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UAV Plume Measurements for Reconstructing Radiological Source Terms

James Carr, Marta Kocemba, Luke Lebel **(CNL)**
Johan Camps, Johan Paridaens, Geert Olyslaegers **(SCK-CEN)**

2023 OCTOBER 9

Introduction & Objectives

Introduction & Background

CNL's UAV Team

- Objectives to support CNL's sites across Canada through:
  - Advanced research projects, collaborating with various S&T Portfolios, and
  - Basic inspections (e.g. mapping, pictures, video).

UAV Radiological Plume Monitoring Project

- Advance Canada's tools, technologies and strategies in emergency dose assessment.
- UAV based shielded & collimated radiation detection sensor package.
- Structured to enable mathematical modelling of a plume for direct source term & release rate estimates.

Shielded & collimated γ-spectrometer

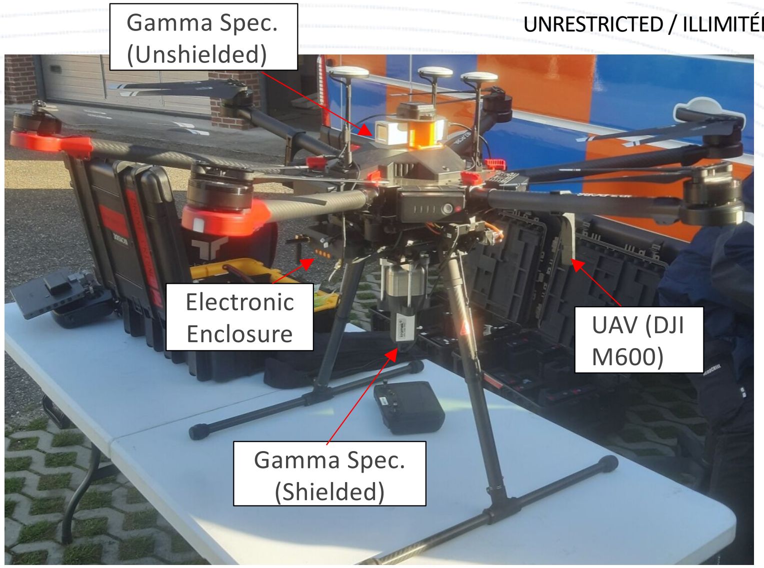
Introduction & Background - continued

Georeferenced Radiological and Environmental Data Acquisition (GEOREDAQ) System

Flight Planning → Flight Execution → Review & Iterate → Flight Planning

- Ground station laptop (Flight planning, data monitoring)
- Electronics enclosure (microcomputer, GPS module, radio, battery, etc.)
- Shielded & collimated gamma spectrometer
- Unshielded gamma spectrometer

Ultimate goal: Development of methodology and tools for the **rapid** evaluation of radiological releases, using high resolution data to **directly reconstruct source term and plume parameters** from an airborne plume.



October 2022 Field Trial Objectives

1. Perform UAV flights around SCK CEN's BR-1 stack releasing a radioactive plume & collect radiation measurements.
2. Analyze flight & radiation data to extract key parameters describing radiation dispersion.
3. Use these parameters to calculate an estimated release rate and source term of the stack (validating methodology).

Routine ^{41}Ar plume used as analog for large reactor accident release

August 2023 Field Trial Objectives

1. Gather additional data with variable meteorological conditions and updates to the sensor package.
2. Perform trials at both SCK CEN's BR-1 reactor stack and Belgium's IRE output stack.
3. Repeat analysis and extract key parameters to estimate release rate and source term of the stack. (further validation of methodology)

Technical Background

Mathematical Modelling of Plume

$$C_a(x,y,z) = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z} \cdot e^{-\frac{y^2}{2\sigma_y^2}} \cdot \left[e^{-\frac{(z-H)^2}{2\sigma_z^2}} + e^{-\frac{(z+H)^2}{2\sigma_z^2}}\right]$$

Gaussian dispersion of plume

$$\Phi = \int_{\varphi=0}^{2\pi} \int_0^{\theta_{lim}} \int_{r=0}^{\infty} C_a(r,\Phi,\theta) \frac{e^{-\mu r}}{2} \sin\theta \, dr d\theta d\varphi$$

Gamma flux at in coordinate frame viewing plume through aperture with viewing angle (θ_{lim})

Combine & simplify

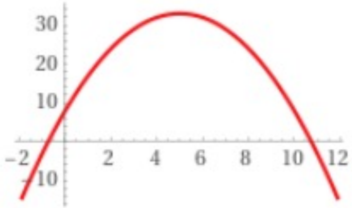
$$\Phi = \frac{\theta_{lim}^2 \cdot Q}{4\sqrt{2\pi}\bar{u}\,\sigma_y} \cdot e^{-\frac{y^2}{2\,\sigma_y^2}}$$

Assumptions

- Within viewing angle, C_a only varies substantially in distance (r or z), is fairly uniform in terms of ϕ and θ
- Gamma attenuation in air is small in vertical direction
- Plume ground reflection term can be ignored and measurements taken >$2\sigma_z$ below centerline elevation *(but slightly different equation available for ground-level measurements)*

Mathematical Modelling of Plume

$\ln(\Phi) = ay^2 + by + c$



$$\Phi = \frac{\theta_{lim}^2 \times Q}{4\sqrt{2\pi}\bar{u}\,\sigma_y} \times e^{\left(-\frac{y^2}{2\,\sigma_y^2}\right)} \longrightarrow \ln(\Phi) = \underbrace{-\frac{1}{2\,\sigma^2}}_{}y^2 + \underbrace{\frac{y_m}{\sigma^2}}_{}y + \underbrace{\ln\left(\frac{\theta_{lim}^2 \cdot Q}{4\sqrt{2\pi}\bar{u}\,\sigma_y}\right) - \frac{y_m^2}{2\,\sigma^2}}_{}$$

'a' contains the parameter σ^2, or lateral dispersion

'b' contains the parameter y_m, or plume centerline

'c' contains the parameter Q, or release rate

Data Analysis Procedure

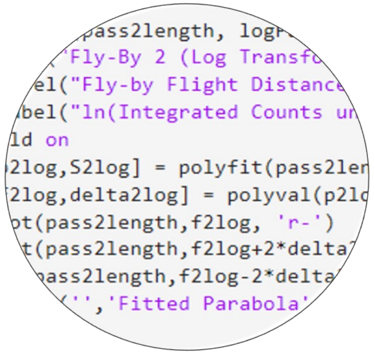
Overview of Data Analysis Process

UAV Flight

The UAV is flown beneath the plume, and sensors collect data

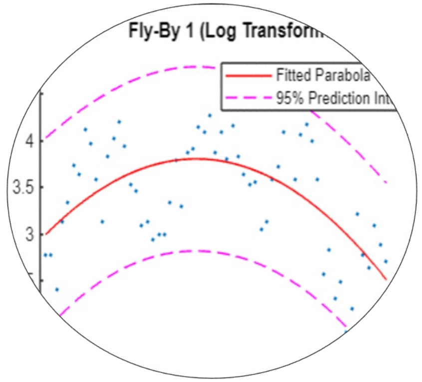
Data Extraction

Data is retrieved from the sensors and uploaded for access



Data Analysis

Models are fitted to extracted radiation data

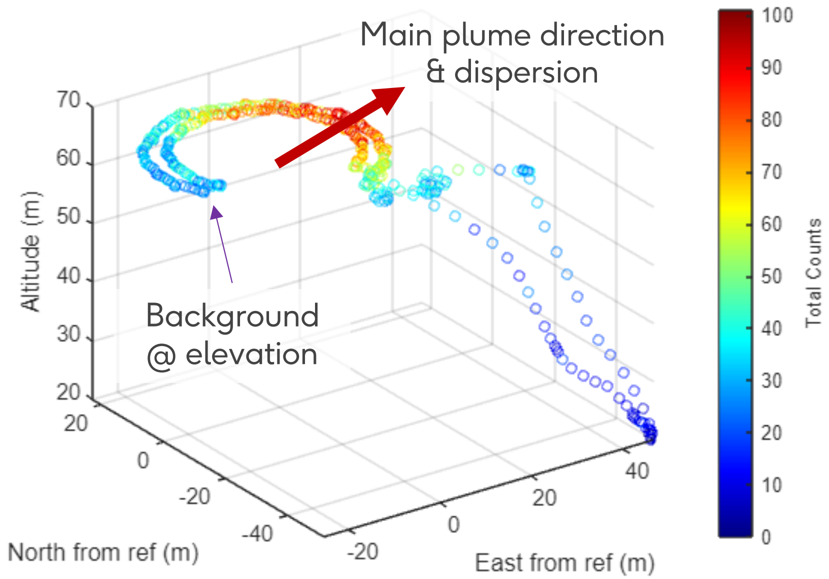


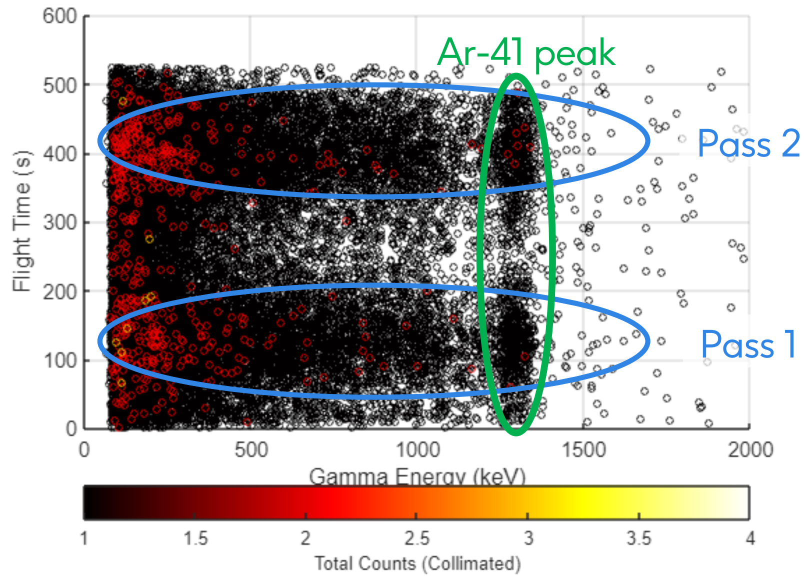
Release Rate

Release rate from the stack is calculated from fitted models

Data Analysis

- Visualize flight path & plume region and spectrum details



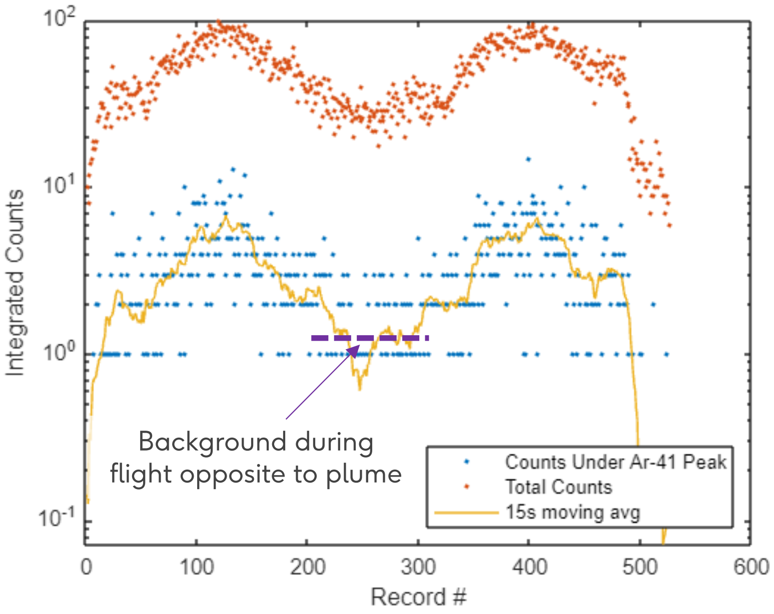


- Full gamma spectrum at each second of flight, can see ^{41}Ar peak vs scattered background counts

Data Analysis

- ^{41}Ar peak integration, background subtraction, and efficiency correction

Total counts and ^{41}Ar peak integrated counts over flight

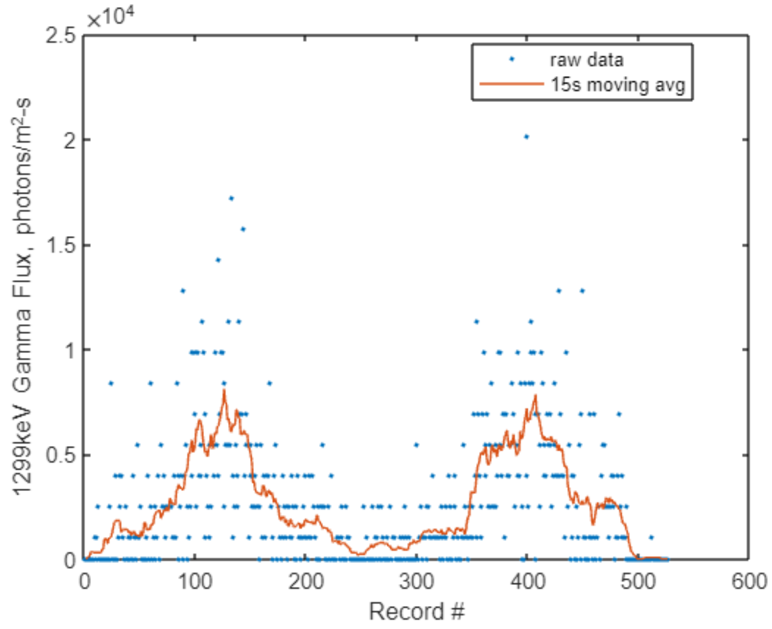


Subtract background @ elevation

Efficiency correction to convert count rate to gamma flux

$$\phi = \frac{count\ rate}{\epsilon \cdot a_{det}}$$

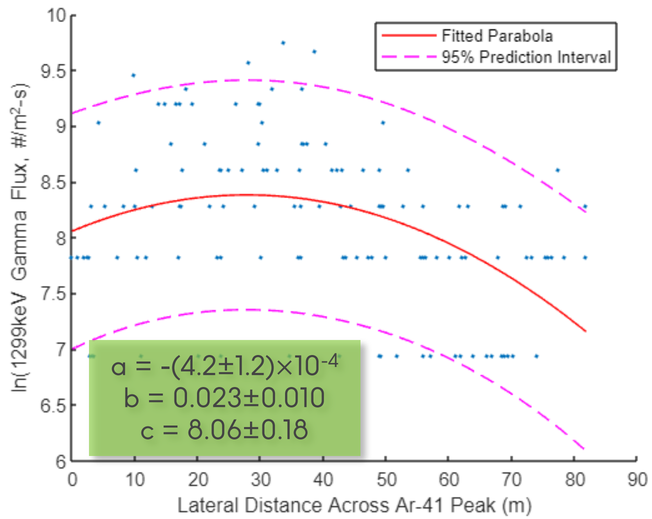
Calculated gamma flux over flight

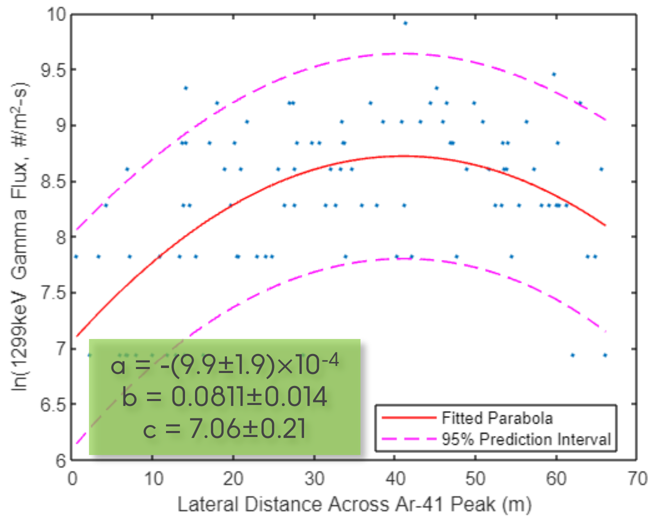


Regression for Release Rate and Dispersion Parameter Estimation

- Stage 1: Fit parabolas to plume fly-by regions
  - Include prediction intervals to assess the fit
- Stage 2: Extract curve parameters
  - Regression parameters 'a', 'b', and 'c'
  - These give important characteristics of plume spread
- Stage 3: Calculate release rate
  - Only missing parameter estimate for <u>wind speed</u>, provided from external source

$$a = -\frac{1}{2\sigma_y^2} \qquad b = \frac{y_m}{\sigma_y^2} \qquad c = \ln\left(\frac{\theta_{lim}^2 \cdot Q}{4\sqrt{2\pi}\bar{u}\,\sigma_y}\right) - \frac{y_m^2}{2\sigma_y^2}$$





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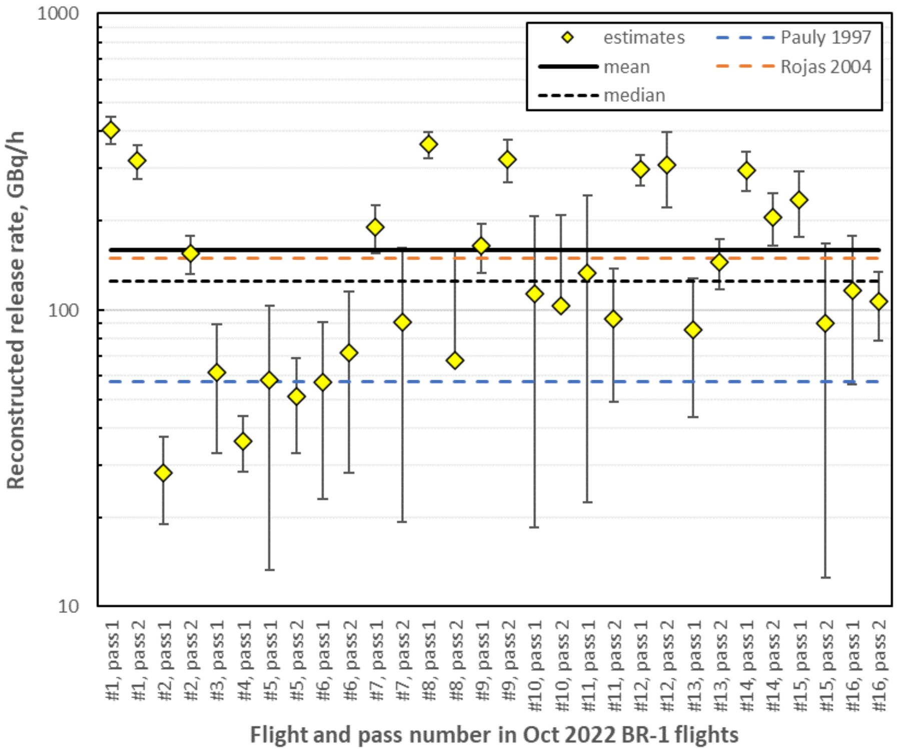
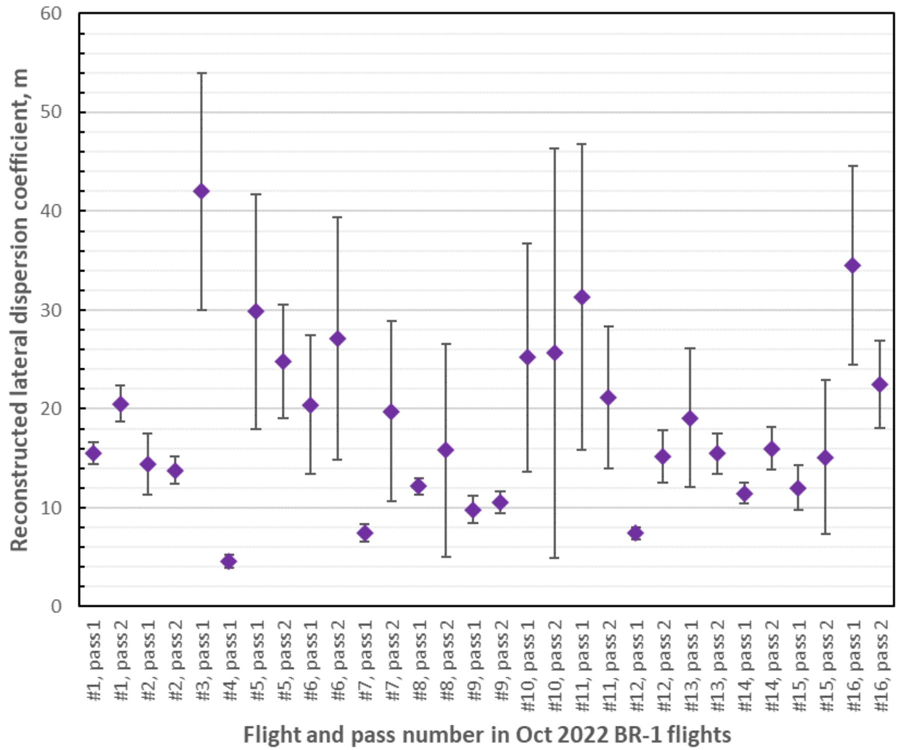
Summary of Flight Analyses – October 2022 Campaign





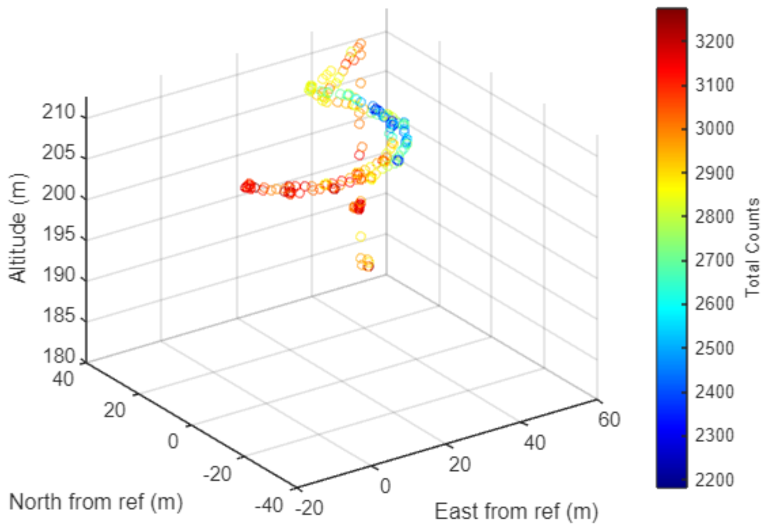
References

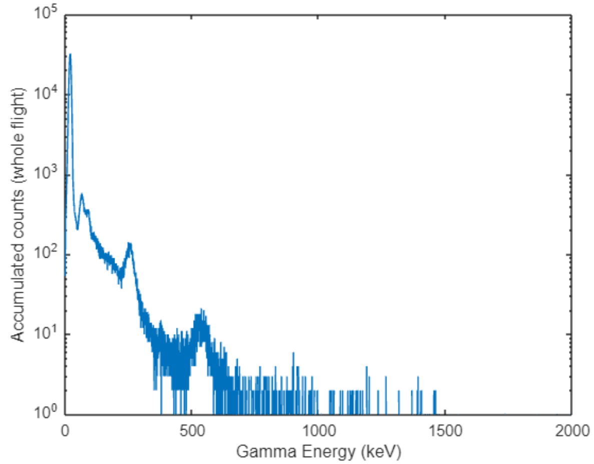
1. Pauly et al. (1997), "Source term estimation based on in-situ gamma spectrometry using a high purity germanium detector," SCK-CEN, Mol, Belgium.
2. Rojas-Palmas et al. (2004), "Experimental evaluation of gamma fluence-rate predictions from argon-41 releases to the atmosphere over a nuclear research reactor site," *Radiation Protection Dosimetry,* pp. 161-168.

Concluding Remarks

- Method proposed for directly reconstructing source term and plume parameters from UAV flight data, using upward facing collimated gamma spectrometer
- Sensor package designed and deployed during two campaigns (2022 and 2023)
- Using 2022 data, the method successfully validated versus known releases from BR-1 reactor with ^{41}Ar plume. Analysis of 2023 data ongoing
- Demonstration of potential use case in automated, rapid reconstruction of radiological source term from nuclear accidents

Flight path and measured spectrum from IRE measurements





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Contact:

James.P.Carr@cnl.ca, Luke.Lebel@cnl.ca

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