SCoTSS* Gamma Imager for CTBTO On-site Inspection

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* Silicon photomultiplier-based COmpton Telescope for Safety and Security

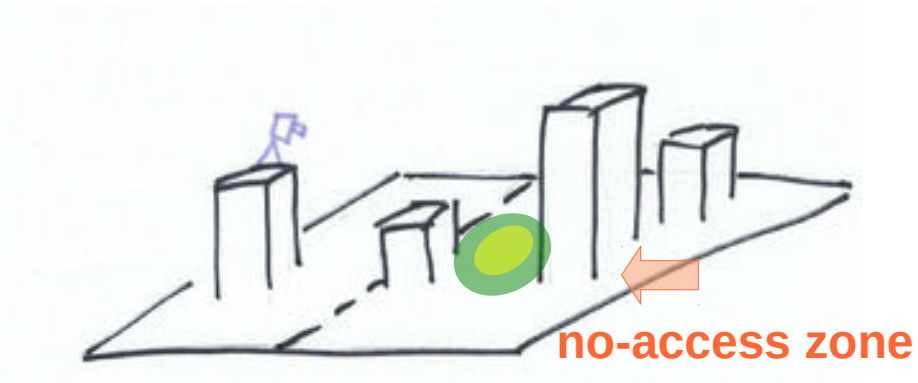
Outline

- **Motivation for imager use at on-site inspections**
- **Compton gamma imaging**
- **A mission-ready imager for safety and security**
- **A study of the scenario played out in the 2014 Integrated Field Exercise (IFE 2014) in Jordan**
  - Simulation and real experimental data used in study

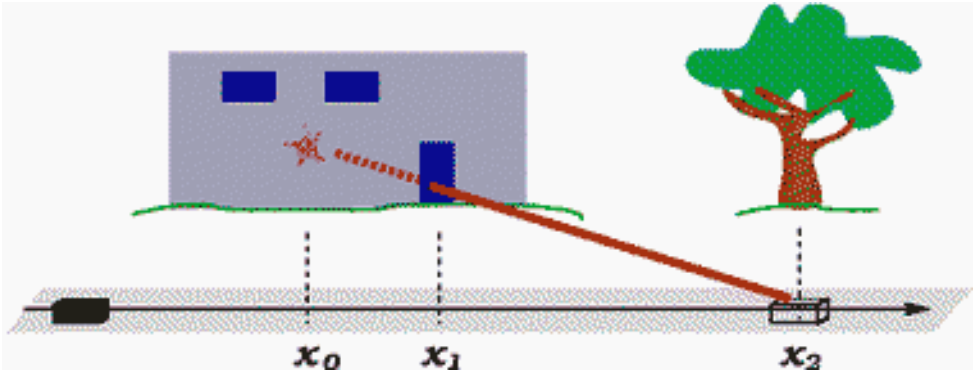
  ➡ *How could an imager have helped?*

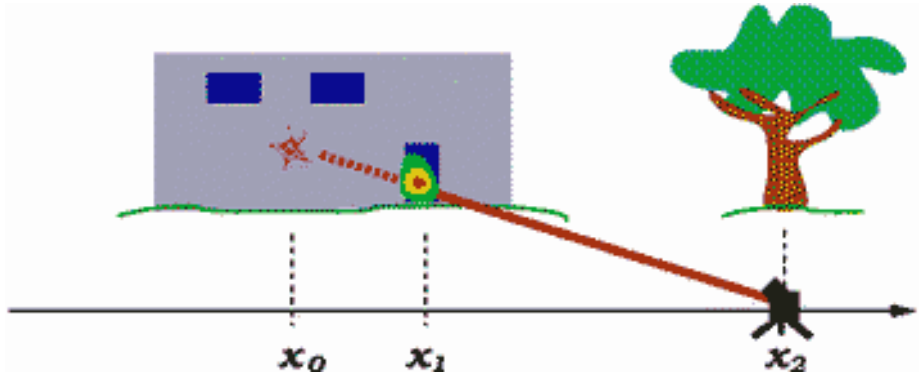
Why an imager?

Restricted areas



Resolving direction-blind data





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IFE 2014 scenario

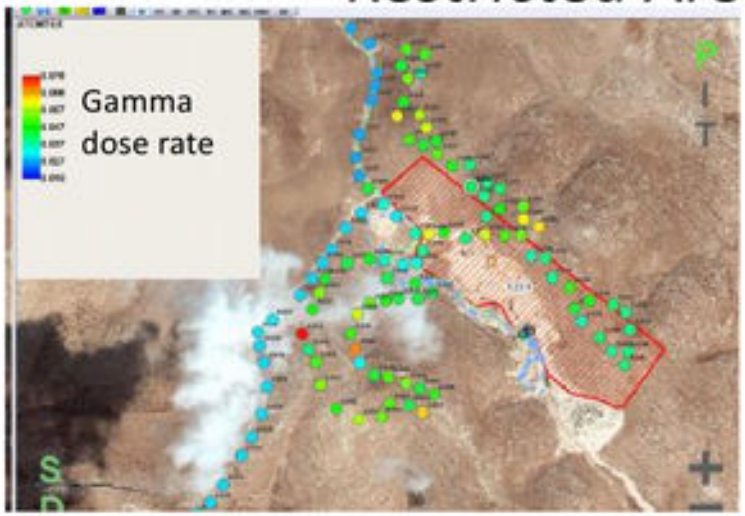
(From Miley and Haas (2015), *Strategy for Use of RN Capabilities in IFE14)*

Inaccessible area could be viewed into.

How would an imager have helped here?

P029 Walking Survey

Restricted Area in Red



Two conclusions:
- Nalin was able to enter the RAS
- Nothing was measurable using backpacks from area we could access, although some post mortem suggestions of creative in situ gamma

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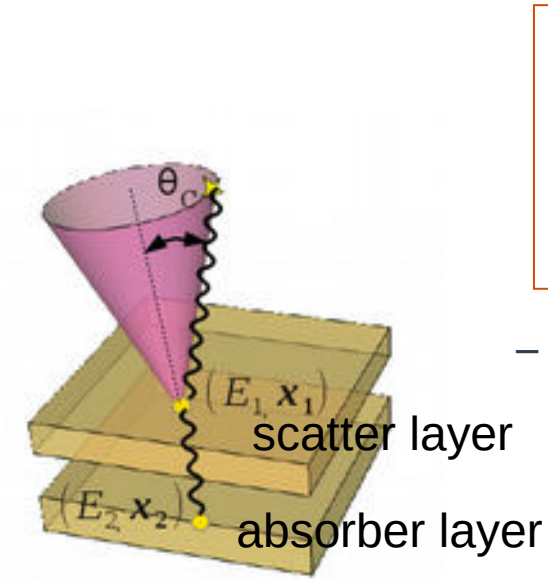
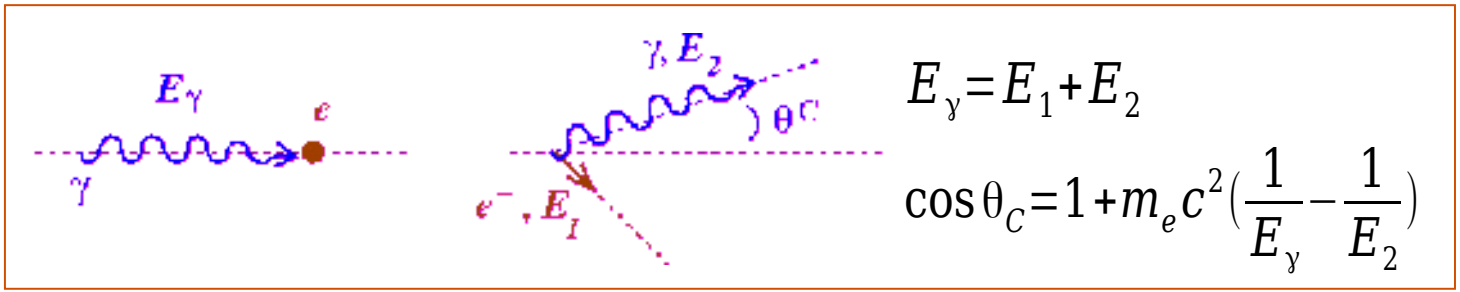
Compton imaging method

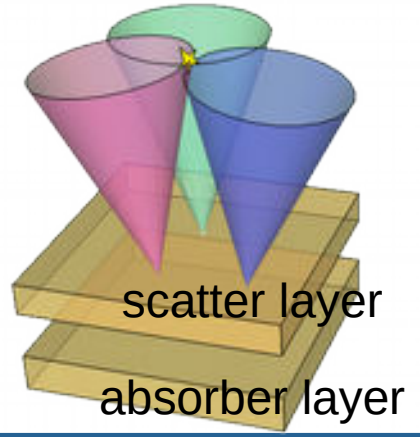




$$E_\gamma = E_1 + E_2$$

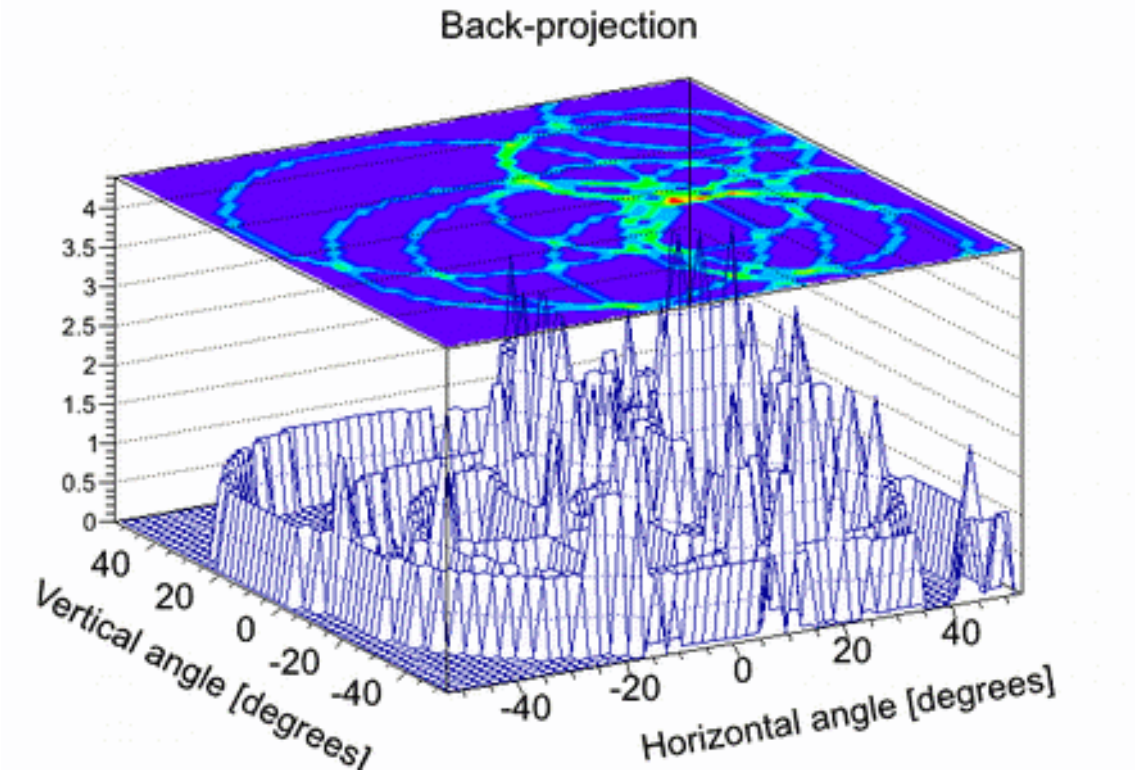
$$\cos\theta_C = 1 + m_e c^2 \left(\frac{1}{E_\gamma} - \frac{1}{E_2}\right)$$

- energies and positions of scatter and absorption determine scattering angle up to arbitrary azimuthal angle
  - Note: electron deposits energy locally and its direction is not observed
- record events with two hits with energy adding up to desired energy
- construct Compton cones from energies and positions
- build up image from overlapping cones



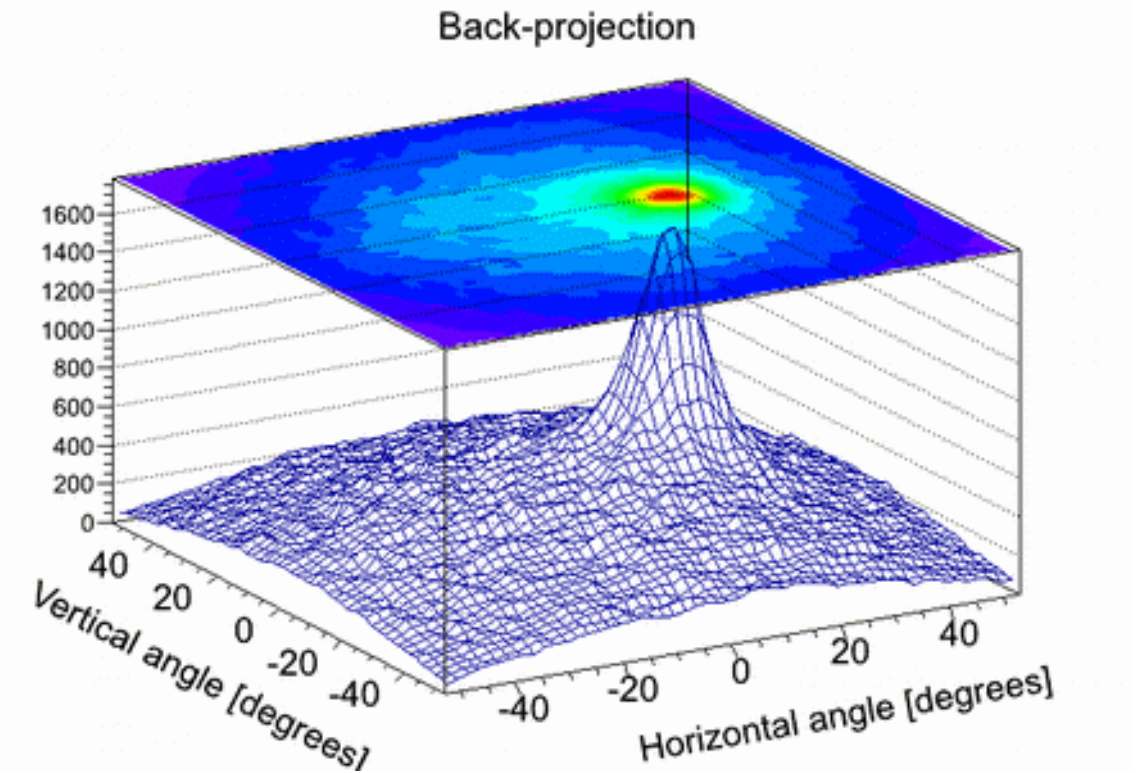
Simple cone back-projection

A few seconds

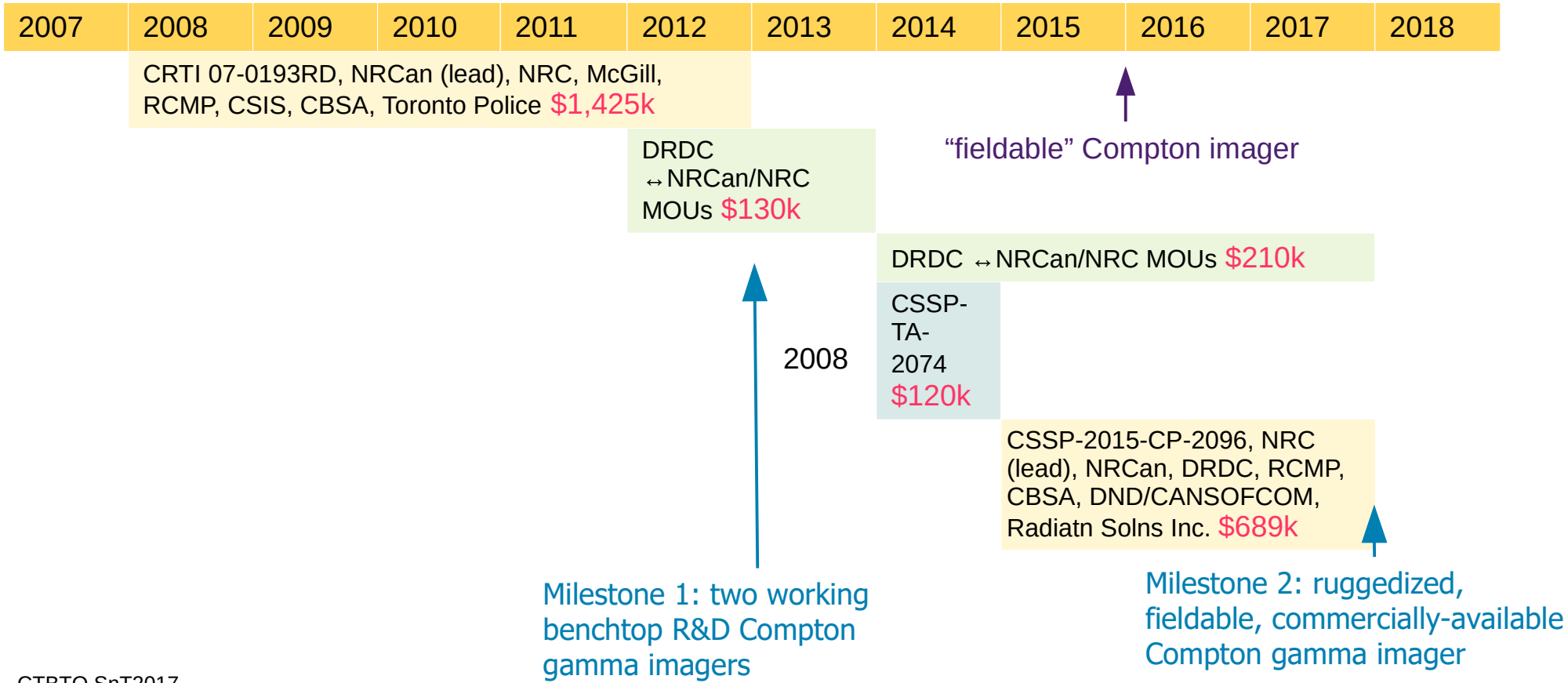


Simple cone back-projection

Several minutes



Toward a Mission-Ready Compton Gamma Imager



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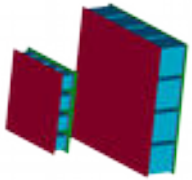
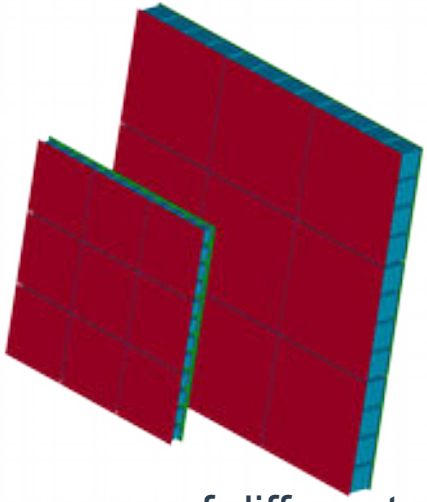
Mission-ready imager - Commercialization

Single-Module Imager



CsI(Tl) read out with
silicon photo-multipliers

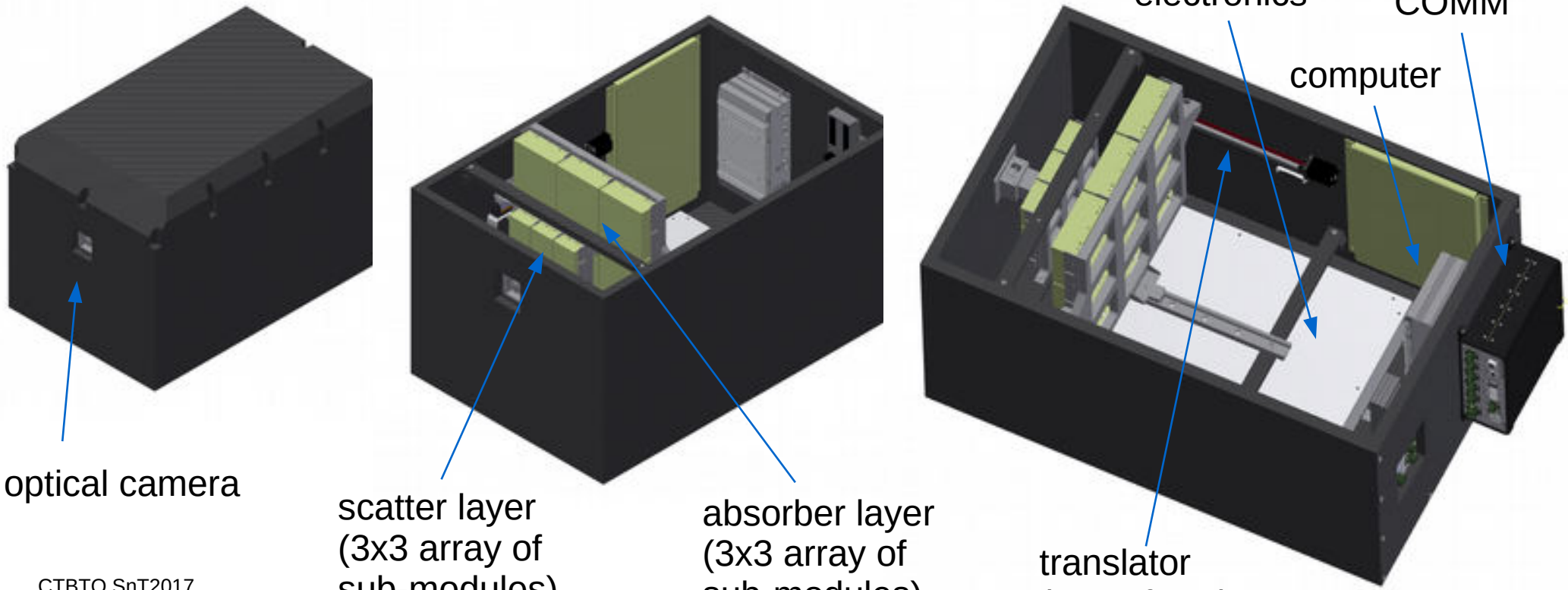
3 x 3 Array of Imager Modules



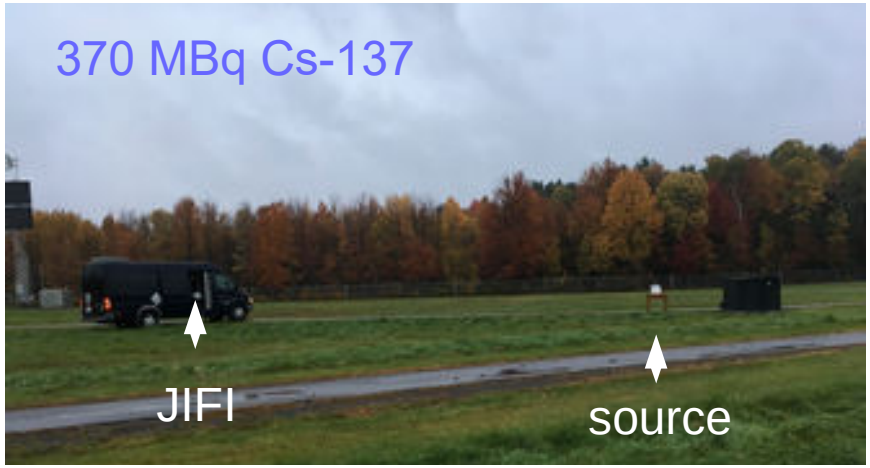
- **Modular design** approach allows construction of imagers of different size and therefore different mission spaces and price points
- Several **end users as partners; Police, Border Services, Armed Forces, Federal Radiological Assessment Team** ensure final design meets their needs
- **Experienced industry partner** (RSI) has wealth of experience fielding rugged radiation detectors for use in the field

SCoTSS 3x3-array imager

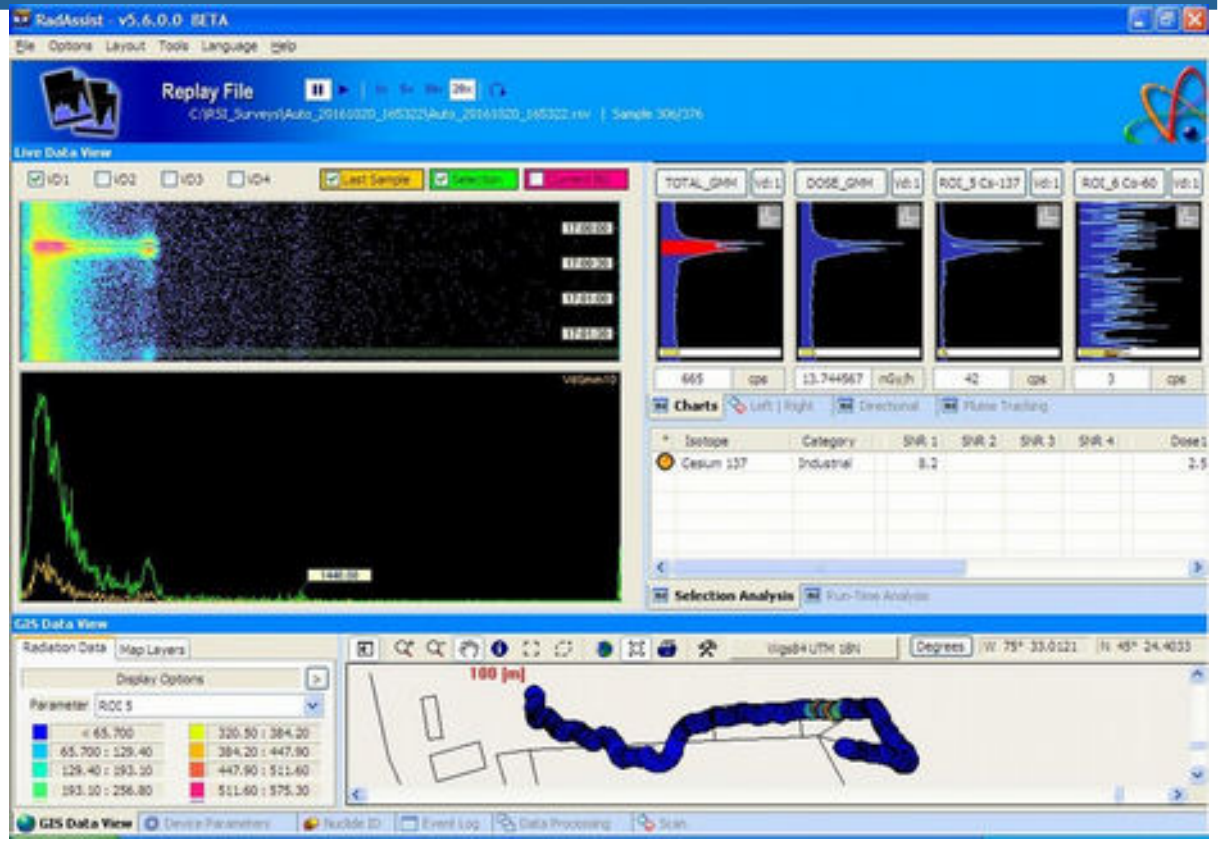
3.5 litres total of CsI(Tl)
288 readout channels



Single-module fieldable JIFI imager



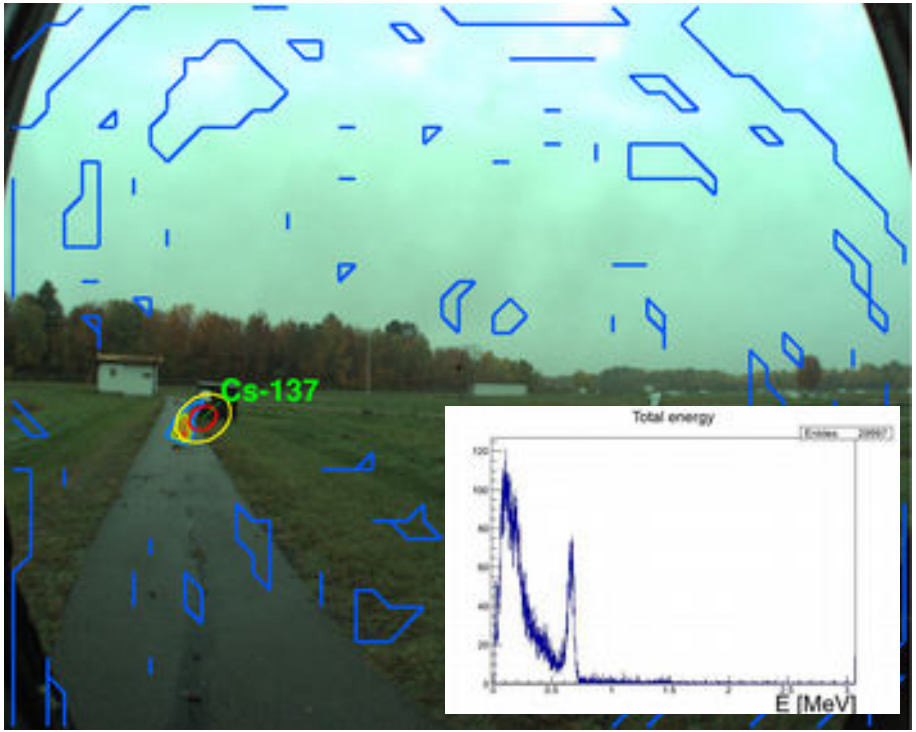
Real-time display including bread-crumb trail map taken with Joyful Interim Fieldable Imager (JIFI) prototype of single module imager, October 2016



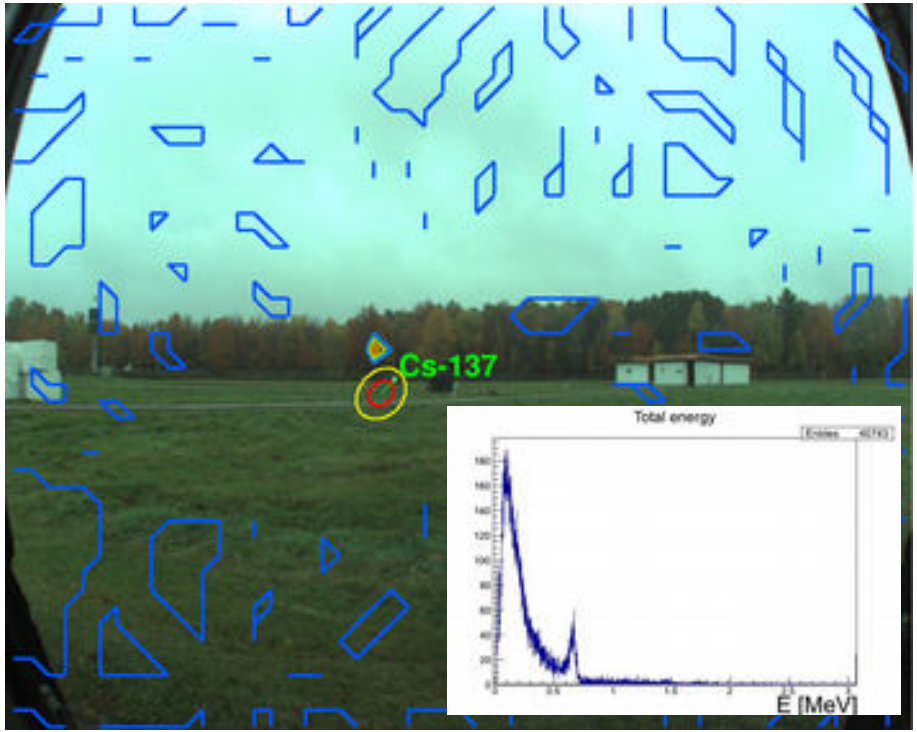
- Deliverable will be a **sensitive spectrometer** suitable for radiation **surveying and mapping** as usual, but augmented with **precision imaging capability**

Single-module fieldable JIFI imager

370 MBq Cs-137 source, JIFI field trial October 2016



D = 15.9 m and t = 25 s



D = 36.9 m and t = 62 s

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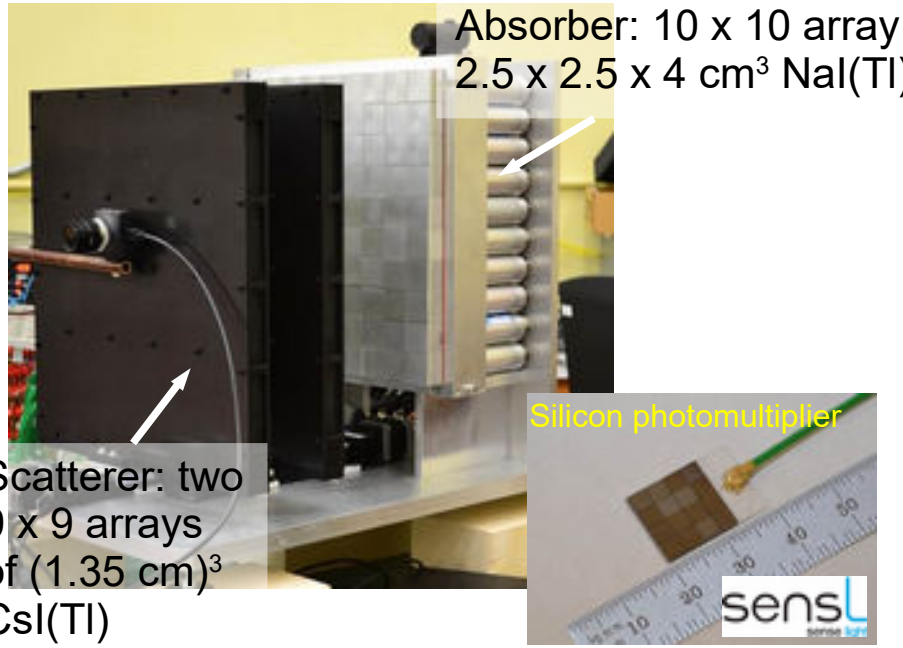
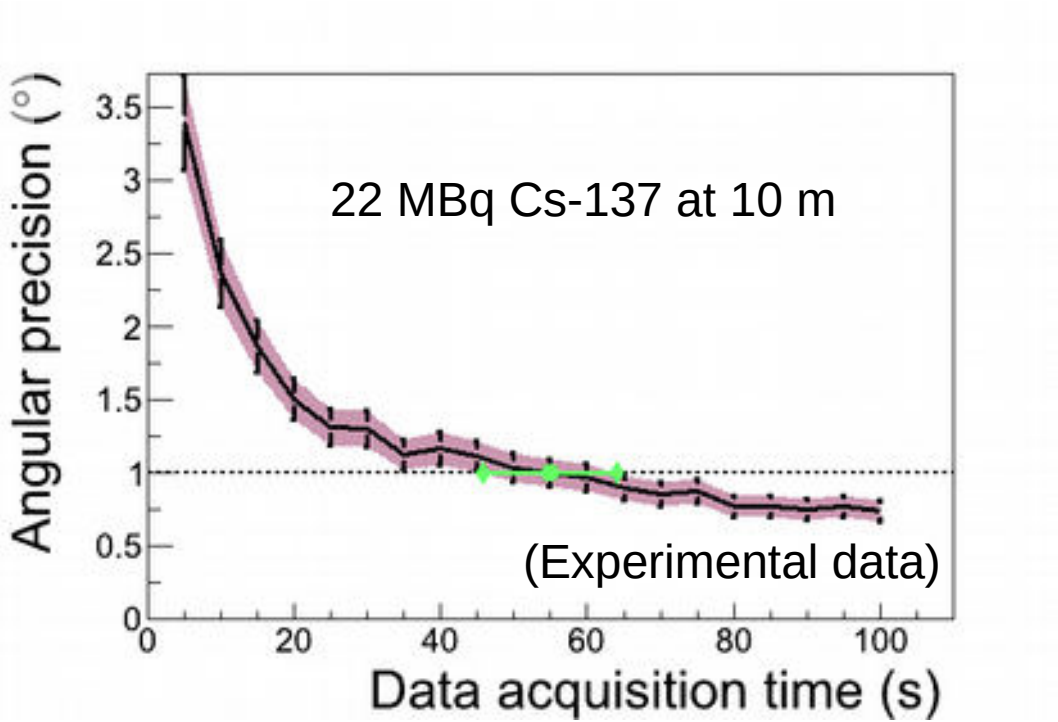
Time to image for lab-based R&D imager





262-channel lab-based imager used to experimentally study expected performance of 3 x 3 array Mission-Ready imager

We define the time to image as the time required to localize a point source to within some number of degrees of precision

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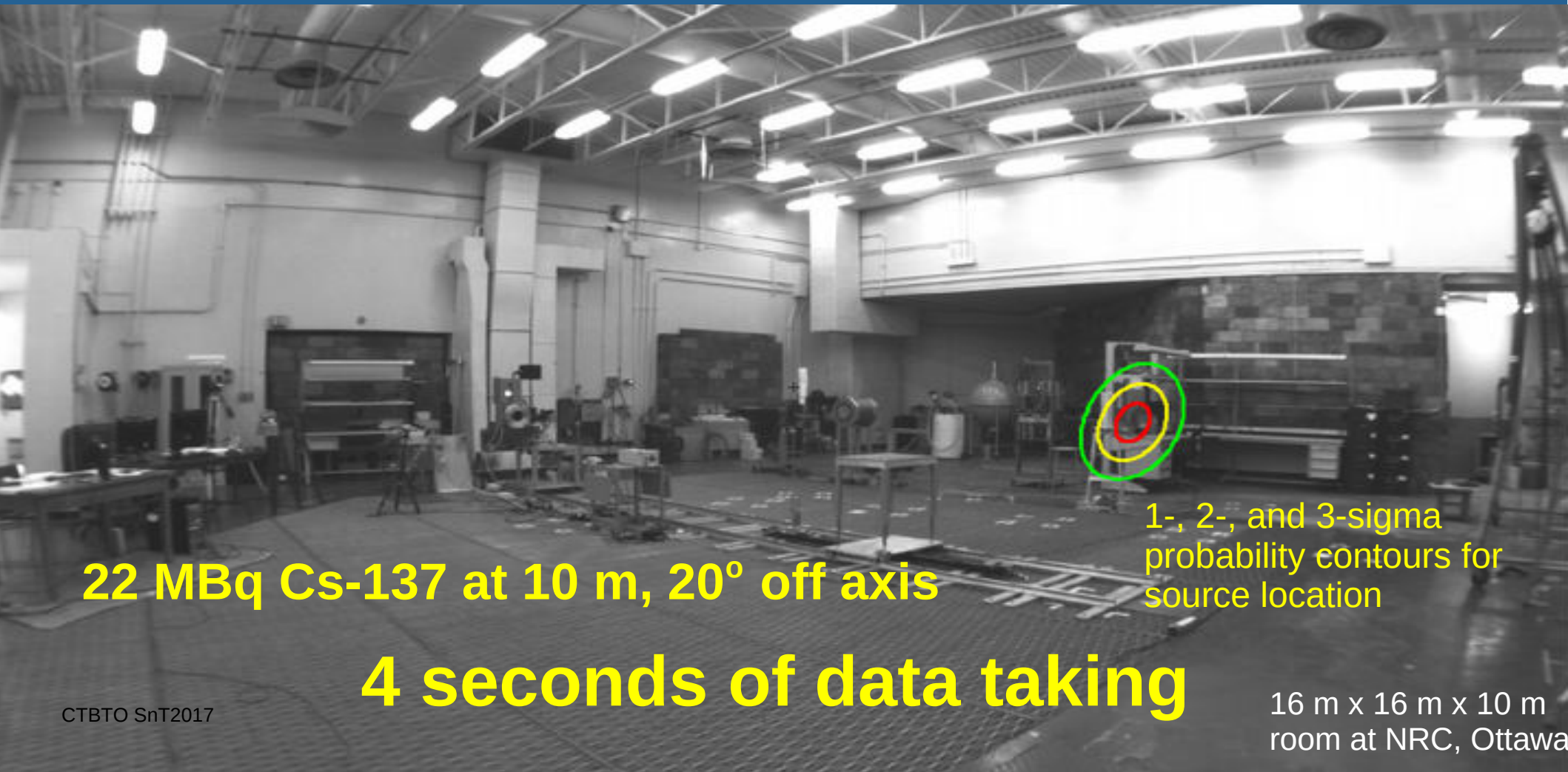
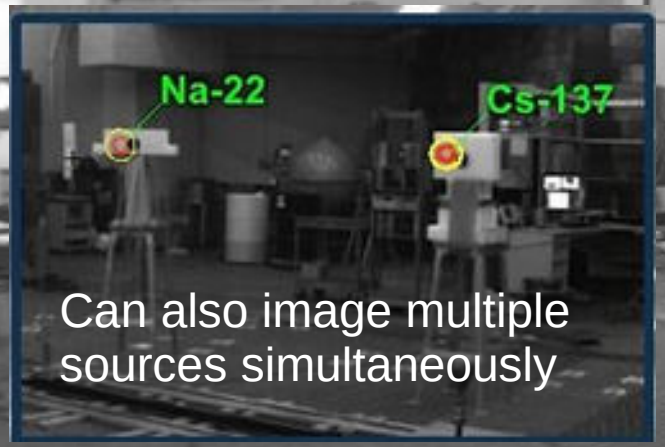
lab-based R&D imager prototype performance



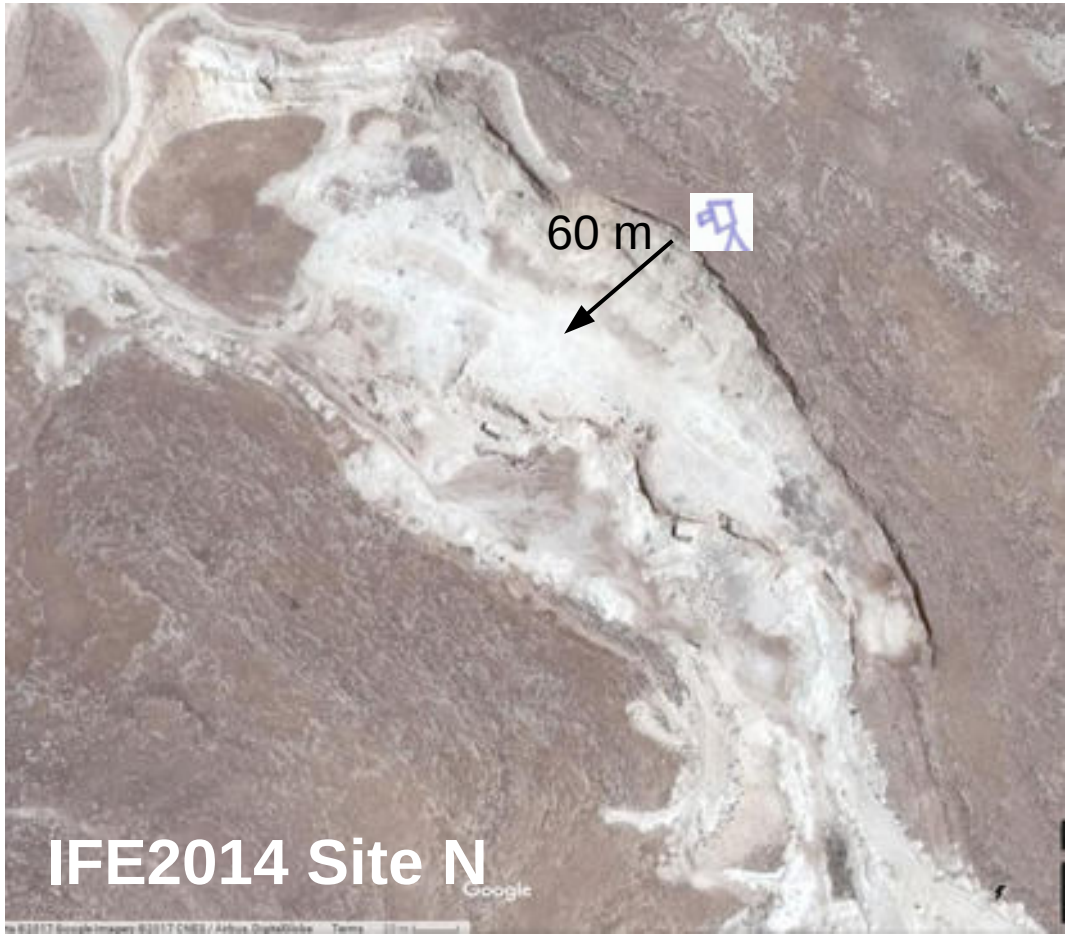
lab-based R&D imager prototype performance



60 seconds of data taking

Imager performance for IFE2014

- **For IFE2014, ten 40 MBq Co-60 source (400 MBq total) were buried 10 cm to 50 cm from the soil surface to mimic I-131**
- **We simulated what one might have expected to see with a 3x3 array imager**
- **We also imaged a Co-60 source of equivalent dose rate in the lab with our prototype imagers**
- **Assumptions:**
  - imagers could have been deployed 60 m from the source area
  - point source



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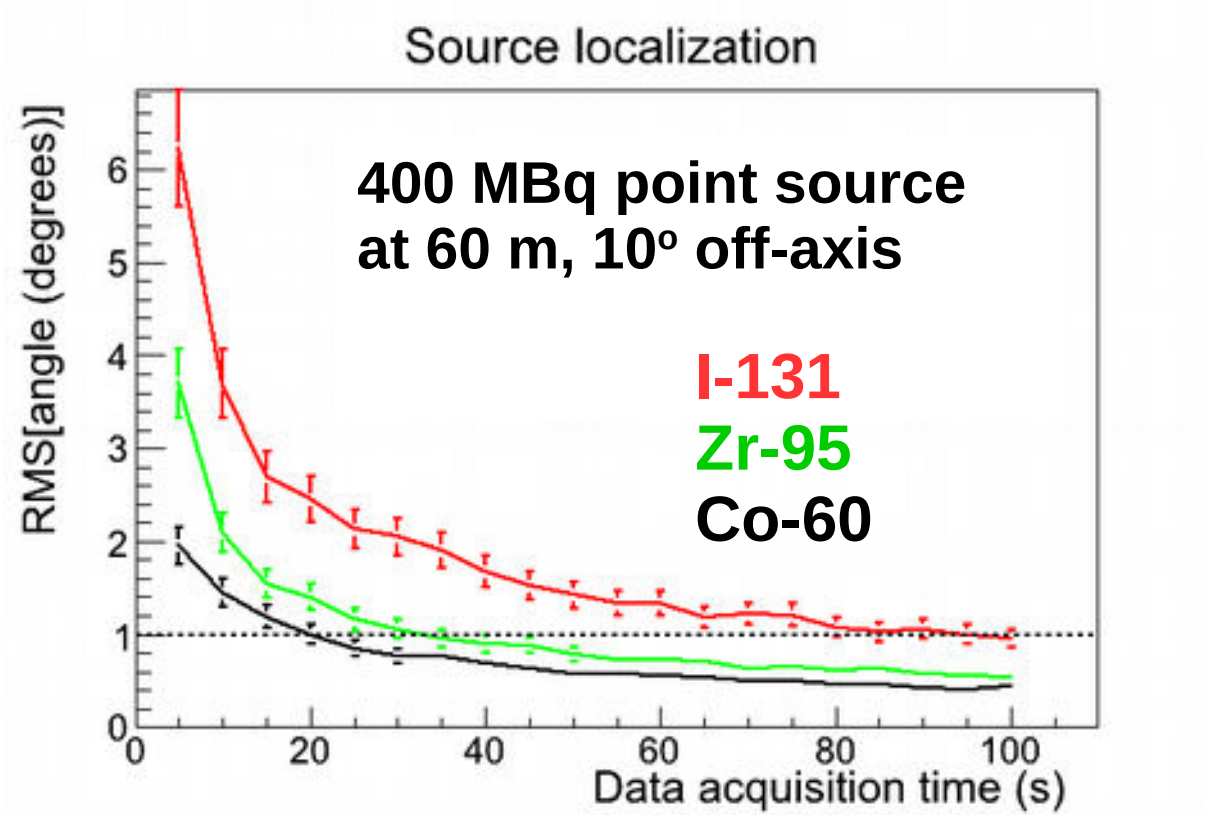
IFE2014 scenario: Monte Carlo simulation



- EGSnrc simulation (results were confirmed with Geant4)
- unshielded src
- air-attenuation included
- no NORM bkgd
- no earth simulated

➔ Imager would have determined source location to within 2° precision in under a minute.

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OSI-relevant isotopes

Nuclide	Half-life (days)	Energy (keV)	Abundance (%)	Ind. yield	Cum. yield	Volatile or refractory
^{95}Zr	64.03	756.7	54.4	1.48×10^{-2}	6.43	R
^{95}Nb	34.99	765.8	99.8	4.42×10^{-6}	6.43	R
^{99}Mo	2.75	739.5	12.1	7.24×10^{-4}	5.94	R
^{99m}Tc *	0.25	140.5	89.1	9.94×10^{-9}	5.23	R
^{103}Ru	39.26	497.1	91.0	9.94×10^{-6}	3.24	V
^{106}Rh	373.61	621.9	9.9	8.70×10^{-7}	5.32×10^{-1}	V
^{132}Te	3.20	228.2	88.0	1.07	4.66	V
^{131}I	8.02	364.5	81.7	1.08×10^{-3}	3.22	V
^{132}I	0.10	667.7	98.7	1.02×10^{-2}	4.67	V
^{134}Cs	754.17	604.7	97.6	Activation	Activation	V
^{137}Cs	10,972.22	661.7	85.1	2.28×10^{-1}	6.22	V
^{140}Ba	12.75	537.3	24.4	2.36×10^{-1}	5.98	V–R
^{140}La	1.68	1596.2	95.4	2.04×10^{-4}	5.98	V–R
^{141}Ce *	32.51	145.4	48.3	3.22×10^{-5}	5.95	V–R
^{144}Ce *	284.95	133.5	11.1	1.68×10^{-2}	5.27	R
^{144}Pr	0.01	696.5	1.3	4.81×10^{-7}	5.27	R
^{147}Nd *	10.98	91.1	27.9	2.81×10^{-5}	2.14	R

(Table shamelessly stolen from *Burnett et a., J Env Rad 153 (2016) 195-200*.)

Times to image (400 MBq, bare, 60m)		
	2^{o}	1^{o}
^{95}Zr	15 s	40 s
^{95}Nb	15 s	40 s
^{106}Rh	5 min	
^{132}Te	>5 min	
^{131}I	40 s	100 s
^{137}Cs	20 s	50 s
^{140}Ba	100 s	5 min
^{140}La	40 s	100 s
^{60}Co	20 s	5 s

OSI-relevant isotopes

Nuclide	Half-life (days)	Energy (keV)	Abundance (%)	Ind. yield	Cum. yield	Volatile or refractory
^{95}Zr	64.03	756.7	54.4	1.48×10^{-2}	6.43	R
^{95}Nb	34.99	765.8	99.8	4.42×10^{-6}	6.43	R
^{99}Mo	2.75	739.5	12.1	7.24×10^{-4}	5.94	R
^{99m}Tc *	0.25	140.5	89.1	9.94×10^{-9}	5.23	R
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^{147}Nd *	10.98	91.1	27.9	2.81×10^{-5}	2.14	R

(Table shamelessly stolen from *Burnett et a., J Env Rad 153 (2016) 195-200*.)

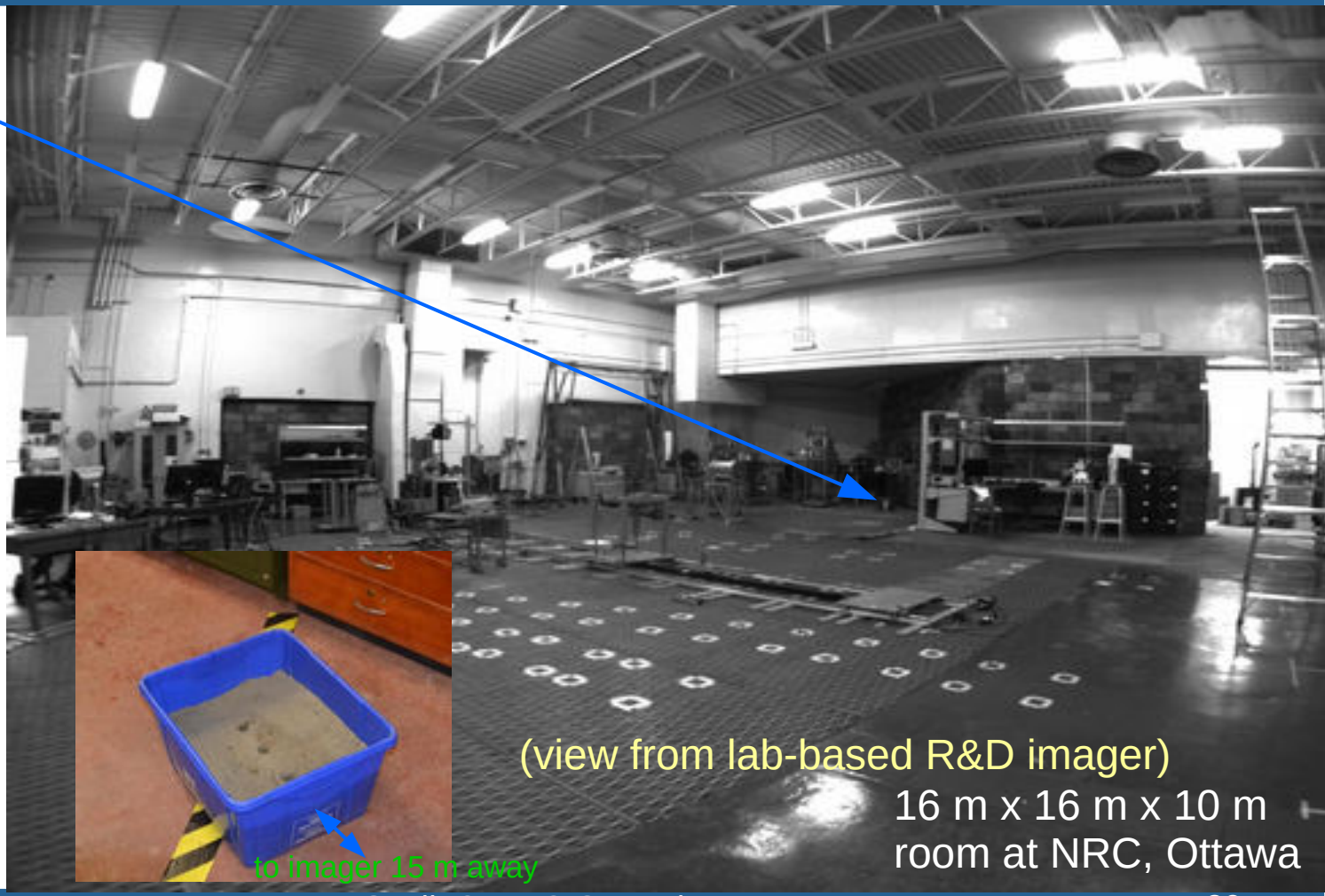
* Gamma rays with energy less than ~180 keV cannot be imaged with the Compton method but other techniques are applicable (e.g. coded aperture imaging, self-shielding or shadowing, pinhole)

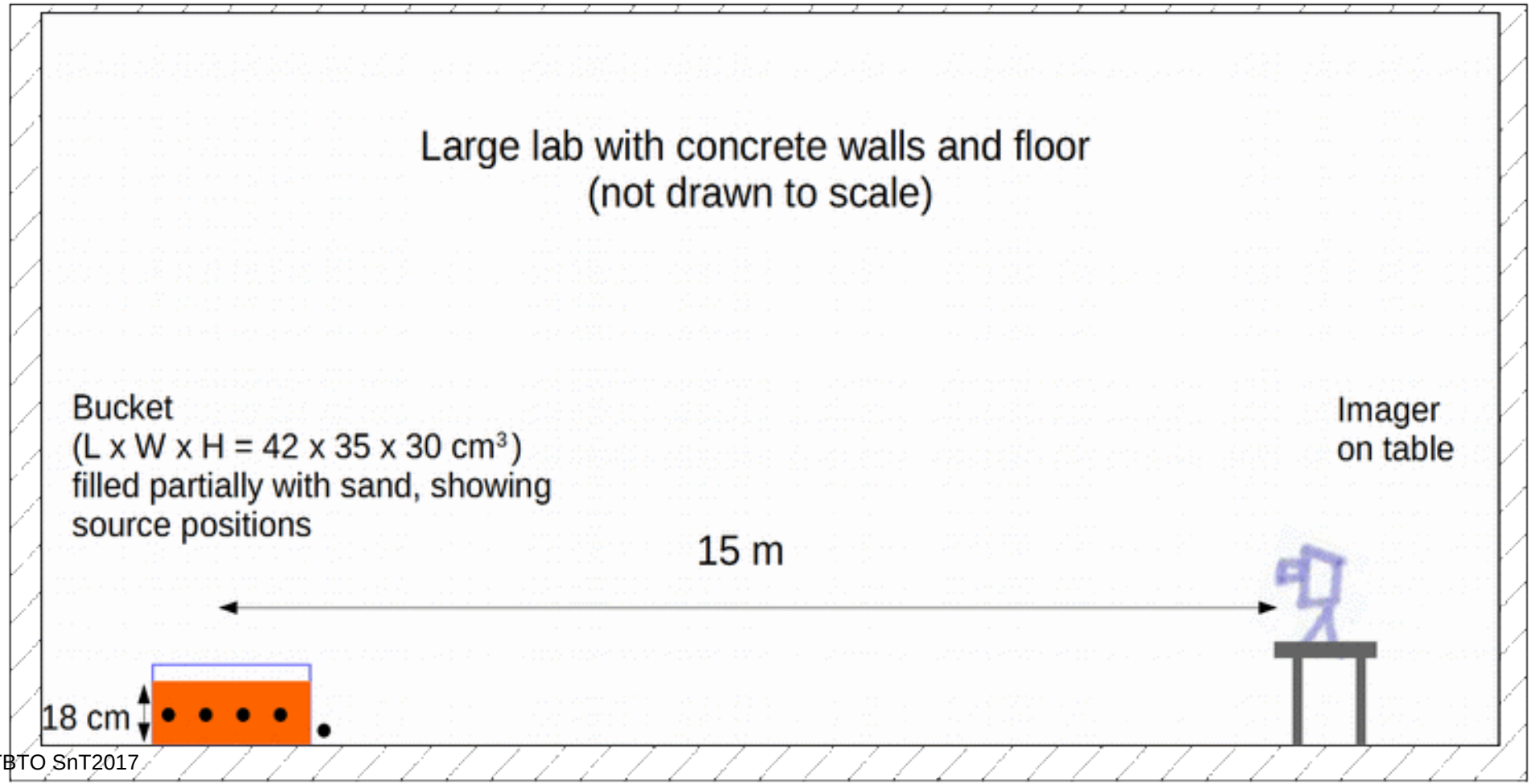
IFE2014 scenario: real experimental data

22 MBq Co-60 pellet at 15 m distance (corresponds to 400 MBq at ~60 m)

First placed bare on concrete floor in front of bucket of sand; then buried at ~10 cm depth at 10, 20, 30, and 40 cm from front face of bucket (this corresponds to the amount of sand through which gamma rays had to travel).

Imaged with lab-based R&D imager and JIFI.





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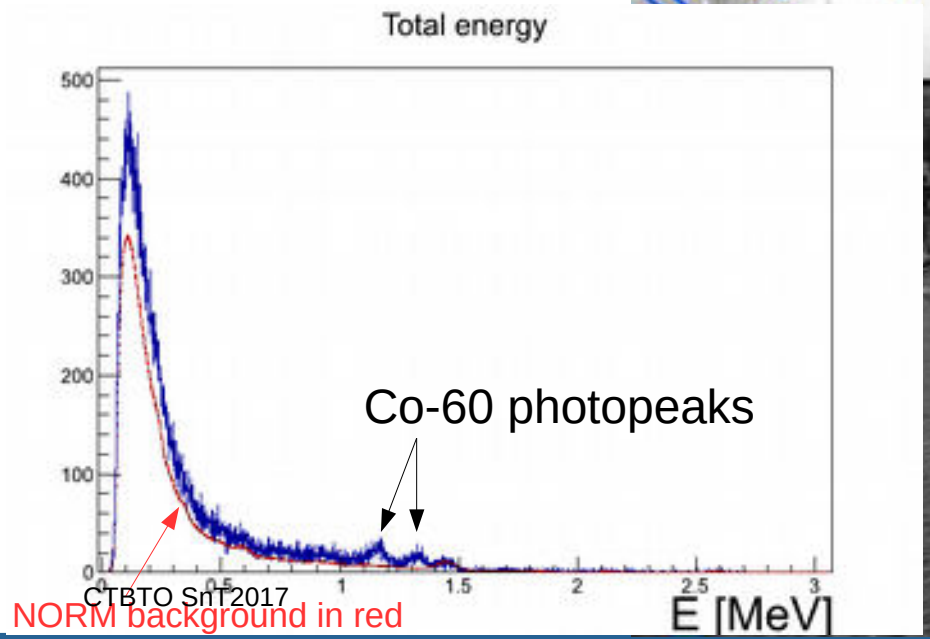
IFE2014 scenario: real experimental data

Lab-based R&D imager

Bare source

20 s integration time



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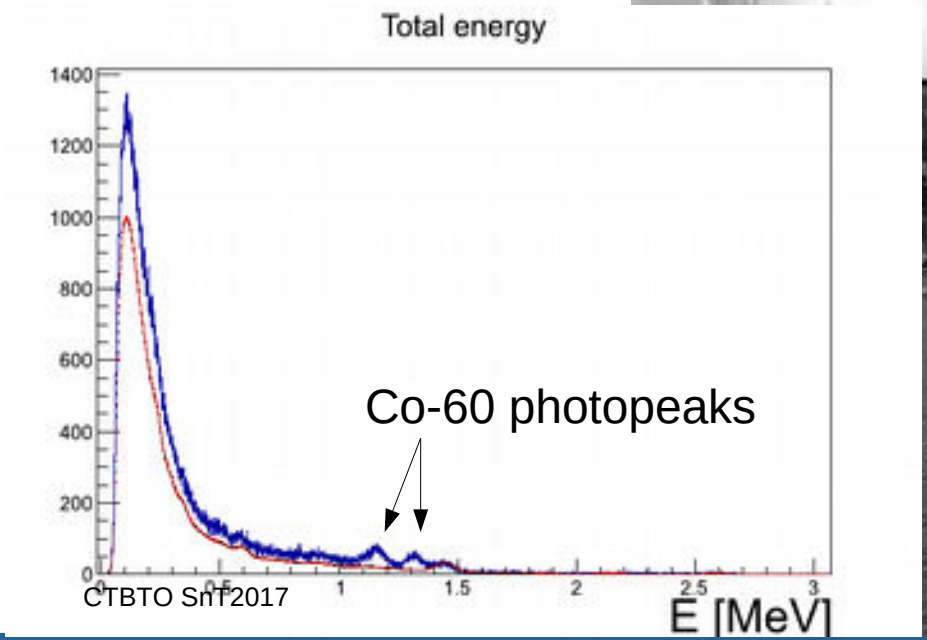
NORM background in red

IFE2014 scenario: real experimental data

Lab-based R&D imager

Bare source

60 s integration time

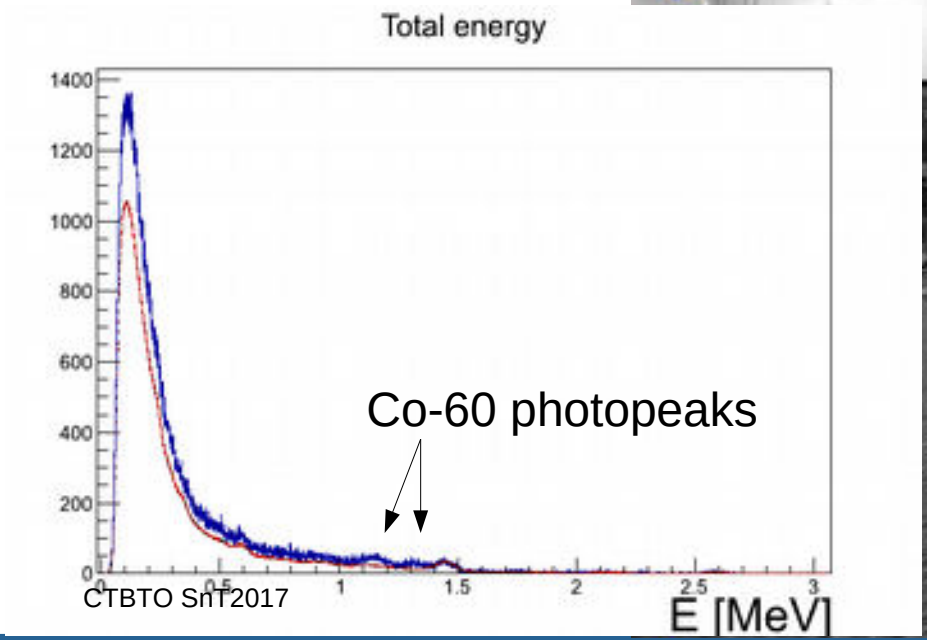


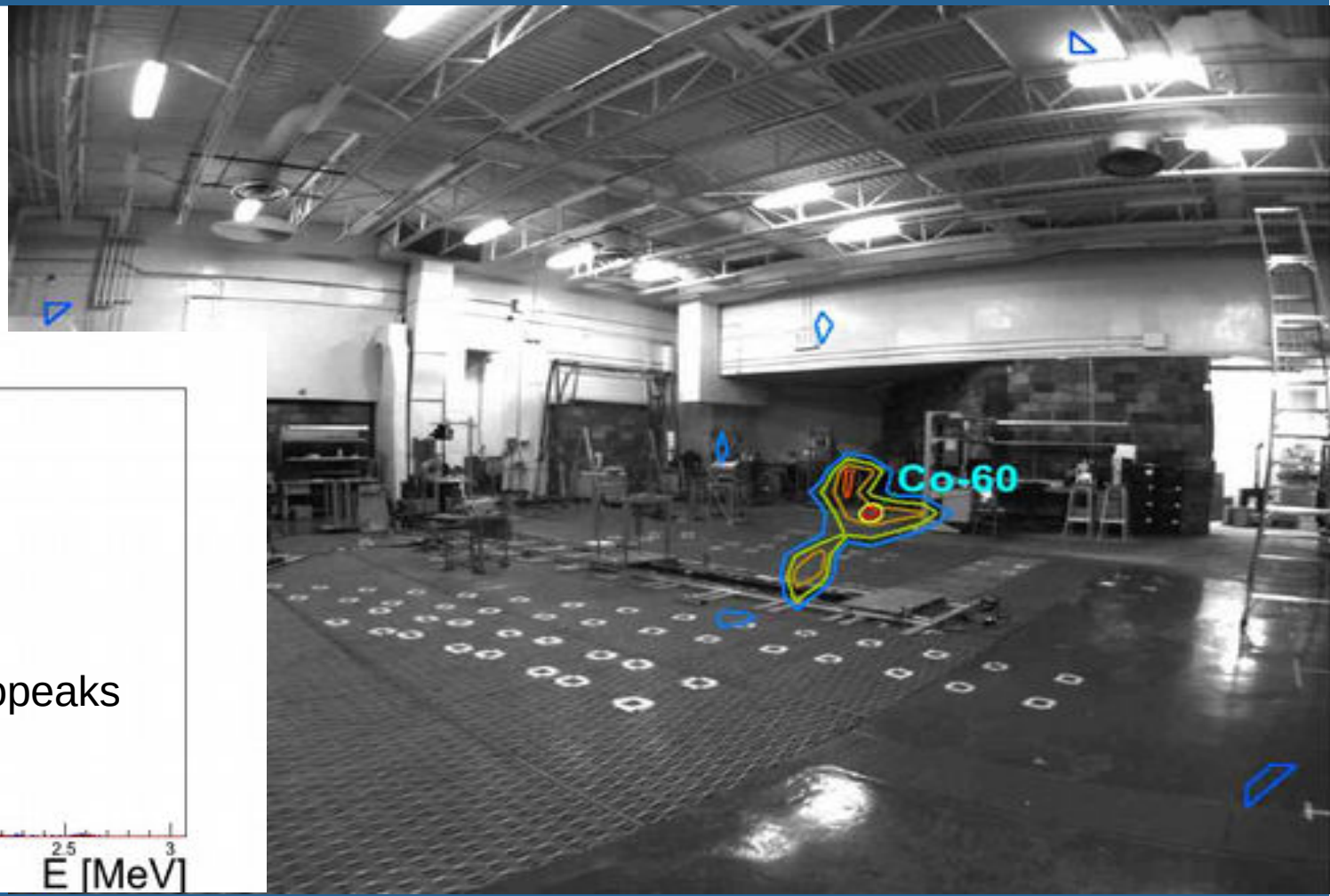
IFE2014 scenario: real experimental data

Lab-based R&D imager

10 cm of sand travel

60 s integration time



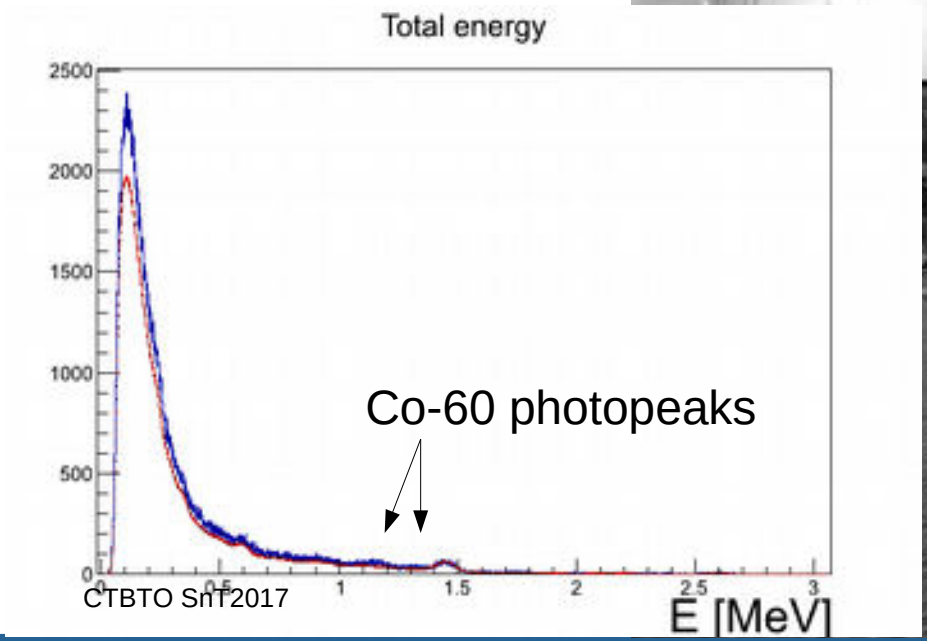


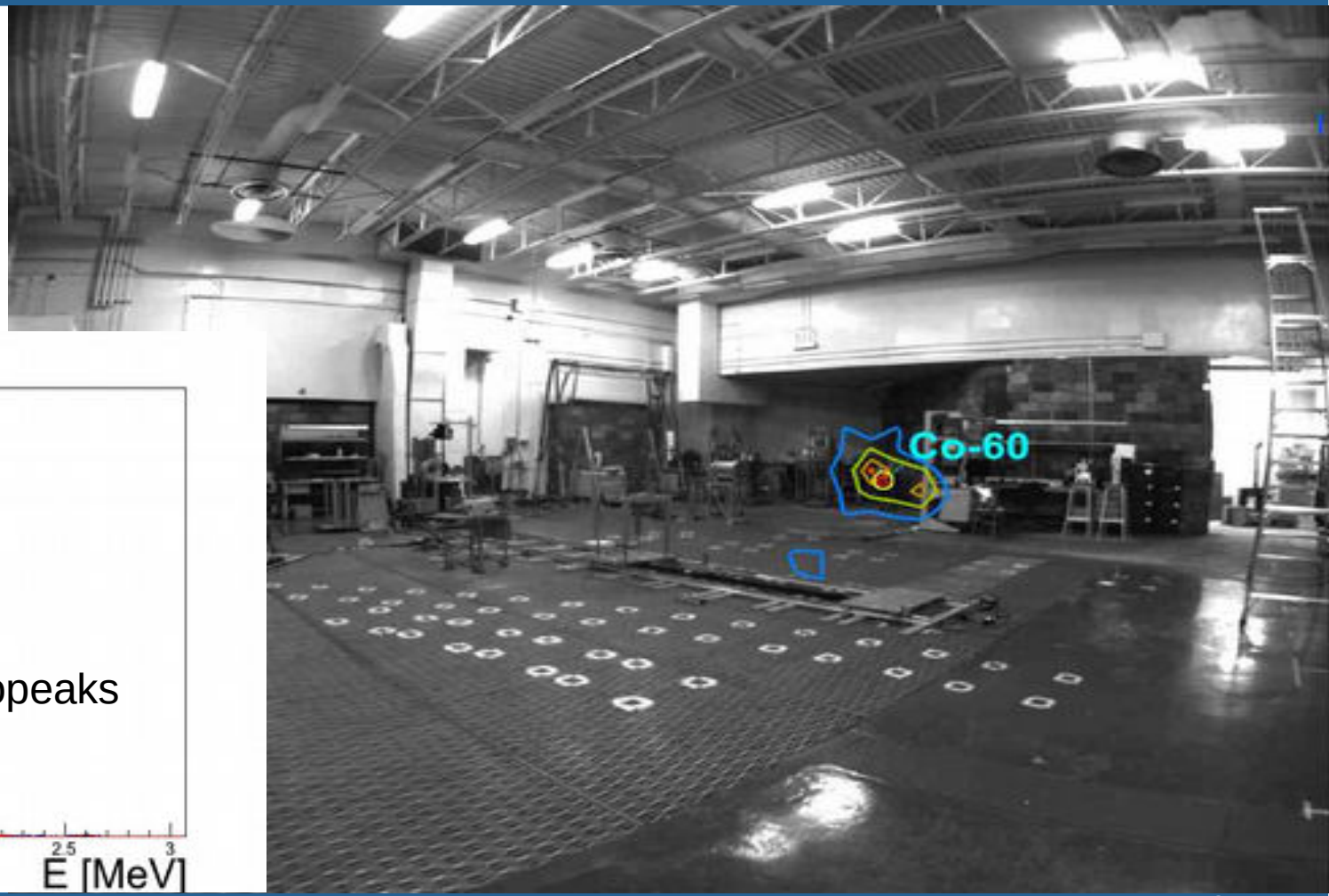
IFE2014 scenario: real experimental data

Lab-based R&D imager

20 cm of sand travel

120 s integration time



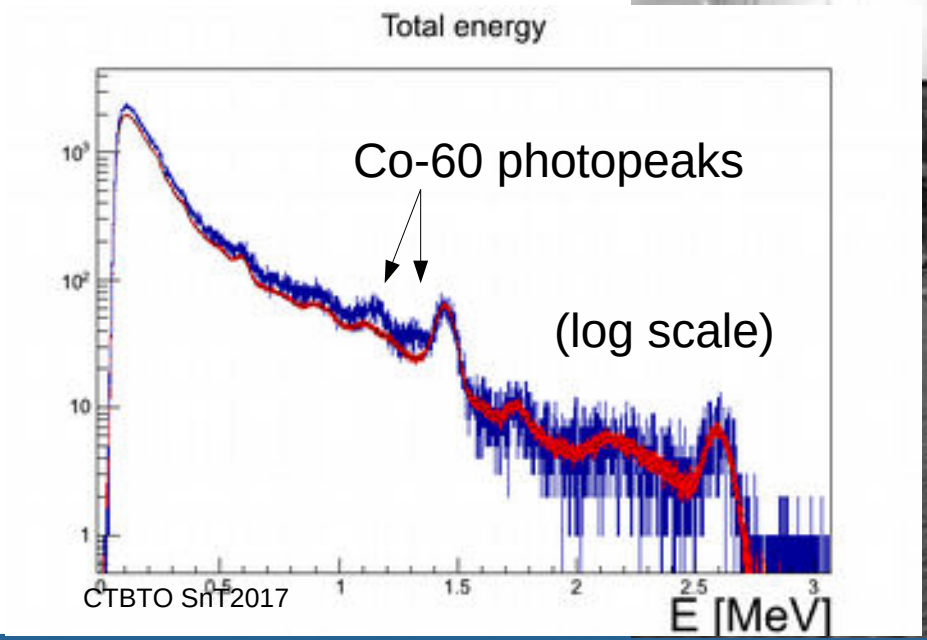


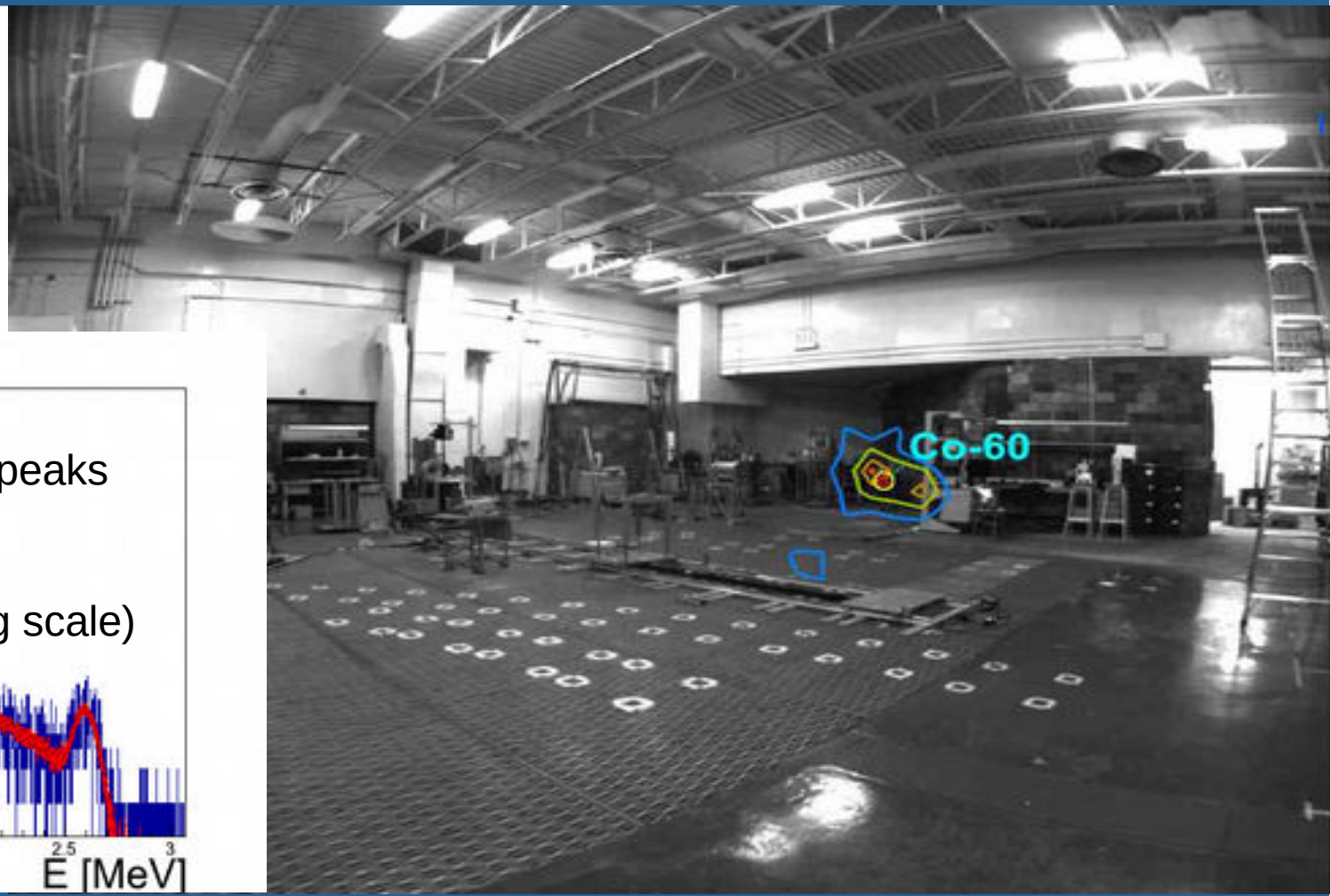
IFE2014 scenario: real experimental data

Lab-based R&D imager

20 cm of sand travel

120 s integration time



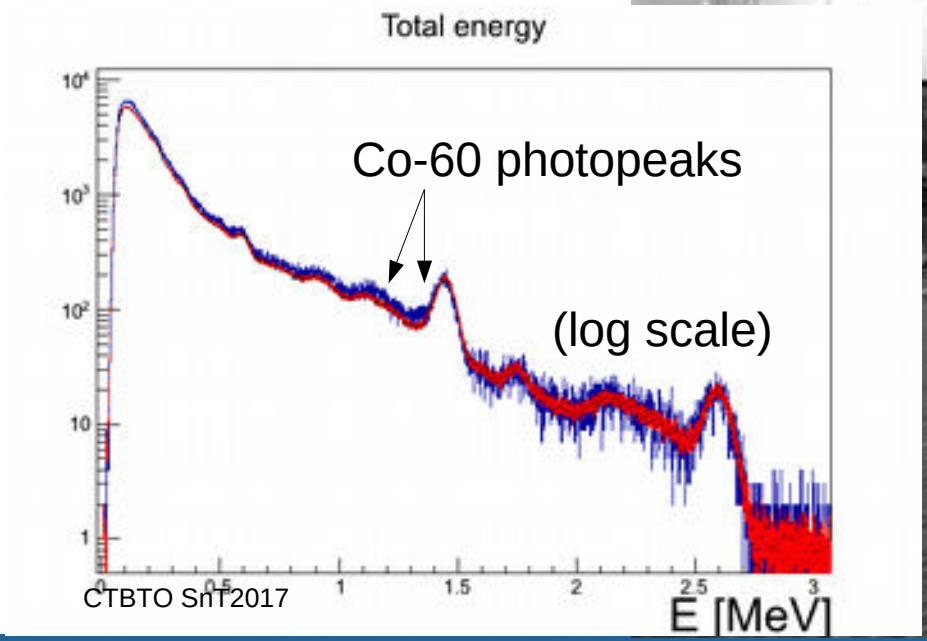


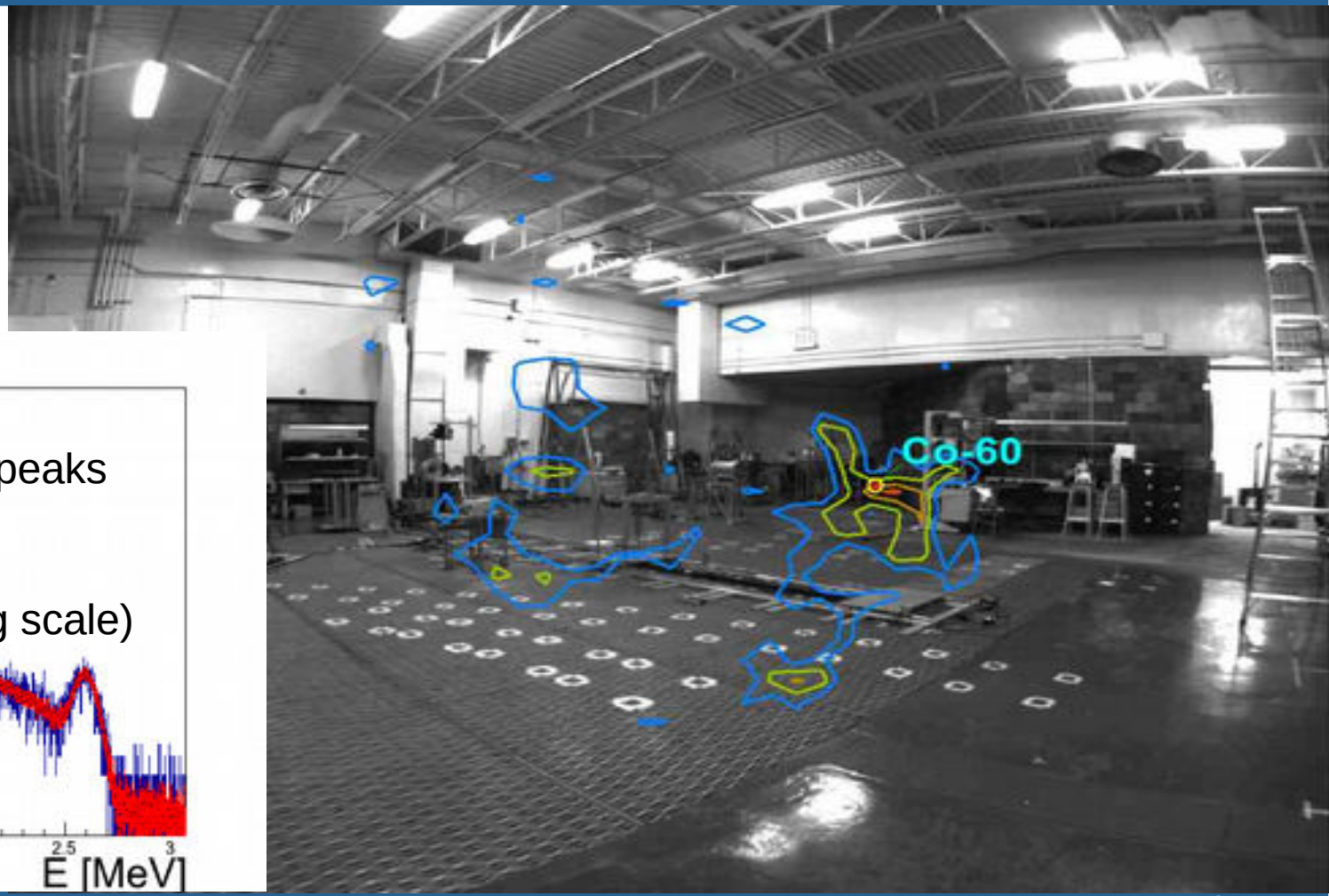
IFE2014 scenario: real experimental data

Lab-based R&D imager

30 cm of sand travel

360 s integration time





IFE2014 scenario: real experimental data

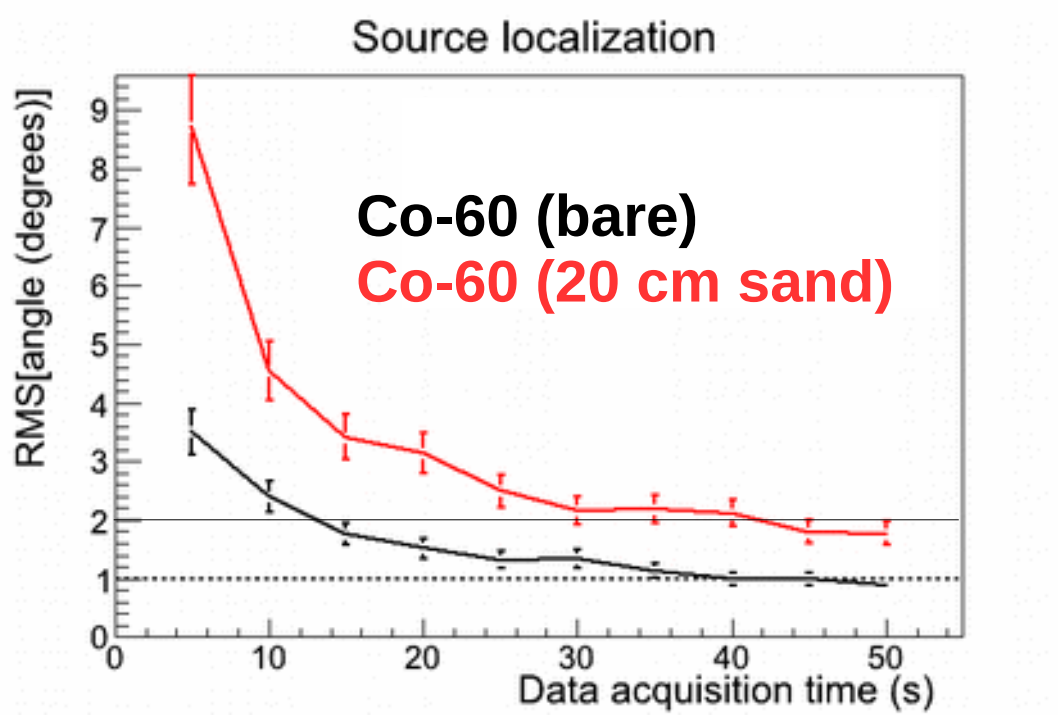
Lab-based R&D imager

40 cm of sand travel

tens of minutes

(At **40 cm** sand travel we failed to localize the source.)

IFE2014 scenario: real experimental data



22 MBq at 15 m

(equivalent to
400 MBq at 60 m)

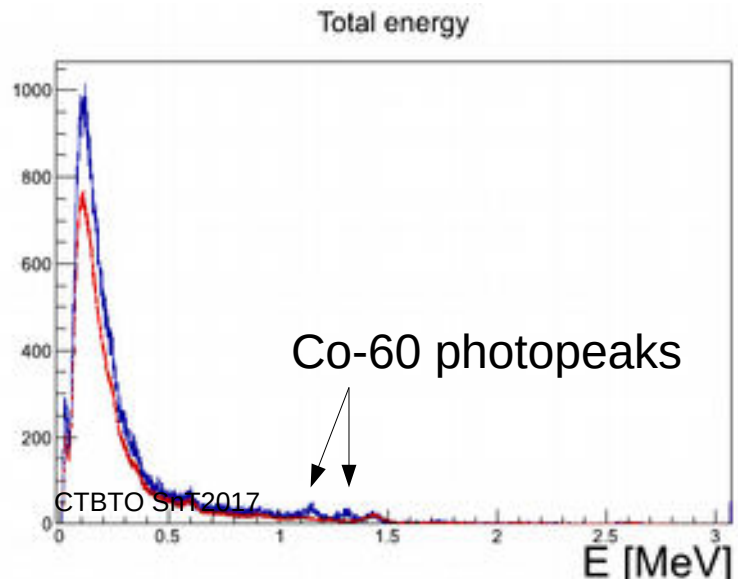
→ Imager reconstructs ^{60}Co source position to within 2^{o} in under a minute.

IFE2014 scenario: real experimental data

JIFI fieldable imager

Bare source

120 s



IFE2014 scenario: real exp. data summary

400 MBq ^{60}Co at 60 m	Bare	10 cm sand	20 cm sand	30 cm sand	40 cm sand
3x3-array proxy imaging (to 2° in < 1 min)	✓	✓	✓	✓	✗
single-module proxy imaging (to 2° in < 10 min)	✓	✓	~	✗	✗
single-module proxy alarm: total counts	✓	✓	✓	✓	✓
single-module proxy alarm: ^{60}Co window	✓	✓	✓	✗	✗

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Summary

- Gamma imagers are ideal for “seeing into” areas inaccessible to inspectors or which are too hazardous to enter.
- We are developing a large-volume, modular Compton gamma imager system based on scintillator read out with rugged, compact silicon photomultipliers.
- The system is designed to be dual use, sensitive enough to be operated as a survey and mapping instrument in addition to an imager.
- Radiation Solutions Inc (RSI) is a well established industry partner, and the CTBTO already makes use of their direction-blind NaI(Tl) log systems for aerial survey.

  (The imager system is a drop in replacement/upgrade for existing direction-blind RSI systems.)
- We have successfully tested a first version of a single-module imager in the field (spectra, alarming, GPS, mapping). Commercial version will be available in 2018.

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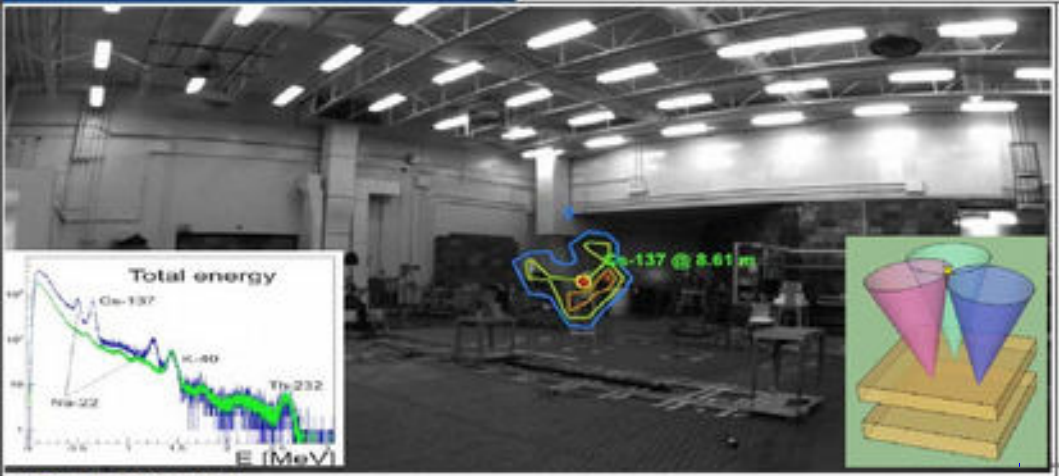
Extra slides

CSSP-2015-CP-2096 A MISSION-READY COMPTON GAMMA IMAGER FOR SAFETY AND SECURITY



Lead : National Research Council

Partnership: Radiation Solutions Inc., Natural Resources Canada, Canada Border Services Agency, Royal Canadian Mounted Police, Defence Research and Development Canada, Department of National Defence CANSOFCOM

Start-End: July 2015 to December 2017

Objective(s):

The objective of the project is to improve safety and security for Canadians from RN threats by providing national border/security, military, and consequence-management teams with a Compton gamma imager designed for their use. Specifically, we aim to transition the high-performance imaging prototypes developed during project CRTI 07-0193RD from TRL 5 to TRL 8, producing a commercially-available, optimized, fieldable, cost-effective, mission-ready imager, thus improving Canada's operational preparedness in the event of an RN incident. The deliverable will provide an image of radiation-emitting objects, superimposed on an optical photograph of the surroundings to aid in detecting and localizing sources in an intuitive manner. It will be modular in nature to suit a wide variety of end users, and include data outputs in the forms of energy spectra, GPS location and direction, and photographic image with radiation map overlay for easy integration of information across sectors.

Deliverable(s):

- One TRL 8 single-module Compton gamma imager and one large-array 3x3 Compton gamma imager ready for deployment in the field
- Availability of further imagers of arbitrary array size for purchase from Radiation Solutions Inc.

Impact(s):

Secure and open borders; connected and protected practitioners.

- Qualitatively new product enables visualization of radiation for the first time, with an order-of-magnitude improvement in source localization over direction-blind instruments
- Stand-off nature of device significantly reduces first-responder risk
- Long-range capability enables rapid screening of stacked containers
- Dual-mode operation as imager and sensitive spectrometer for isotope ID and threat attribution.

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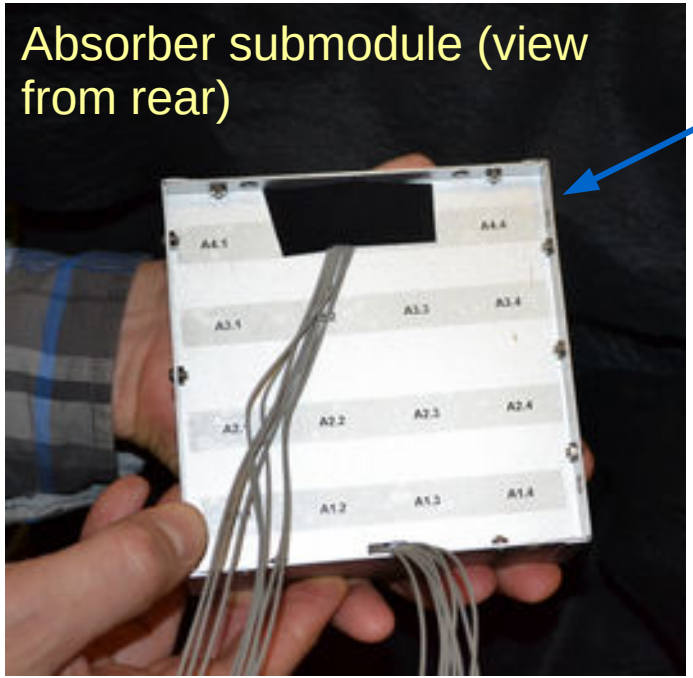
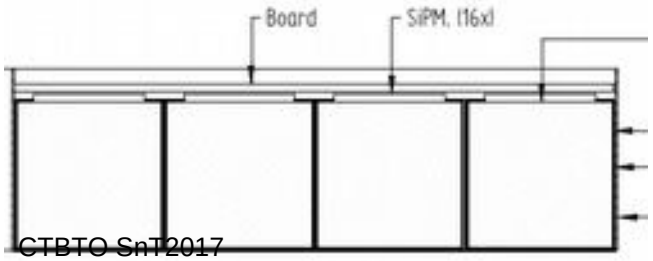
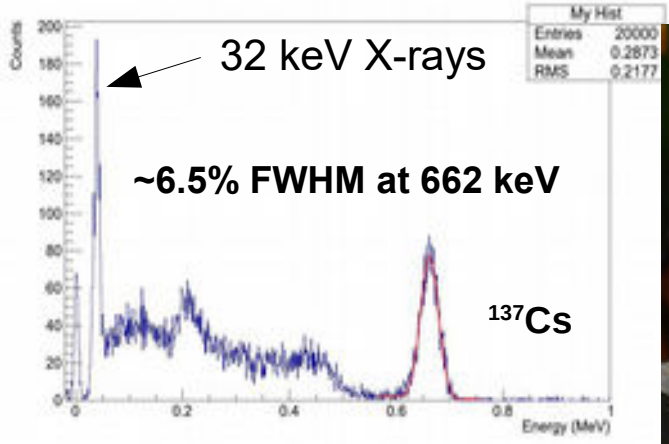


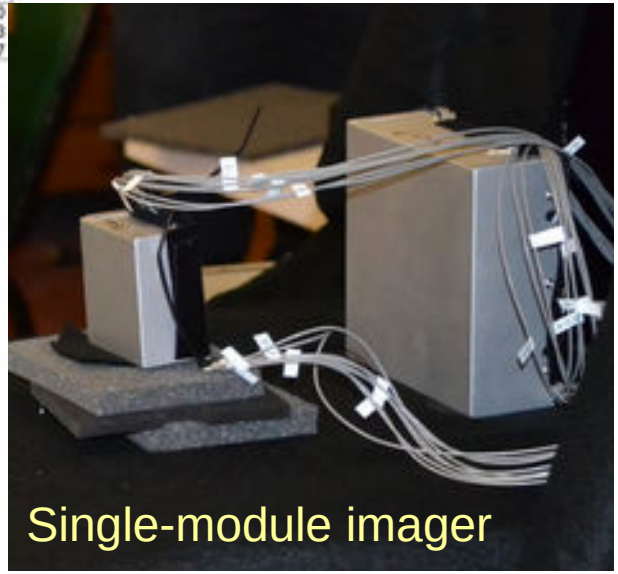
Absorber sub-module: 4 x 4 array of close-packed 2.8 cm cubes of CsI crystal read out with silicon photomultipliers (SPMs).

Scatter sub-module: 4 x 4 array of close-packed 1.35 cm cubes of CsI crystal read SPMs.

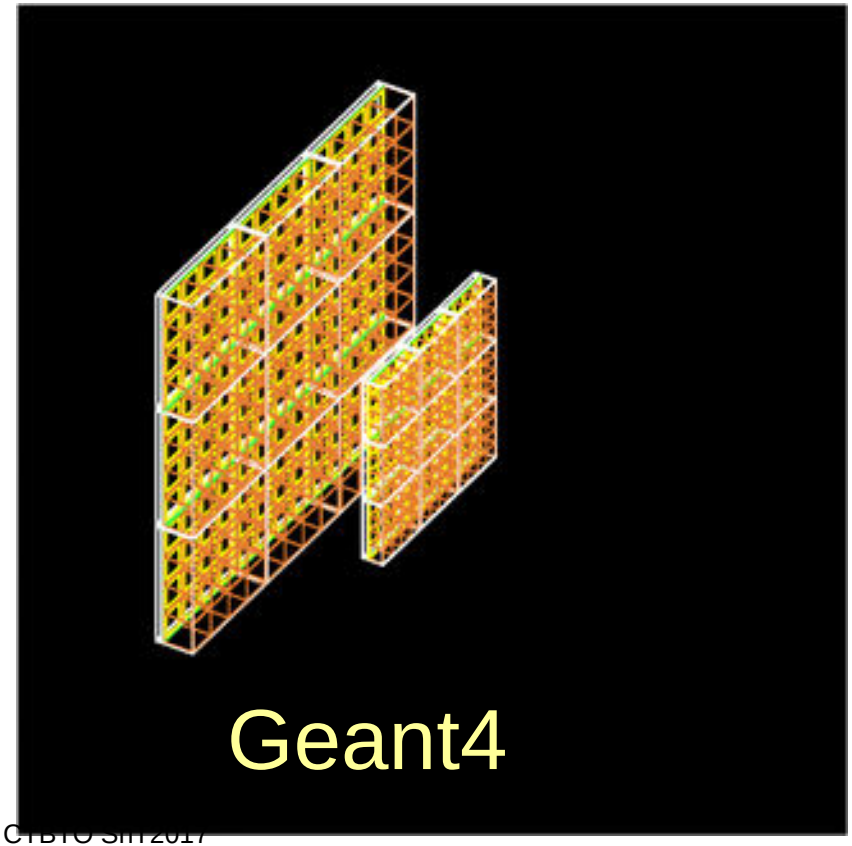


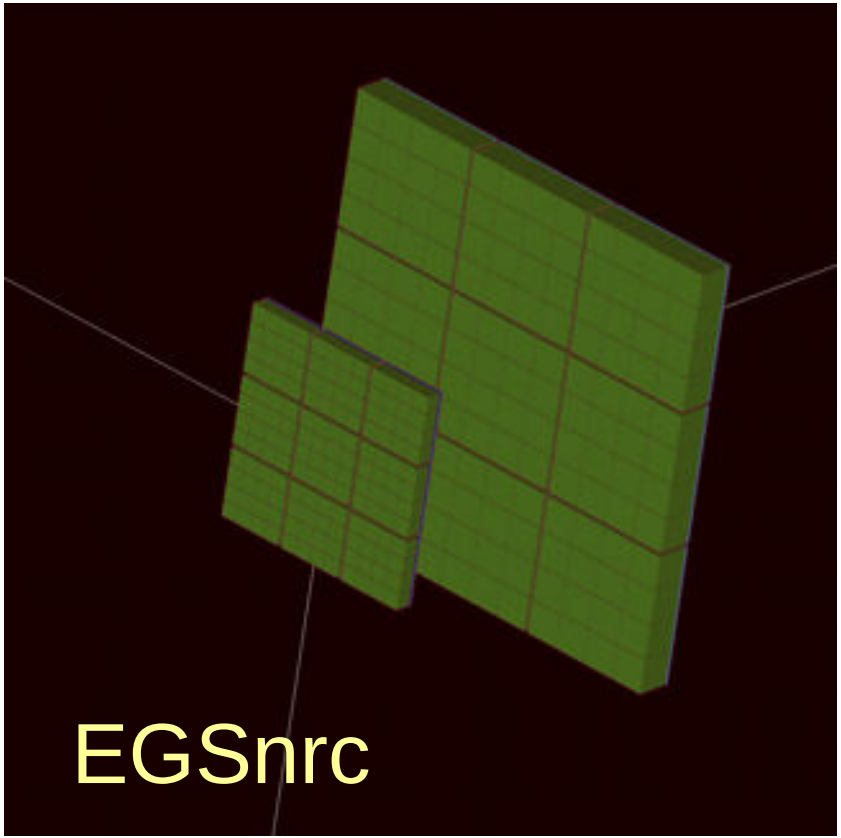


ArrayC-60035-4P
SPMs sensL



Simulation geometry (two packages)





GAIA reconstruction algorithm

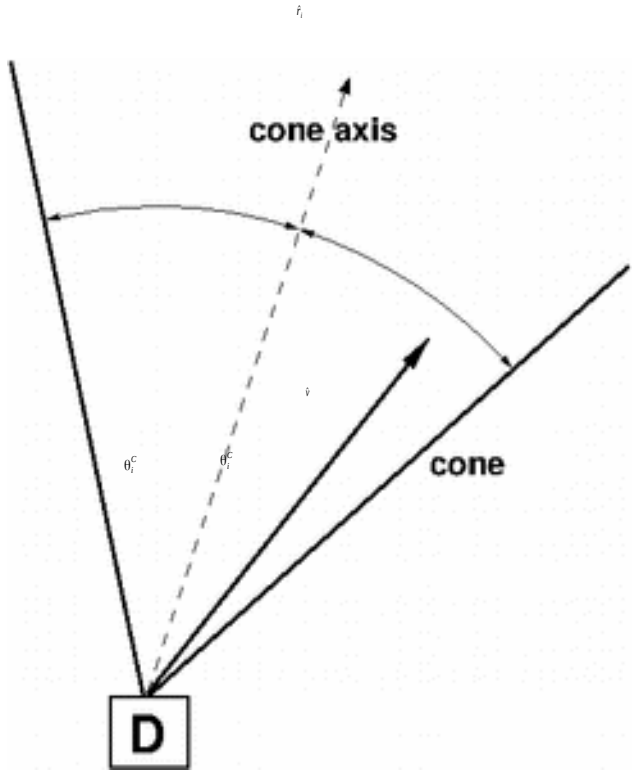
ACA = angle of closest approach to cone

$$\mathrm{ACA}_i = |\arccos\, \hat{v} \cdot \hat{r_i} - \theta_i^C|$$

$\hat{v}(\theta, \phi)$ is the source direction to be found (fitted)

Cone axis

Compton angle



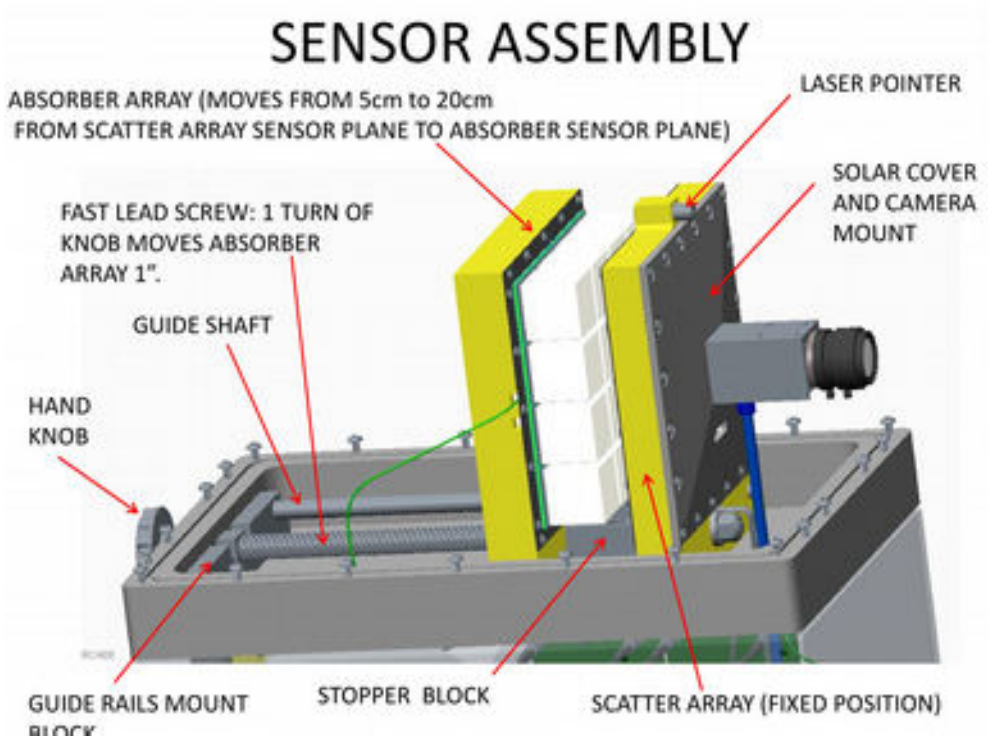
For *N* events, minimize the following χ^2 expression iteratively:

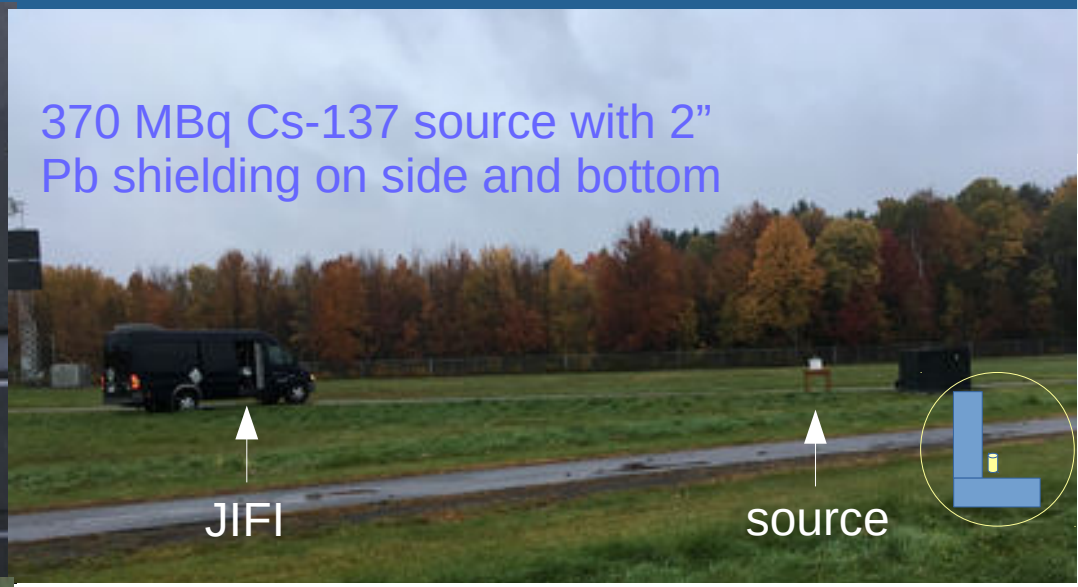
$$\chi^2 = \sum_{i=1}^{N} \left[\frac{\mathrm{ACA}(\theta, \phi)_i}{\sigma_{\mathrm{ACA}i}} \right]^2$$

ACA uncertainty

Joyful Interim Fieldable Imager (JIFI)

A quick prototype to gain field experience for feedback into mission-ready imager design




370 MBq Cs-137 source with 2”
Pb shielding on side and bottom
JIFI
source


NRCan Anderson Road, Ottawa
6
8
X
0
11
110 m
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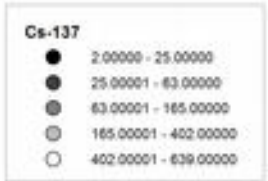
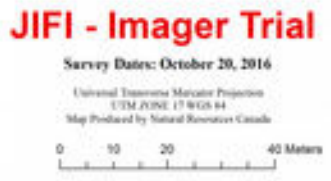
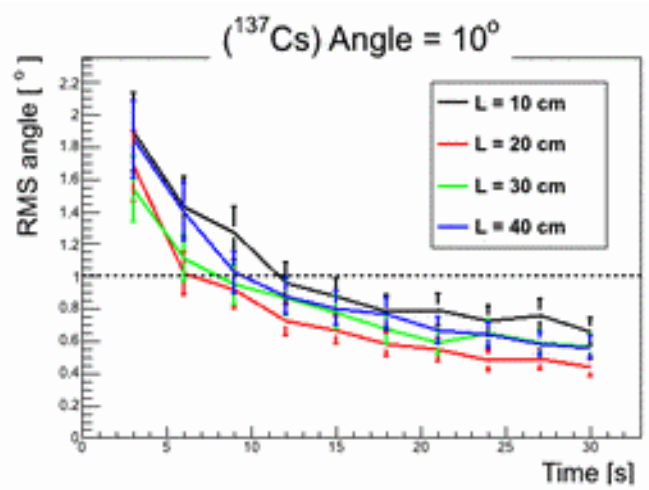
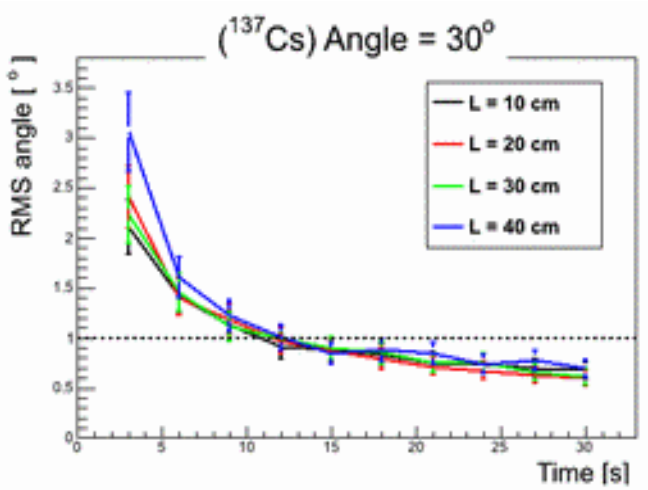
GPS track

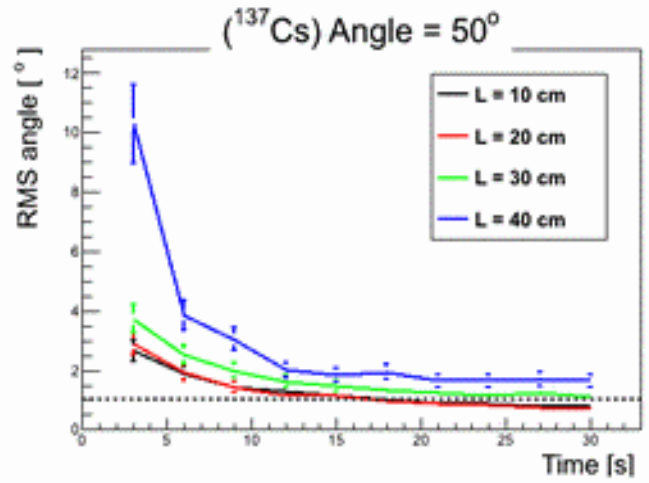

Cs-137
2.00000 - 25.00000
25.00001 - 63.00000
63.00001 - 165.00000
165.00001 - 402.00000
402.00001 - 639.00000


JIFI - Imager Trial
Survey Dates: October 20, 2016
0
10
20
40 Meters

Mission-ready 3x3 array is expected to perform better than the R&D pixel imager prototype:







→ Can localize a 44 MBq Cs-137 source at 10 m to one-degree angular precision within a +/- 50° field of view in less than 20 secs

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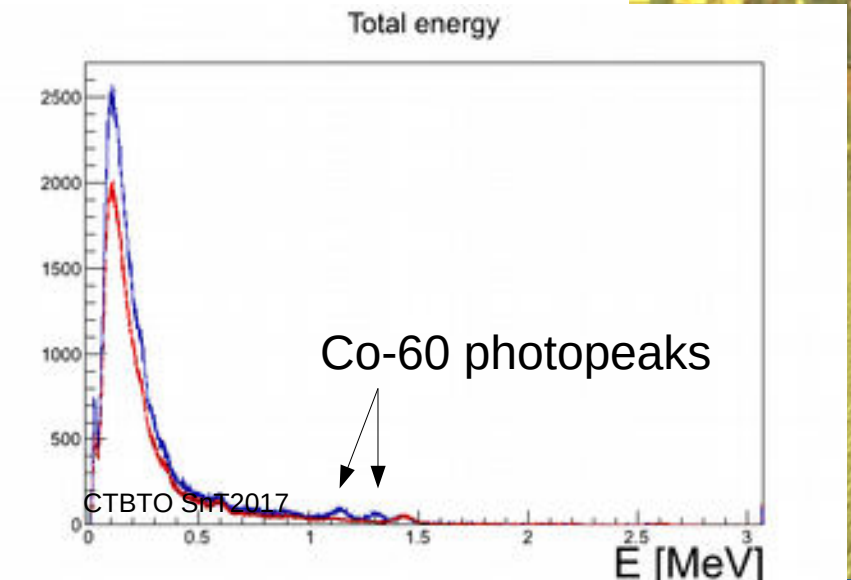
JIFI fieldable imager

Bare source

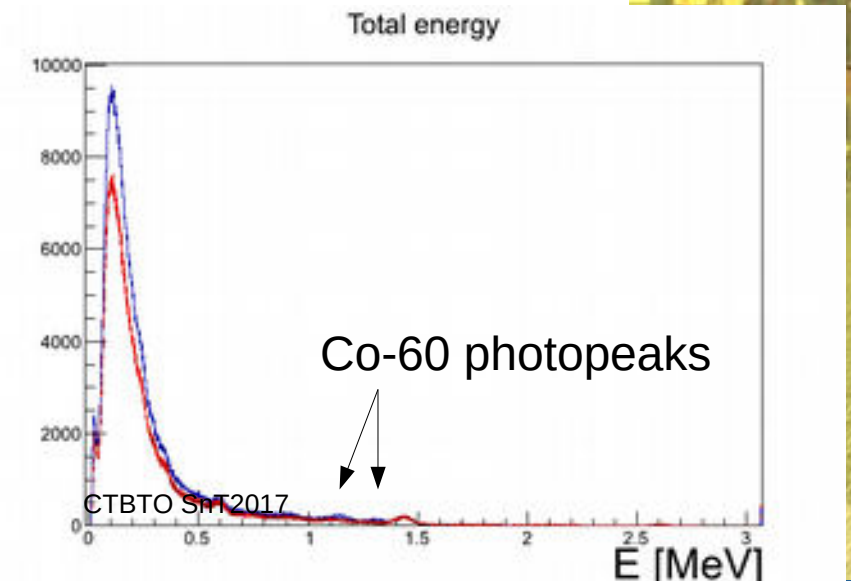
320 s



JIFI fieldable imager

20 cm sand travel

1200 s



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P.R.B.Saull, L.E.Sinclair, H.C.J.Seywerd, P.J.Boyle, A.M.L.MacLeod and D.S.Hanna, "A two-pixel Compton imager", Proc. SPIE, Vol. 7665, 76651E, 2010

PRB Saull, LE Sinclair, HCJ Seywerd, DS Hanna, PJ Boyle and AML MacLeod, *First demonstration of a Compton gamma imager based on silicon photomultipliers*, NIM A679 (2012) 89

A.M.L. MacLeod, P.J. Boyle, D.S. Hanna, P.R.B. Saull, L.E. Sinclair, H.C.J. Seywerd, "Development of a Compton Imager based on bars of scintillator", NIM A767, 397 - 406, 2014