the gamma-ray image in 3D. The simultaneous localization and mapping (SLAM) algorithm was implemented to estimate the location and orientation of the instrument relative to the scene. The reconstruction of the 3D scene, the SLAM algorithm, and the 3D fused gamma-ray image reconstruction can be done in real-time, i.e. while moving the cart or carrying the instrument through the scene. Most recently, we have demonstrated this concept with HEMI for several different radioisotopes simultaneously with all source activities in the order of $10\text{ }\mu\text{Ci}$ and minimum distances of 1-5 m from the trajectory.

Figure 4 Illustration of 3D volumetric imaging. 3D point clouds are registered using a Microsoft Kinect sensor mounted to the CCI2 gamma-ray imaging systems. By moving the cart through the cluttered scene, the 3D point cloud is obtained and subsequently used to reconstruct the gamma-ray image in 3D. The red line indicates the trajectory of the instrument, the blue arrows represent the gamma-ray scatter directions. These events have been used to reconstruct the location of the Cs-137 source. The total acquisition time was less than 90 sec. while the cart was moved over a distance of about 12 feet.

In collaboration with JAEA, HEMI has also been deployed to Fukushima to evaluate contamination-mapping capabilities when mounted on a RMAX unmanned and remotely controlled helicopter. The dimensions and the weight of HEMI are well suited for these demonstrations. The HEMI instrument itself was packaged in an environmental box that allowed an operation independently from the helicopter operation. The whole package included a video camera, a GPS/ IMU system, thermal stabilization, data storage, batteries, a control unit, and HEMI. The video information is used to reconstruct three-dimensional surfaces on the ground stereoscopically. These surfaces are then used to project the gamma-ray images onto as shown in Fig 5. Although these 3D surfaces improve the reconstruction, it still provides limited reconstruction capabilities. This is due to the fact that the surfaces are typically the surfaces of vegetation and not the source of the radiation which is located beneath the surfaces, e.g. in the soil or within the plant. More work remains to be done to increase the quantitative reconstruction capabilities in the complex environments of Fukushima.

Figure 5 Left: HEMI as mounted in an environmental box and on a RMAX helicopter in the evacuated area of the Fukushima Prefecture. Right: Compton image reconstruction of Cs onto 3D surfaces obtained by using the onboard video camera.

2.3. Large-scale systems for standoff-detection

As the third example of the development and demonstration of new concepts in radiation detection and measurements in our program, the challenging task of detecting and localizing radioactive materials in so-called standoff detection will be discussed. Standoff typically implies distances between 10 m and 100 m between the instrument and the material of interest. Larger standoff distances suffer attenuation and solid angle losses requiring source activities for detection that are typically too large to be of relevance for most operations.

We have been operating the truck-based Radiological Multi-sensor Acquisition Platform RadMAP in the Bay Area for the last three years. RadMAP contains arrays of HPGe, NaI(Tl), and liquid scintillator detectors that enable standoff detection of gamma rays and neutrons. We are pursuing three main objectives with this system: 1.) Systematic mapping of radiation backgrounds; 2) Evaluation of detection concepts in realistic environments; 3.) Development of the Nuclear Street View [17]. A systematic mapping of radiation backgrounds in a range of environments with their temporally and temporary variations is important in order to evaluate and develop improved detection concepts. When searching for weak sources, the ability to estimate the background is critical. For detection, not only is the sensitivity to detect a source important but also the specificity in avoiding false alarms. Conventionally, predominantly the statistical noise terms have been considered when evaluating detection performance, neglecting systematic variations in backgrounds that are found in realistic environment, particularly when operating on a mobile platform. The concept of the Nuclear Street View is an extension of the 3D volumetric imaging and the 3D Google Streetview[®]. It is based on the ability to reconstruct buildings in 3D as the conventional Streetview, but in addition, it is able to classify objects such as buildings and can associate gamma-ray emission spectra to these objects in 3D. It will be discussed further below in more detail.

Figure 6 The Radiological Multi-sensor Acquisition Platform RadMAP with its nuclear radiation detectors as well as contextual and environmental sensors.

RadMAP as shown in Fig. 6 is a truck-mounted platform that contains a range of nuclear radiation detectors as well as contextual and environmental sensors [17]. The nuclear radiation instruments consist of up to 24 large-

volume HPGe gamma-ray spectrometers, 100 4"x4"x2" NaI(Tl) gamma-ray detectors arranged in a 10x10 array behind a passive coded mask, and 16 large-volume liquid scintillation detectors for neutron detection. The HPGe detectors provide excellent spectroscopic detection capabilities and the coded aperture system provides gamma-ray imaging capabilities. The NaI(Tl) detectors are also being used for detection. Two Ladybug video cameras and two rotating Lidar systems are mounted in the front of the truck to obtain a near-complete coverage of the environment. A digital weather station is mounted on the top to provide meteorological data. In addition, two hyperspectral cameras are mounted on the passenger side to study objects with regard to their emission spectra between 400 nm and 1700 nm, i.e. the visual and near-infrared spectrum.

With this system, large sets of background data and contextual information are observed and stored at the NERSC computing facility at LBNL. Fig. 7 shows a map of routes driven in the areas of Oakland and Alameda. The colors represent the intensities of gamma rays associated with the decays of the main primordial background sources, K-40, Th-232, and U-238. The insert shows the three intensities observed close to a stainless steel bridge in Alameda [18].

Figure 7 Measured average gamma-ray count rates in HPGe detectors associated with K-40, U-238, and Th-232 (KUT). During 74 days of measurements almost 4000 miles in the greater Bay Area were traveled. The highest count rate is about 2 cts per HPGe detector. The insert illustrates the differentiated count rates in K-40, U-238, and Th-232 and their variations in the vicinity of a stainless steel bridge.

Of particular interest in using RadMAP in this configuration is not only the ability to obtain extensive sets of gamma-ray and neutron backgrounds with contextual information, it also enables important comparisons of detection concepts and modalities [18]. Using the concept of source injection, it is possible to create so-called Receiver Operator Characteristic or ROC curves for a range of gamma-ray sources and intensities, standoff distances, truck speeds, etc. and for each of the detection instruments on board. The spectroscopy of the HPGe detectors can be compared with the spectroscopy of NaI(Tl) detectors or their imaging capability when operated with the coded mask. Algorithms can be evaluated and optimized for all detection modalities and detector types. In addition, the number of detectors can be varied and its impact in detection can be studied [19]. As an example, Fig. 8 shows ROC curves for HPGe and NaI(Tl) detectors when searching for a 1 mCi Cs-137 source at 100 m standoff distance and driving at 25 mph. Such plots enable the comparison of different spectroscopic and imaging approaches. The axes were scaled so that a Gaussian distribution will result in a straight line in the log-log presentation. We have performed extensive benchmark measurements and simulations and find excellent agreement in the full-energy efficiencies of the HPGe and NaI(Tl) detectors. We are currently developing and demonstrating new detection algorithms that make use of the whole spectra and contextual information to better estimate the background contribution to the total spectrum.

Figure 8 ROC curves for detecting 1 mCi of ^{137}Cs at 100 m standoff using the 1 m² NaI array for both spectroscopy and imaging algorithms, as well 3 HPGe (each 100% relative efficiency) for comparison. Both axes are plotted on a normal deviate scale. Shaded regions indicate 68% confidence intervals.

The large sets of data collected in the measurement campaigns are being stored, processed, annotated, and indexed using tools such as the FastBit and FastQuery developed at LBNL [20]. The goal is to make these data available to the user community. It also allows us to establish benchmarks for a wide range of detection hardware and software that is critical in guiding further developments and improvements. We have established the Berkeley Nuclear Data Cloud that allows registered users to access selectable data sets.

2.4. Nuclear Street View

As mentioned before, one of the goals of RadMAP is the development and demonstration of the Nuclear Street View. Fig. 9 illustrates the concept. The Lidar and visual sensors are used to reconstruct surfaces in 3D, including the relative position and orientation of the truck within the reconstructed scenes. Semantic segmentation is being used to automatically classify objects such as building, vegetation, sidewalks, cars, persons, etc. The Nuclear Street View concept is able to associate spectral signatures to these specific objects. It is enabled by combining the semantic segmentation with the gamma-ray imaging data and the knowledge of the precise response of the instrument. The Nuclear Street View concept will not only allow us to associate gamma-ray signatures with objects

such as buildings, it can potentially enable the prediction of backgrounds given specific non-radiation signatures. Such signatures are currently being studied by using the hyperspectral cameras on board of RadMAP.

Figure 9 Conceptual illustration of the Nuclear Street View. Semantic segmentation algorithms are applied to data collected with the video cameras and Lidar systems on board of RadMAP. Specific objects such as buildings, sidewalks, vegetation, cars, or people can be associated with gamma-ray emission signatures. Other classes can be identified, particularly when using different sensors such as the hyperspectral cameras that were recently mounted on RadMAP.

3. Berkeley Radwatch and Beyond

With the releases of radioactive materials on and shortly after March 15, 2011 from the Dai-ichi nuclear power plant we set up initially rudimentary, later more sophisticated means to measure radioisotopes in rainwater, air, and food samples in Berkeley. The goal of this activity was two-fold: 1.) To study the characteristics such as type and quantity as well as the appearance and the disappearance of radioactive materials that we could associate with the releases in Fukushima; 2.) To publish our results and to engage the public in a dialogue about radiation and to put our findings in the context of the radiation we are exposed to naturally or electively on a daily basis. Our Berkeley Radwatch activities have enabled us to address concerns by the public on the impact to radiation from Fukushima.

Figure 10 Example of measurements and data displayed at <http://radwatch.berkeley.edu>. Left: The appearance and disappearance of Cs-137 in milk collected locally. The measurements were performed with a high-purity germanium gamma-ray spectrometer. It is important to note that the activity due to naturally occurring K-40 is about 50 Bq/l, e.g. about 10 times higher than the highest Cs activity measured once. The red line reflects the detection limit. Right: Near-real time display of radiological and meteorological data collected on UC Berkeley campus. The radioisotopes are observed with a particulate filter in front of a high-purity germanium detector, the meteorological data are collected with a weather station located close to the gamma-ray spectrometer. Of importance are the observations that we are continuously exposed to decay products of uranium and thorium as well as potassium (specifically K-40) and that the activity levels can vary by a factor of 10.

We have established a website where we publish and discuss our results as well as claims and results from elsewhere [21]. Early in 2014, we installed an automatic and near-realtime air monitor that provides activities of radioactive particulates captured in a filter mounted in front of a mechanically-cooled HPGe detector on an hourly basis. Associated with our Radwatch activity, we have established the Kelpwatch project in collaboration with California State University in Long Beach, CA [22]. The goal of this activity is the measurement of radioisotopes in marine Kelp that is collected along the Pacific Coast of North America. Similar to the radioisotopes from Japan that arrived in California by means of the jet stream within about 70 hours after the releases into the atmosphere in Japan, the main goal of Kelpwatch is to observe the arrival of radioactive materials that were released into the Ocean in March 2011 and are transported by means of the Pacific Ocean currents. While we expect the arrival of radioisotopes such as Cs-134 and Cs-137 that can be associated with the releases in Japan over the next year or so, the concentrations will be extremely small, close to the detection limit of our monitoring system of about 10 mBq/liter and will not pose any health risk [23-25]. The Woods Whole Oceanographic Institution recently published the first observation of Cs-134 off the Northern California Coast. The observed concentration of 2

mBq/liter is significantly less than the about 10 Bq/liter of the naturally occurring K-40 observed in the Pacific Ocean [26]. The ongoing releases of contaminated water in the Ocean in Japan result only in fairly small concentrations even close to the harbor of the power plant. For example, the water concentration of Cs-134 in close proximity of the harbor of the Dai-ichi nuclear power plant is about 20 mBq/liter, if detectable at all [27].

The Berkeley Radwatch activity was recently combined with ongoing research in Japan under the umbrella of the new Institute for Resilient Communities. The Institute for Resilient Communities is dedicated to developing and improving scientific and technological capabilities to assess, predict, and minimize the impact of sudden or long-term changes that could have disastrous consequences on local and global communities. It combines science, technology, education, and outreach by involving academic and educational institutions as well as communities in an international, multi-disciplinary, and multi-cultural context. Our research within the context of radiological resilience at LBNL is currently engaged in 4 different scientific and technology domains, which address current needs in the evacuated areas to ensure the safety of the population when they return and in the future. As of October 2014, about 85,000 people are still evacuated and many, particularly older people want to move back to their homes and communities [28]. The research areas we are currently pursuing in collaboration with scientists from JAEA aim at more effective means to map the contamination, at a better understanding and improved predictive power of environmental transport models, enhanced understanding and measurements of internal human radiation dose, and at the removal of contamination from soil. While the focus initially is on the most abundant contaminant left, cesium, and the environment of Fukushima, the knowledge gained and technologies developed will provide significantly improved means in the aftermath of any radiological event in the future that is associated with the release of radioactive materials. The Fukushima Prefecture represents a very different environment than for example the region of Chernobyl as it consists of large portions of forests and mountains with significant precipitation over the whole year causing continuous changes in the contamination patterns. Fig. 11 summarizes the four areas of research and their relationships. These activities are coordinated with the substantial efforts by the JAEA in Japan.

In addition, we are expanding the Berkeley Radwatch activities to include not only gamma-ray detection of samples of interest but also alpha-particle spectroscopy. Of particular interest is the routine measurement of Po-210

in food and environmental samples. Po-210 is part of the naturally occurring decay chain and taken up by animals and humans.

Figure 11 The four main research areas currently pursued as part of the Berkeley Initiative for Radiological Resilience. The goal is to enhance the effectiveness in monitoring and predicting radiological transport in the environment, to better understand and minimize the impact of radio-isotopes in the biospheres, particularly humans, and the remediation of these radiological materials, particularly cesium.

We believe that such measurements and the publication of the results are important in order to establish better baselines of the radiation world we are living in.

4. Summary and outlook

Advances in radiation detection and sensor technologies along with fast signal processing capabilities and algorithms continue to provide new and improved capabilities in the detection, characterization, and mapping of radiological and nuclear materials. New μm resolution radiation detectors create information that enables unprecedented capabilities in reconstructing the direction and energies of gamma rays. Hand-portable, high-energy resolution and position sensitive semiconductor detectors are now available that provide good spectroscopy and imaging performance. In combination with contextual sensors, gamma-ray image data can be fused with 3D scene data simultaneously and in near real-time. The use of contextual object data significantly increases the accuracy in the reconstruction of gamma-ray source location, the speed in the reconstruction, and ultimately enables the determination of the source strength. This 3D volumetric imaging can be applied inside nuclear processing or waste

facilities or outdoors when searching for weak sources or mapping contamination in complex terrains. The establishment of the new Institute of Resilient Communities reflects the need to improve the scientific understanding and technologies required in the aftermath of a disastrous event and the integration of communities in the process before and after such an event.

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