Gamma-ray imaging for assessing radiation source distributions in on-site inspection

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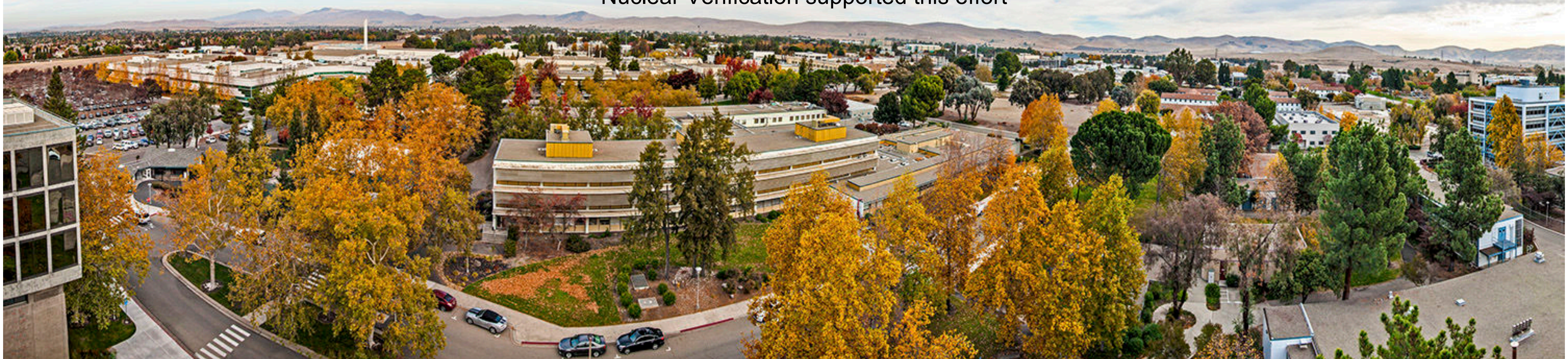

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Detection of "Relevant Radionuclides" (RRs) is important to the on-site inspection regime

Ar-37, Zr-95, Nb-95, Mo-99 (Tc-99m), Ru-103, Ru-106 (Rh-106) I-131, Te-132 (I-132), Xe-131m, Xe-133, Xe-133m, Cs-134, Cs-137, Ba-140, La-140, Ce-141, Ce-144 (Pr-144), Nd-147

Discrimination

- Within elements, ratios robust against fractionation
- Refractories ratios next most robust against fractionation
- Activation nuclides unique to nuclear explosive test scenarios

Aid with location

- Early timeframe, high specific-activity fresh fission products
- Intermediate & late timeframe, lower specific-activity nuclides
- Gas-only release, limited particulate debris nuclides at all times

Chronometers

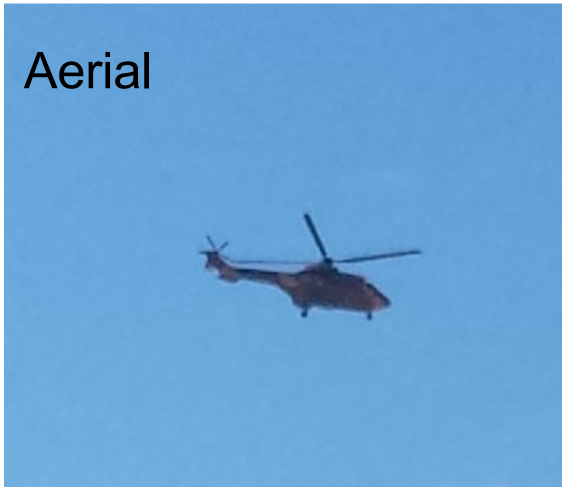
Relevant radionuclide gamma emissions range broadly in energy

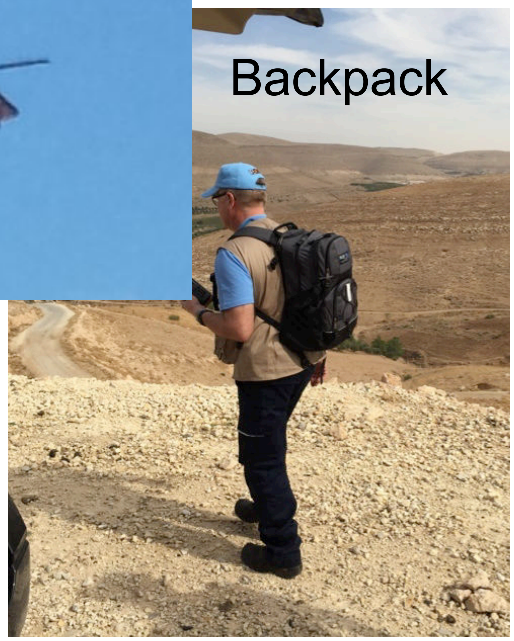
f	E_γ	RR	E_γ	RR	E_γ
^{95}Zr	756 keV	^{134}Cs	604 keV	^{131}I	364 keV
^{95}Nb	765 keV	^{137}Cs	661 keV	^{140}Ba	537 keV
^{99}Mo	739 keV	^{103}Ru	497 keV	^{140}La	1596 keV
^{132}Te	228 keV	^{106}Rh	622 keV	^{147}Nd	531 keV
^{99m}Tc	140 keV	^{141}Ce	145 keV	^{144}Ce	133 keV

Highest intensity gamma energy listed, many RRs have multiple gamma emissions, some higher and lower in energy

Noble gases are omitted from this list, their emissions are mostly low $E\gamma$ / conversion electrons, etc.

Gamma emitting RRs are detected via a suite of gamma survey techniques



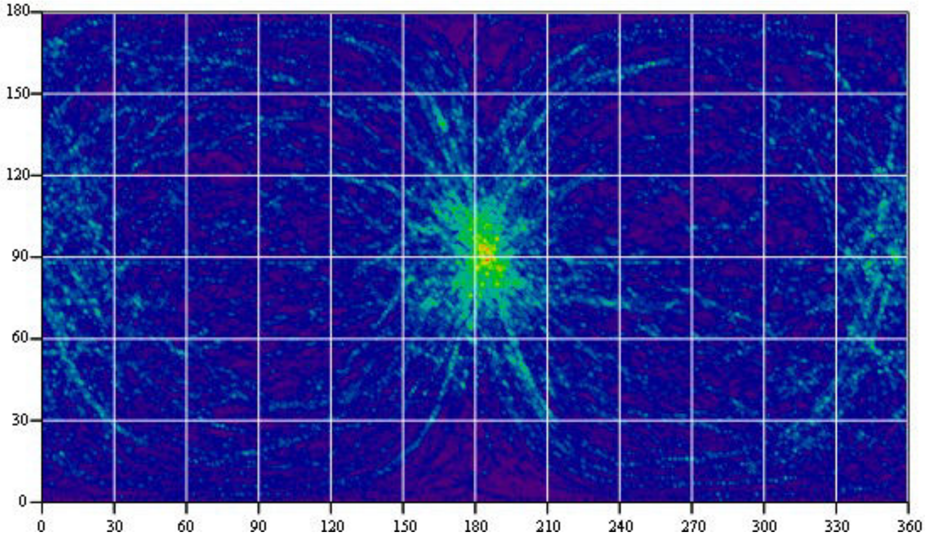


Survey techniques aid with source localization, *in situ* also useful to source quantification – is there a role for examining source distribution?

Gamma imaging places radiation sources into an operational context

- **Example:** High-purity Ge (HPGe)-based Gamma Imager (GeGI)

Spatial distribution of detected gamma rays (^{137}Cs in this case)



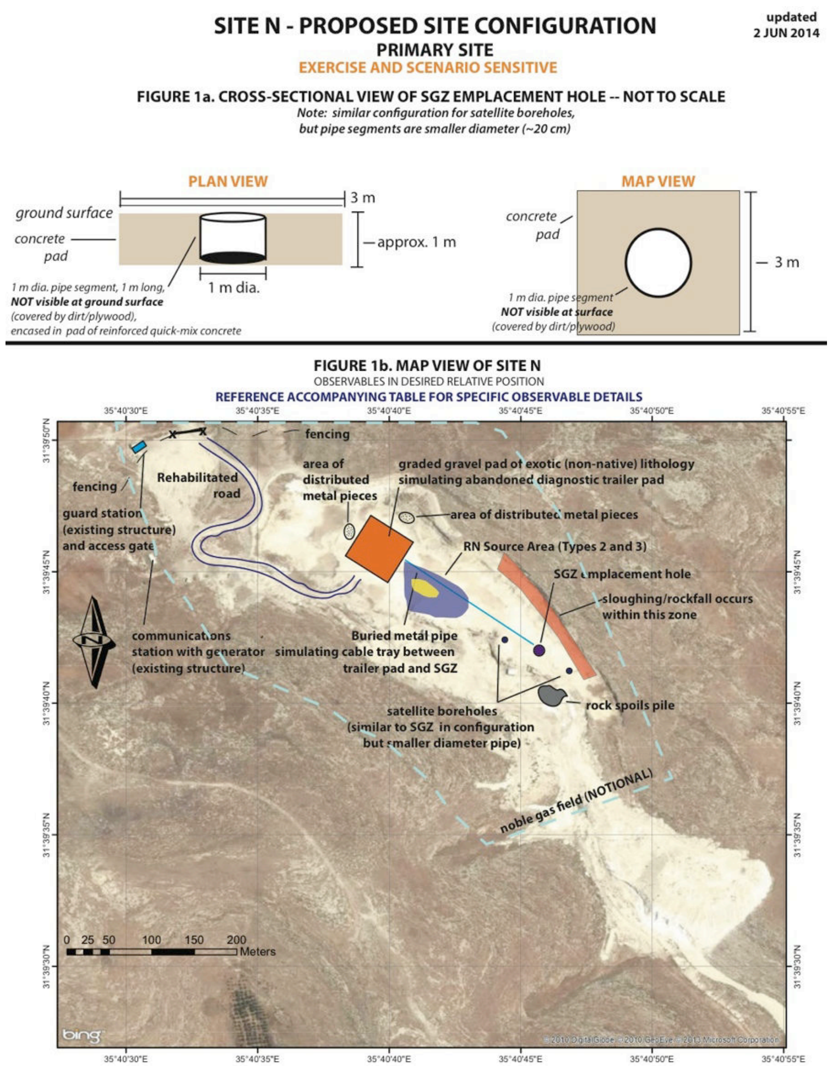
Raw, unprocessed data from a 37 MBq ^{137}Cs source measured at about 25 m

Optical image of same location, taken at the same time

Source overlay achieved in less than 20 minutes to within a few degrees accuracy

HPGe energy resolution analysis identifies the "what", gamma imaging shows the "where"

In IFE14, a quarry simulated the "actual" test location – the "real" site – polygon 29

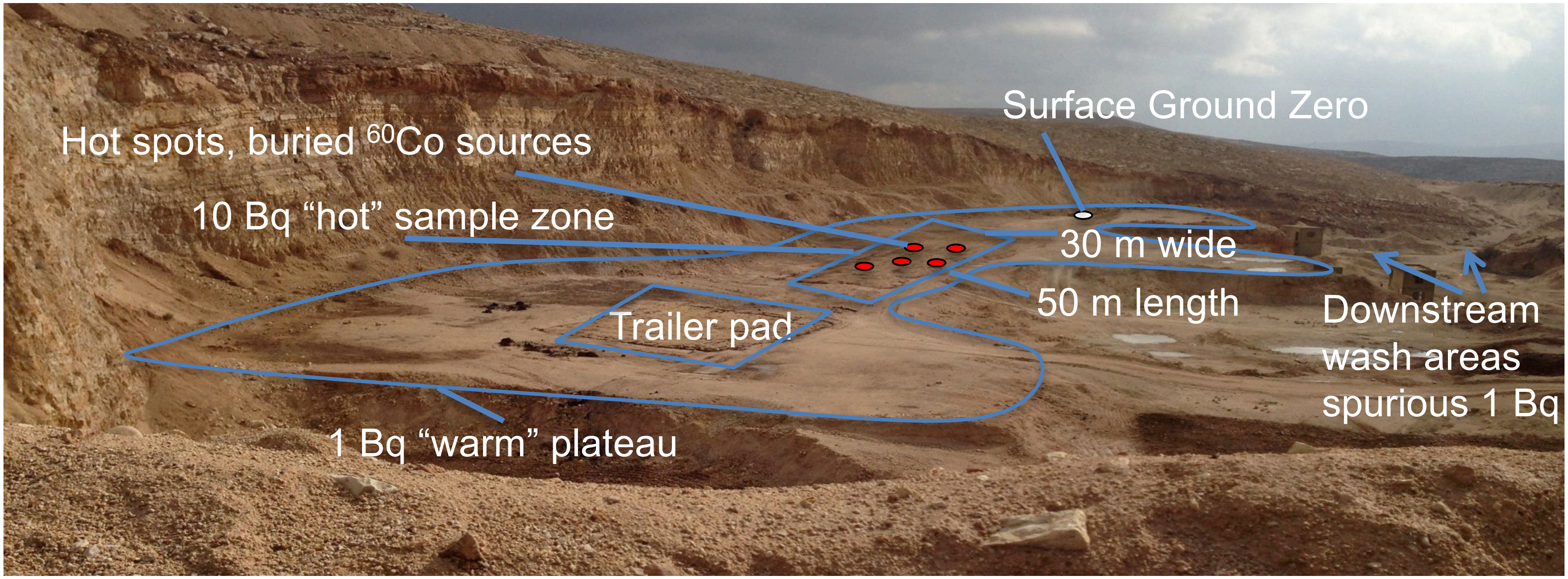


General view along quarry site looking SE – "pad"

Engineered "emplacement hole" at site – later covered

Fractured limestone along quarry face

IFE14 used point radiation sources to mimic hotspots in an artificial contamination scene



- *Release scenario highly simplified, localized iodine release & deposition, simulated with emplaced ^{60}Co sources*
- *Surrogate sources were buried so IT would have something to measure in the field, and to trigger H&S.*
- *Zones reflected contaminated sample surrogate substituted in the base camp lab*

The ten 40 MBq ^{60}Co sources were slightly buried and represented contamination

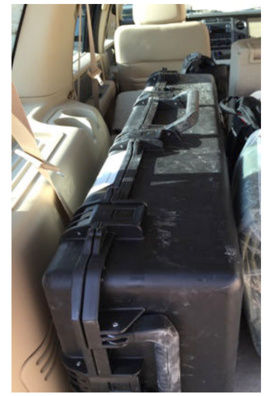
Covered in plywood as a barrier to light digging at depths of 10-15 cm

LLNL provided hardware, based upon our 2005 R&D100 award winning Adaptable Radiation Area Monitor (ARAM)*, to verify the sources were observable

*LLNL Science & Technology Review, October 2005 at http://str.llnl.gov, and University of California Report No. UCRL-ABS-206935 (2004)

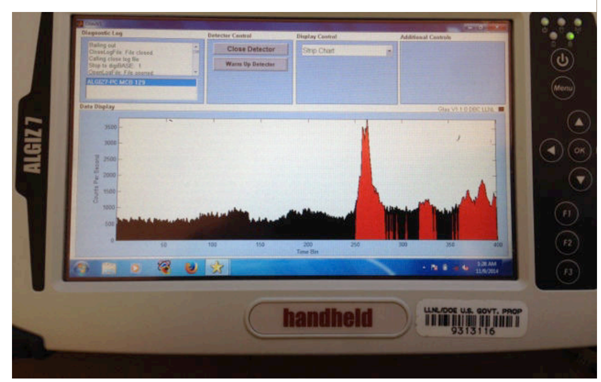
Sources provided & handled by the Jordanian authorities

2-L NaI in case

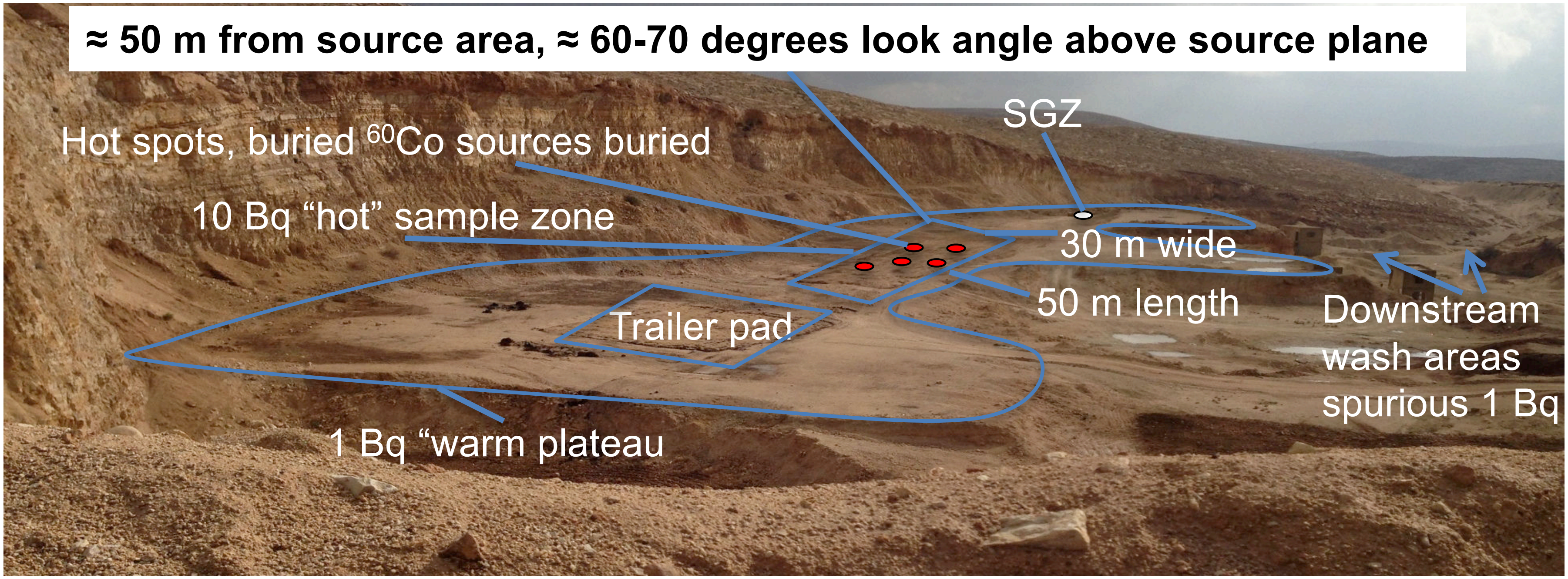


3x3-in NaI in backpack and as carborne

Sources observed in drive-by mode – count rate histogram (1s intervals)



Could gamma imaging provide additional information useful to the inspection?

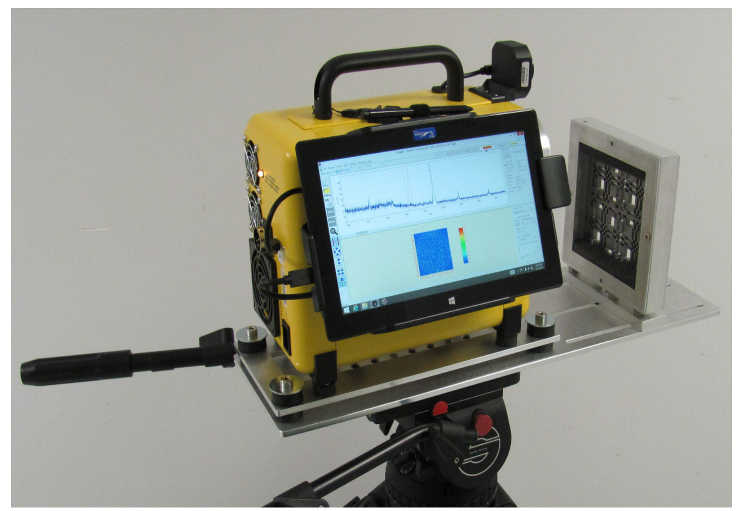


- Initially, area was restricted access zone (RAZ), gamma emissions may have been observable from outside the RAZ
  - Roadway entrance to the polygon?
  - Hillside to the right?
  - Peering over the cliff edge (yikes)?
  - Looking down from a UAV?
  - Carbourne didn’t observe sources in drive by measurements

LLNL's Ge-based Gamma-ray Imager (GeGI) is a compact detector and optical imaging system

Specifications

- High-purity germanium (HPGe) crystal:
  - 9 cm diameter x 1 cm thick planar
- Spectral resolution: 2 keV at 1332 keV
- Imaging modalities: Compton, coded aperture, pinhole
- Cool-down time: 5 hours
- User interface: Surface tablet
- Optical: 180^{o} panoramic camera
- Power: AC power or swappable battery (2 h)



Leverages LLNL's compact electrocooled HPGe technology

Assessed the potential of GeGI to detect and image one IFE14 ^{60}Co source from two locations

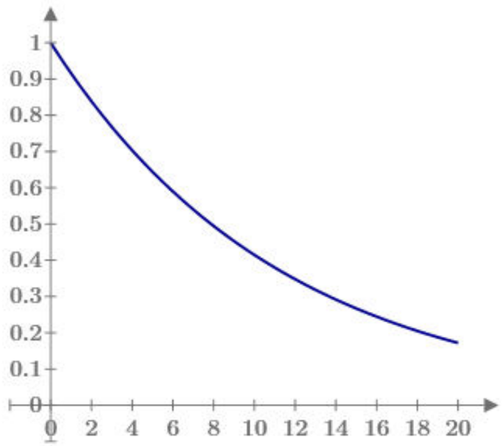
- Ten ^{60}Co sources of 40 MBq in strength each
  - Sources distributed with 7 to 10 meters distance between them
- Buried under 10 - 15 cm soil
  - At a look angle 60-70° above plane, effective depth is 11-17 cm soil
- From distances of 25 m - 50 m
- Factors considered in model
  - Source strength
  - Attenuation in soil and air (separately)
  - Geometry and detector efficiency at 1332 keV
  - Background, crude NORM
  - Imaging resolution

If detectable with GeGI, would imaging be operationally practical?

Soil & air attenuation reduce gammas available for detection (1332 keV γ-ray for ^{60}Co)

Linear attenuation constant for soil:
0.088 cm^{-1}

I_soil(x) = $e^{-\mu\_soil*x}$



$I\_soil(x)$

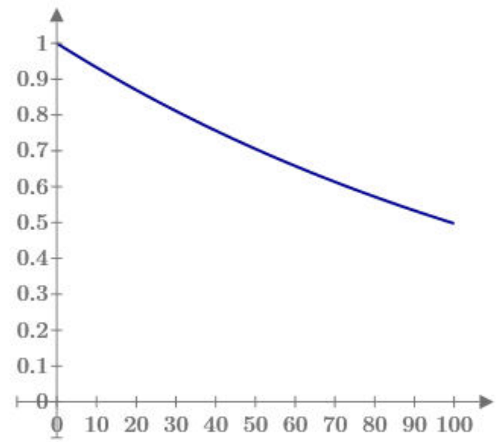
$x\ (cm)$

Soil thickness	Fraction escaping
10 cm	41.5%
15 cm	26.7%

Notes: assume typical soil composition and dry air

Linear attenuation constant for air:
6.98 x10^{-5} cm^{-1}

I_air(x) = $e^{-\mu\_air*x}$



$I\_air(x)$

$x\ (m)$

Distance in Air	Fraction escaping
25 m	84%
50 m	70.5%

About 1 in 5 gammas at 1332 keV make it through 15 cm soil and 50 m air

Must also account for other factors such as solid angle and intrinsic detector efficiency

$$\text{Rate} = S \times I_{soil} \times I_{air} \times \omega \times Eff_{det}$$

Symbol		Best Case Soil (10 cm) Distance thru air (25 m)	Worst Case Soil (15 cm) Distance thru air (50 m)
S	Source strength	10 x 40 MBq*	10 x 40 MBq*
I_{soil}	Attenuation in soil	0.415 (at 10 cm)	0.267 (at 15 cm)
I_{air}	Attenuation in air	0.84 (at 25 m)	0.705 (at 50 m)
ω	Detector solid angle	6.4E-7 (at 25 m)	1.6E-7 (at 50 m)
Eff	Detector efficiency at 1332 keV	0.01	0.01

- **Time to detect**: identifying the presence (but not location) of ^{60}Co at 8-σ significance (assumes 50 counts in photopeak and nominal background)
- **Time to image**: Locating the source to +/- 5 degrees with 3-σ significance (assumes 750 counts in the photopeak which is based on benchmark field tests and nominal background)
  - Lower because already identified with 8-σ significance
- **Background**: Assumes nominal background, but this of course can vary significantly

Sources would have varying distances and angles

A typical *in situ* measurement was ≈30 min, gamma imaging appears operationally practical

$$\text{Rate} = S \times I_{soil} \times I_{air} \times \omega \times Eff_{det}$$

Time to det (8 σ) = 50 counts / Rate

Time to image (3 σ) = 750 counts / Rate

Symbol		Best Case Soil (10 cm) Distance thru air (25 m)	Worst Case Soil (15 cm) Distance thru air (50 m)
S	Source strength	40 MBq	40 MBq
I_{soil}	Attenuation in soil	0.415 (at 10 cm)	0.267 (at 15 cm)
I_{air}	Attenuation in air	0.84 (at 25 m)	0.705 (at 50 m)
ω	Detector solid angle	6.4E-7 (at 25 m)	1.6E-7 (at 50 m)
Eff	Detector efficiency at 1332 keV	0.01	0.01
Time to detect	**SINGLE SOURCE**	**9.3 min**	**1.15 h**
Time to detect	**Combined sources**	**≈3 min**	**25 min**
Time to image	**Single or multiple sources***	**140 min**	**17.3 h**

*Each point source appears in independent image pixels, times are independent of the number of sources

Measurements of minutes to a few hours is operationally reasonable, of course actual results are entirely scenario dependent

Caveats and considerations

- Source activity level biggest factor
  - Activity/area
  - Comparatively lower $E\gamma$ of the RRs
    - Gamma branches also smaller than ^{60}Co
- Angle and distance to source
  - Geometric factors
  - More attenuation loss compared to ^{60}Co
- Intrinsic efficiency of detector is better for many RR
  - ≈ 1% at 1332 keV for ^{60}Co
  - Higher at lower $E\gamma$ (≈ 4% at 662 keV, for example)

Nuclide	Energy, E_γ	Mean Free Path, Length in Air (STP)
^{131}I	80 keV	46 m
^{144}Ce	133 keV	52 m
^{131}I	364 keV	81 m
^{137}Cs	662 keV	104 m
^{140}La	1596 keV	160 m

Conclusions

- Gamma imaging to detect and image is likely operationally practical for (at least this) OSI-relevant scenarios
  - Will not be as sensitive as *in situ* gamma & environmental sampling, view as augmenting those techniques
  - Could help inform “where best” to perform *in situ* and sampling activities
- Systems such as GeGI are commercially available, have good operational characteristics, and are relatively easy to use

Gamma imaging may be useful to OSI for assessing source distribution as an aid to other techniques

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