Network of National Laboratories for

NNLEMS

Environmental Management and Stewardship

National Laboratories for Environmental Management and Stewardship (NNLEMS) National Lab Capabilities in Unmanned Aerial Systems (UAS)

August-2025

NNLEMS-2025-00004

U.S. DEPARTMENT OF ENERGY

Printed in the United States of America

Prepared for
U.S. Department of Energy

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Acknowledgements

The Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) Unoccupied Aircraft Systems (UAS) topical team gratefully acknowledge the support of the US Department of Energy Office of Legacy Management (DOE - LM).

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Acronyms and Abbreviations

AI	Artificial intelligence
ANL	Argonne National Laboratory
C2H6	Ethane
CATALOG	Consortium Advancing Technology for Assessment of Lost Oil & Gas Wells
CH4	Methane
COA	certificate of authorization
COTS	commercial off-the-shelf
CUAS	Counter-UAS
DoD	Department of Defense
DOE	Department of Energy
DoF	Degree of Freedom
EES	Earth and Environmental Sciences
EO	electro-optical
EoD	Explosive Ordinance Disposal
FAA	Federal Aviation Administration
FPV	First Person View
GOTS	government off the shelf
GPR	Ground Penetrating Radar
H2O	Water
IR	Infrared
ISR	Intelligence, Surveillance, and Reconnaissance
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley National Laboratory
LiDAR	Light Detection and Ranging
LLNL	Lawrence Livermore National Laboratory
LM	Office of Legacy Management
ML	machine learning
NEST	Nuclear Emergency Support Team
NETL	National Energy Technology Laboratory
NNLMES	National Laboratories for Environmental Management and Stewardship
NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
OCONUS	Outside the Continental United States
OGAs	other government agencies
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RAP4	Radiological Assistance Program Area 4
RASL	Robotics and Autonomous Systems Laboratory
RDT&E	Research Development Testing and Evaluation
RF	radio frequency

SNL	Sandia National Laboratories
SPIINe	Self-propelled Interior Inspection of Networks
SRNL	Savannah River National Laboratory
TLDAS	Tunable diode laser absorption spectroscopy
TRL	Technical readiness level
UAS	Unoccupied Aircraft Systems
UAOU	UAS Aviation Operations Unit
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-Off and Landing
UGS	unattended ground sensors
WIPP	Waste Isolation Pilot Plant
YOLO	You Only Look Once

Introduction

The Network of National Laboratories for Environmental Management and Stewardship (NNLEMS) formed an Unoccupied Aircraft Systems (UAS) topical team in spring 2025 for the purpose of documenting the capabilities of the National Laboratories relevant to the goals and needs of the Department of Energy (DOE) Office of Legacy Management (LM). The team was comprised representatives from eight National Laboratories (Table 1), thereby bringing diverse skillsets from across the DOE complex. Recognizing that LM has extensive experience working with UAS contractors and using data collected from UAS, the topical team focused on the National Laboratories' unique capabilities and types of scientific investigations that are not yet commercially available or easily contracted as services.

The topical team focused on emerging/alternative UAS platforms, innovative sensor technologies, and novel methods of data management and data analysis. These capabilities are summarized and organized in this report in the form of the 'rolodex,' with participating Laboratories providing individual entries. Each rolodex entry includes sections on the respective Laboratory's general capabilities, unique sensors and data types, references (i.e., reports, publications or web pages), and graphics highlighting field investigations. In developing rolodex entries, the team focused on documenting established and demonstrated capabilities rather than unproven and untested research tools. Going forward, the topical team will continue to meet and will focus efforts on challenges related to (1) managing and visualizing the large, complex datasets acquired by UAS, and (2) identifying new sensors and data streams that could be valuable to LM in the future.

Table 1. Topical team members and their respective laboratory affiliations.

Team member	Laboratory affiliation
Yuki Hamada	Argonne National Laboratory (ANL)
Brian Van Acker	ANL
Steve Jankiewicz	ANL
Brandon Crawford	Los Alamos National Laboratory (LANL)
Eric Guiltinan	LANL
James Lee	LANL
Damien Milazzo	LANL
Brian Quiter	Lawrence Berkeley National Laboratory (LBL)
Kenneth Hurst Williams	LBL
Jacob Trueblood	Lawrence Livermore National Laboratory (LLNL)
Jaisree Iyer	LLNL
Colton J Kohnke	National Energy Technology Laboratory (NETL)
Patrick Royer	Pacific Northwest National Laboratory (PNNL)
Frederick Day-Lewis	PNNL
Jonathan Salton	Sandia National Laboratories (SNL)
Kristopher Klingler	SNL
Troy Lorier	Savannah River National Laboratory (SRNL)
Carol Eddy-Dilek	SRNL
Emily Fabricatore	SRNL
Brian Looney	SRNL
Holly VerMeulen	SRNL

Applicability to Legacy Management Sites

Applications for use of UAS at LM sites in the report are focused on the capabilities for UAS to (1) safely operate over hazardous areas or challenging terrain, (2) cover large areas efficiently with minimal labor, and (3) perform flyover surveys for inspection of caps or covers where access by foot or vehicles is problematic. Compared to surveys using conventional fixed-wing or helicopter platforms, UAS surveys are commonly lower cost and offer enhanced resolution (e.g., Mangel et al., 2022). In addition, UAS can be programmed for repeat missions, thus allowing for cost-effective and highly repeatable surveys to support long-term monitoring. UAS are used increasingly by both the National Laboratories in research and by contractors in practice across the DOE complex, with a history of application to LM sites.

Laboratory Capabilities

The UAS capabilities of the National Laboratories contributing to this report are briefly summarized in Table 2. Where applicable, supplementary information about other platform types (e.g., ground-based platforms) within the National Laboratory fleets are also included in Table 2 to provide a more comprehensive overview of their programs' capabalities. The various sensor payloads provide information about radiation (e.g., gamma detectors), topography (e.g., LIDAR), vegetation (multispectral), air quality and gases (e.g., methane detection), water quality and aqueous contamination (e.g., water sampling), soil and geologic structure (e.g., ground penetrating radar, electromagnetics), and groundwater/surface-water exchange (e.g., thermal infrared). More exhaustive lists of the contributing National Laboratories' capabilities, drone models, sensor payloads, and example applications are provided in Appendices A through Appendix F, which are a compilation of the National Laboratories' individual responses to a capabilities questionnaire (Appendix G).

Table 2. Summary of National Laboratory capabilities and platform types.

Laboratory	Sensor Capabilities	Platform types
Sandia National Laboratories	Gamma detection; magnetometer, air sampling; gas sampling; LIDAR; photogrammetry; intelligence, surveillance and reconnaissance (ISR) payloads	UAS (including rotary, jets, balloons, VTOL), ground (tracked, quadruped, wheeled)
Los Alamos National Laboratory	Gamma detection; magnetometer, air sampling; gas sampling; LIDAR, photogrammetry; ground penetrating radar; multispectral	UAS (including rotary, VTOL and fixed wing)
Lawrence Berkeley National Laboratory	Lidar; hyperspectral; magnetometer; EM sensor; infrared; RBG cameras	UAS
Lawrence Livermore National Laboratory	Magnetometer; ground penetrating radar; hyperspectral imaging; methane detection; spectrometers	UAS
Savannah River National Laboratory	LIDAR; sprayers (for herbicide)	UAS (rotary)
Pacific Northwest National Laboratory	Radiation; LIDAR; electro-optical (EO)/IR imaging; multi-spectral imaging; radiation mapping; radionuclide particulate detection/collection; gas sampling, water sampling; ground debris sampling; electromagnetic geophysical surveys	UAS (including rotary, jets, VTOL), ground robots

Appendix A. Laboratory Capabilities: Sandia National Laboratories

Sandia National Laboratories	
Drone Fleet Summary	
Summary	Sandia's UAS Aviation Operations Unit (UAOU) was established in 2019 to be the single entity at Sandia conducting UAS Ops in support of all the labs Uncrewed Aircraft Systems (UAS) activities. The UAOU currently consists of more than 330 FAA Registered UAS with a large variety of primarily Class 1&2 UAS: fixed wing (> 90), multi-rotor (> 230), hybrids, Vertical Take-Off and Landings (VTOLs), jets, and balloons. Many are threat vehicles for testing Counter-UAS (CUAS), with the remainder in support of many UAS projects across Sandia often with custom payload needs. The team has ~15 primary pilots of the ~60 Federal Aviation Administration (FAA) Certified Remote Pilots. The team conducts testing at many test locations, including Outside the Continental United States (OCONUS). In FY24, the team flew at 41 unique test locations across 5 states. We support the National Nuclear Security Administration (NNSA) Nuclear Emergency Support Team (NEST) Radiological Assistance Program Area 4 (RAP4) area including in support of 3 real-world call outs and other training events in FY24. FY24 resulted in 140.5 hours of flight time for 1,139 flights with flight events occurring during 43 of the 52 weeks. Sandia was awarded the 2024 DOE Federal Aviation Safety Program Award. FY24 Testing-centric Mission Types: • CUAS detection (red teaming, radio frequency (RF) characterization, research and development (R&D)) • CUAS mitigation (R&D, net, kinetic, energetic, RF, small arms, etc.) FY24 Sensing-centric Mission Types: • Custom payload development • Custom sensor dart drops/tests • Air Sampling • Magnetometer • CUAS RF characterization • Data/imagery collection • Radiological sensing • Ordinance debris detection • Buried debris detection • UAS threat intrusion detection
Primary point(s) of contact	Kristopher Klingler, Manager Mobile Robotics Research Development Testing and Evaluation (RDT&E) krkling@sandia.gov; (505)369-9058
Core competencies	• Formal testing and characterization of UAS and CUAS • UAS platform and payload R&D, to include kinetic intercept and explosives

	• UAS design and modification to meet unique sponsor requirements across a broad set of government sponsors • Custom sensor, controls, and algorithm development • Real-world Uncrewed Air/Ground/Other (UxS) support including tools for bomb squads, NEST/RAP
Sensors/Detectors	
Sensor name	Radiation Detector, LIDAR, Cameras
Make/model	FlyAbility ELIOS 3
Platform	Air, First Person View (FPV)
Information provided	Utilized in support of Nuclear Emergency Response Team (NEST) Radiological Assistance Program Area 4 (RAP4) support to collect radiation levels, LIDAR, and live video. The 3D LIDAR and radiation measurements are combined to visualize volumetric radiation levels. Other applications have included DOE-EM Waste Isolation Pilot Plant (WIPP) underground 3D LIDAR and sampling.
TRL	TRL-8
References	See Figure A-1
Sensor name	Radiation Detector, Cameras
Make/model	Boston Dynamics Spot Robot Quadruped
Platform	Ground (extreme terrain), Mine
Information provided	Utilized in support of Nuclear Emergency Response Team (NEST) Radiological Assistance Program Area 4 (RAP4) to access the area, enable communications relays and provide live video. Other quadrupeds include Ghost Robotics.
TRL	TRL-8
References	See Figure A-2
Sensor name	Cameras
Make/model	Sandia Custom M2 Mighty Mouse, ~2' x 2' x 5', > 200 lbs
Platform	Custom tracked vehicle build for Explosive Ordinance Disposal (EoD) able to climb stairs. Has a 6 Degree of Freedom (DoF) arm with ~6' reach, high dexterity and precise user control, quick tool swap to standard construction tools.
Information provided	Significant utilization in EoD and real-world recovery of stuck radiological sources recovery.
TRL	TRL-8
Sensor name	Cameras, 3D scanning
Make/model	Skydio X2 and Skydio X10
Platform	Air, Mine
Information provided	Utilized in DOE-EM WIPP surface ops. Able to create 3D site reconstruction.

TRL	TRL-8
Sensor name	Air sampling, cameras
Make/model	Warthog
Platform	Ground
Information provided	Platform includes a robotic arm capable of traversing extreme terrain. Utilized in DOE-EM WIPP underground ops.
TRL	TRL-8
Sensor name	Intelligence, Surveillance, and Reconnaissance (ISR), Payloads
Make/model	Sandia Custom NightDawg
Platform	1/4 Scale Rock Crawler. A ground up design for Department of Defense (DoD) applications requiring traversing extreme terrain.
Information provided	Use cases include persistent ISR, payload delivery, comms repeater, live video, and modular radio and payload for many use cases.
TRL	TRL-7
References	See Figure A-3
Sensor name	Persistent ISR Camera Payload
Make/model	Sandia Custom Tethered UAS
Platform	Active tether to enable extended time on station with power up and high-bandwidth video/signal down the tether.
Information provided	Designed for use on moving vehicles and/or a maritime vessel under non-calm sea states.
TRL	TRL-7
References	See Figure A-4
Sensor name	Gas sensing, camera
Make/model	Sandia Custom Gemini Scout and Gamma Platforms
Platform	2 body, 4 track, 4' x 2' x 2' 190 lbs
Information provided	Designed for extreme mine environments requiring zero-spark emissions. Extremely capable vehicle in water/mud terrestrial environments. Outfitted with pay-out signal fiber for comms.
TRL	TRL-7
References	See Figures A-5 and A-6
Sensor name	Camera, small payload
Make/model	Sandia Custom Hopper --> Boston Dynamics Sand Flea

Platform	~10 lbs, 4-wheeled vehicle capable of > 20 jumps as high as 2 story building with accuracy to enter an open window.
Information provided	Capability tech transferred to Boston Dynamics as Sand Flea. Unique mobility for custom applications.
TRL	TRL-8
References	See Figure A-7
Sensor name	Camera
Make/model	Sandia Custom Self-propelled Interior Inspection of Networks of Pipes (SPIINe)
Platform	2-3" diameter pipe inspector
TRL	TRL-5
Sensor name	Various
Make/model	Sandia Custom Arial Manipulation
Platform	3-DOF arm able to draw on surface and pull a suitcase on the floor
Information provided	Demonstrator of UAS plus manipulator controls RDT&E
TRL	TRL-4
References	See Figure A-8
Sensor name	Varies
Make/model	(Many Additional)
Platform	Varies
Information provided	Sandia has a very broad set of UAS activities beyond ops specific to include payload development, counter UxS, UxS characterization, UAS/CUAS RDT&E, arial photography, etc. Sandia's ground robotics program has been ongoing formally for >40 years with a very broad set of unattended ground sensors (UGS) capabilities beyond ops specific to include platform and payload RDT&E, counter UxS, RDT&E, etc. Most programs are modifying or design/build custom application platforms, controls, sensing, and autonomy specific to mission need.
References	See Figures A-9 through A-11

Figure A- 1. Elios

Figure A- 2. Ghost Robotics (front) and Boston Dynamics Spot Robot (back)

Figure A- 3. NightDawg

Figure A- 4. Sandia Tethered UAS

Figure A- 5. Gemini Scout

Figure A- 6. GAMMA actively articulated, dual-body, highly mobile platform

Figure A- 7. Sandia Hopper (left), Boston Dynamics Sand Flea (right)

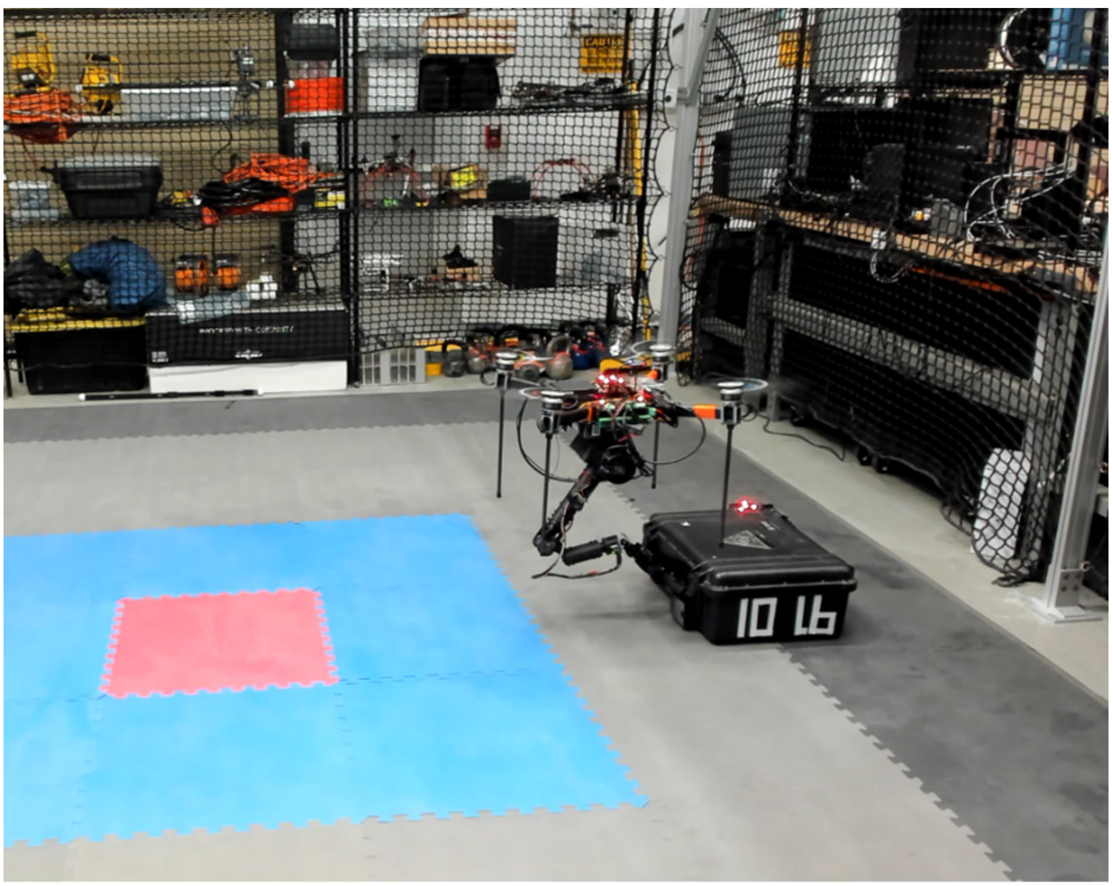

Figure A- 8. UAS Arial Manipulation pulling a 10lb Pelican case while in flight

Figure A- 9. Sandia UAS/CUAS Lab

Figure A- 10. CUAS testing at Nevada National Security Site (NNSS)

Figure A- 11. Some of Sandia's UGS platforms

Appendix B. Laboratory Capabilities: Los Alamos National Laboratory

Los Alamos National Laboratory (LANL)	
Drone Fleet Summary	
Summary	The Earth and Environmental Sciences (EES) UAS Team utilizes 7 different platforms for our operations. This includes a small trainer drone, 1 light duty drone, 2 heavy lift drones, and 3 vertical take-off and landing fixed wing drones. We deploy a variety of instruments on these platforms including 3 different magnetometers, 2 models of RGB (red/green/blue) cameras, 2 thermal sensors, a lidar sensor, 2 models of gamma spectrometers, a multi-spectral imager, and trace gas sensors. Most sensors are commercial off-the-shelf (COTS) but have been adapted for integration onto UAS platforms and computational system and analytical procedures developed to achieve project goals. The EES UAS team supports R&D efforts across DOE mission space, including national security, environmental research, agricultural, and fossil energy and carbon management. We have a team of approximately 10 people composed of several UAS pilots and specialists in different sensors to deliver custom solutions for difficult projects. Ground-based Robotic Systems: LANL develops, deploys, and operates ground-based robotic systems across multiple directorates in support of both mission-driven operations and research and development. These efforts span robotic platform development, autonomy and control software, sensor and payload integration, and the application of robotic systems to novel tasks and operational environments relevant to national security and laboratory missions. At LANL, ground-based robotic systems are used to support quality control and quality assurance in manufacturing processes, facility surveying and mapping during construction and modification activities, radiation safety monitoring and vehicle confinement verification, material inventory validation, and the enhancement of safety, efficiency, and effectiveness in environmental remediation operations.
Primary point(s) of contact	Damien Milazzo, dmilazzo@lanl.gov
Core competencies	• Gamma detection • Magnetometry Surveys • Trace gas and plume survey • Photogrammetry • LiDAR
Sensors/Detectors	
Sensor name	Gamma Spectrometer
Make/model	Imitec/Kromek RIAS; LANL Lighthouse

Platform	Aerial / Ground
Information provided	The Lighthouse detector was developed in collaboration between LANL and Quaesta Instrument. The Kromek is a COTS device while the LANL Lighthouse is a TRL-9 product. Integration of these sensors onto UAS are lower TRL. These systems have supported small-scale identification (1 km x 1km) and quantification of waste sites within New Mexico. The Lighthouse detector has been used for larger scale deployments in an underwater environment.
TRL	Sensor: TRL-9 UAS integration: TRL 5-7
Sensor name	DSLR Cameras
Make/model	Various. Gremsy T7 Gimbal
Platform	Aerial.
Information provided	General purpose of building high-precision digital elevation models and detection of changes to surface features. Developed workflows to measure centimeter-scale changes in topography which have been applied to characterizing subsidence in different rock types following underground detonations.
TRL	Sensor: TRL-9 UAS Integration: TRL-9
References	https://doi.org/10.1007/s00024-017-1649-0; https://doi.org/10.1016/j.rse.2020.111871; https://doi.org/10.3390/drones5020025;
Sensor name	Magnetometers
Make/model	Geometrics MagArrow; Sensys R3;
Platform	Aerial
Information provided	The MagArrow measures magnetic total field while the Sensys mag sensors are fluxgate sensors and measure the principal components of the magnetic field (x,y,z). These sensors have been used for detection of subsurface tunnels, surface features, and oil and gas infrastructure. They have sampling frequencies in the hundreds to thousands of hz and resolution in the single nanoTesla range. We field commercial versions of these sensors but have also integrated these sensors into custom payloads for our specific platforms. The team has fielded these instruments for characterizing and comparing their performance in detecting different types of objects while integrated into different UAS platforms.
TRL	Sensor: TRL-8 UAS Integration: TRL-6
References	https://doi.org/10.1021/acs.est.4c02069;

	U.S. DOE, ``Geophysical surveys and emissions quantification to detect and characterize undocumented oil and gas wells, Osage County, Oklahoma'' *US DOE* (2024).
Sensor name	LiDAR
Make/model	Routescene Unmanned Aerial Vehicle (UAV) LiDAR System / Routescene
Platform	Aerial/ground/platform and brief manufacturer details if pertinent
Information provided	Digital elevation models and detection of changes to surface features. While commercial software exists to integrate readings from UAS sweeps, we have developed solutions to improve precision and reliability of the sensors by addressing challenges in measuring the same objects from different perspectives that cause location uncertainties.
TRL	Sensor: TRL-9 UAS Integration: TRL 7
References	https://doi.org/10.5194/isprs-archives-XLIV-M-2-2020-1-2020; https://doi.org/10.3390/drones5020025 https://doi.org/10.14358/PERS.21-00058R2; https://doi.org/10.48550/arXiv.2202.13501
Sensor name	Infrared (IR) imaging
Make/model	FLIR Duo Pro R
Platform	Aerial
Information provided	This sensor has been developed for by the EES UAS team to upscale resolution to create superimages of landscapes. At NNSS, the superimage products have been used to identify changes in thermal emissivity within the scene due to objects of approximately 1 pixel size. For other customers, the IR imager to identify areas of near-surface groundwater.
TRL	Sensor: TRL-9 UAS Integration: TRL 7
Sensor name	Trace Gas Sensors
Make/model	Aeris MIRA Pico CH4|C2H6 Spectrometer; Aeris MIRA Ultra C1-3 Spectrometer; Aeris MIRA Strato CH4|C2H6 Spectrometer; Aeris PICO N2O|CO Spectrometer
Platform	The platforms can be deployed both in the air or on the ground.
Information provided	Plume detection and quantification systems have been developed at LANL and are comprised of trace gas and meteorological sensors and R&D analytical packages. Currently, the trace gas sensors measure methane, ethane, carbon dioxide, carbon monoxide, nitrous oxide, and water vapor. This system has been used to find leaking oil and gas infrastructure and determine their leak rates by detecting gaseous effluents and using alkane-ratios and local-scale atmospheric transport models for attribution.

TRL	Sensors: TRL-9 UAV integration/deployment: TRL 6
References	U.S. DOE, ``Geophysical surveys and emissions quantification to detect and characterize undocumented oil and gas wells, Osage County, Oklahoma" *US DOE* (2024).

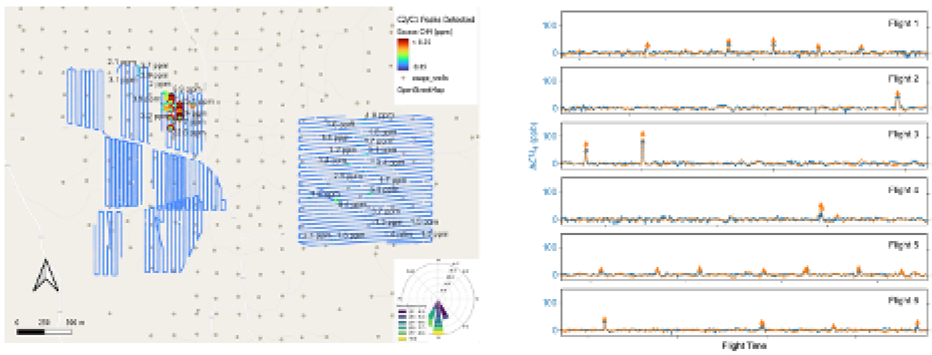

Figure B- 1. Plume Detection and Localization: UASs were deployed with gas and wind sensors to find plumes and attribute and localize their sources. In this case, we deployed an infrared absorption spectrometer to measure methane and ethane concentrations to identify leaking infrastructure in a 2 square mile area of an oil-and-gas field.

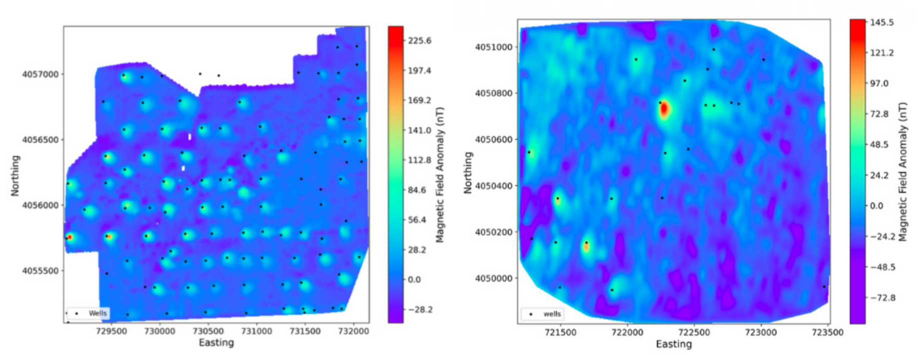

Figure B- 2. Magnetic Surveys to Inventory Infrastructure: The ability of various combinations of magnetic sensors and UAS platforms were tested for inventorying infrastructure in an oil-and-gas field. A conventional, rotary UAS surveyed 2.1 sq miles over 24 flights and 2 days of deployment (left). In comparison, a fixed wing drone surveyed 1.8 sq miles of area in a single, 45 minute flight (right), but requires higher flight altitudes and coarser flight patterns. A custom python package was developed and published to process the magnetometry data. On-going work at LANL is using AI to define signatures of different types of infrastructure within the survey areas.

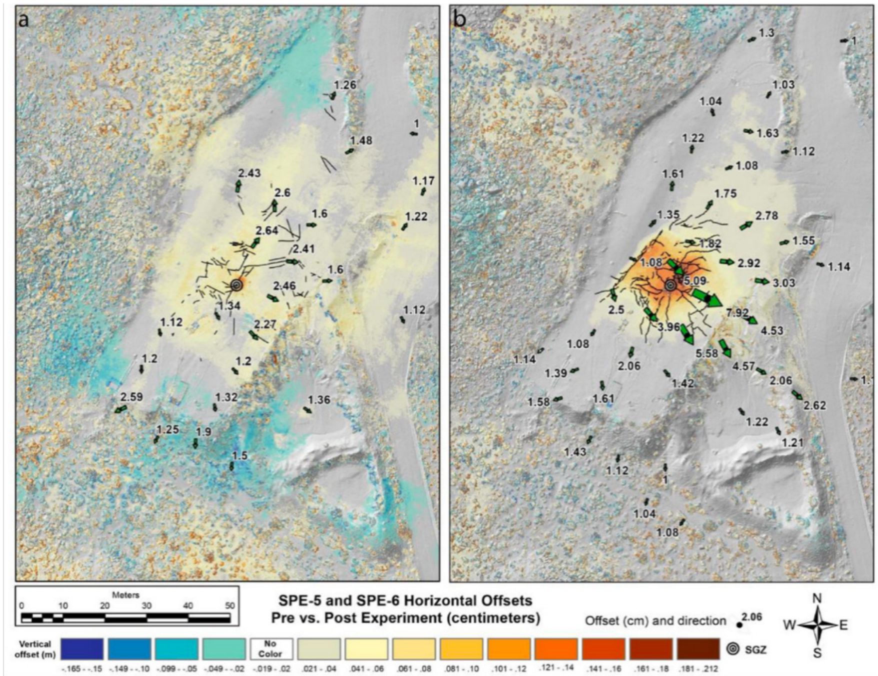

Figure B- 3. Digital Elevation Models: Cameras were deployed on rotary UAS platforms to detect subtle changes in topography. In this figure, we show the surface expression of two underground detonation experiments. These changes are calculated as the difference from photogrammetric digital elevation models constructed before and after the experiments. This figure originally published in Schultz et al (2020, https://doi.org/10.1016/j.rse.2020.111871).

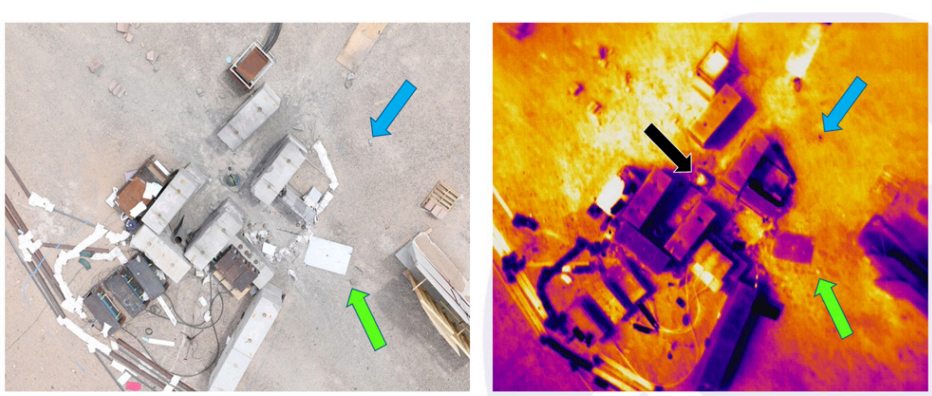

Figure B- 4. IR Heat and Reflectance: Cameras with infrared capability can locate hot objects that are difficult to observe in traditional RGB imagery. Here, IR cameras were flown on a rotary UAS to map

the dispersal of metal fragments following a detonation performed at NNSS. Several objects are highlighted in the RGB imagery (left) and IR imagery (right).

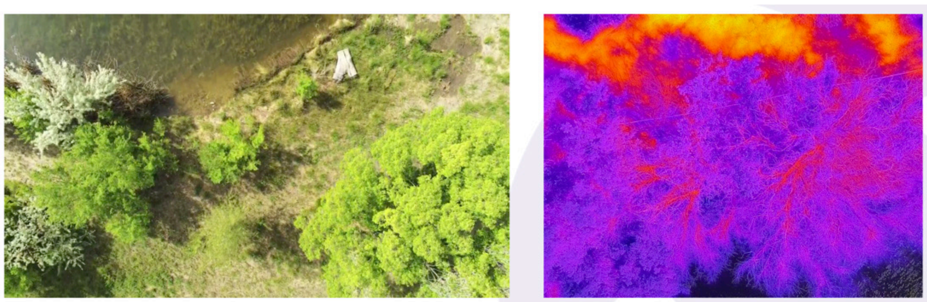

Figure B- 5. IR Heat and Reflectance: Agricultural microclimates were assessed through IR imagery collected from a small UAS to support local orchards. This imagery was used to assess thermal stress on crops from frost and to engineer predictive crop and agricultural yield protection systems.

Appendix C. Laboratory Capabilities: Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory (LLNL)	
Drone Fleet Summary	
Summary	LLNL is working on several different UAS applications areas, our primary focus is developing a ground penetrating radar (GPR) system for buried threat detection for our DOD customers. We also support the DOE Consortium Advancing Technology for Assessment of Lost Oil & Gas Wells (CATALOG) program where we are using a variety of sensors to locate and characterize undocumented orphaned wells. We also support other customers for infrastructure and border security applications. We are also developing control algorithms for swarming capability. LLNL has an FAA certificate of authorization (COA) that allows us to operate up to 100 drones per single operator on the main LLNL campus. LLNL develops both the sensor and drone platforms for these applications and currently has over 100+ drones and 12+ FAA PART 107 pilots.
Primary point(s) of contact	Jaisree Iyer, iyer5@llnl.gov Jacob Trueblood, trueblood4@llnl.gov
Core competencies	• Magnetometer and other sensors to detect oil and gas wells. • Spectrometers to detect emissions from oil and gas infrastructure • Ground Penetrating Radar to detect buried threats
Sensors/Detectors	
Sensor name	Magnetometer
Make/model	Sensys MagDroneR4
Platform	Aerial on Inspired Flight Drones
Information provided	Sensor measures the total field magnetic above vertical steel well casing. Steel cased wells appear as positive magnetic monopole anomalies in the magnetic flux measured by the sensor.
TRL	7 or more
References	https://sensysmagnetometer.com/products/magdrone-r4-magnetometer-for-drone/
Sensor name	Artificial intelligence (AI) based processing of UAV Magnetometer data
Make/model	You Only Look Once (YOLO) based AI model
Platform	AI based framework for automated processing of aerial or ground-based magnetometer surveys
Information provided	The AI based model automatically detects the presence of steel cased wells from large magnetometers surveys thereby reducing manual processing. Post detection, the magnetic flux measurement for each well can be used to infer buried depth and other characteristic of the well.
TRL	3 – 5

References	Being written for publication
Sensor name	GPR – LLNL Mirage GPR
Make/model	LLNL
Platform	Aerial and ground, aerial platforms are made by LLNL with GPR payload integrated into the drone design. LLNL drone with radar is under 20 lbs and 40 mins flight time. Ground systems can be mounted on vehicles like a Polaris Ranger or John Deere Gator.
Information provided	LLNL in house developed GPR, multistatic ultra-wide band, provides real time tomographic image of subsurface. Used for buried threat detection and utility localization
TRL	TRL 6
References	https://ipo.llnl.gov/technologies/national-security-and-defense/ground-based-gpr-ground-penetrating-radar-buried-hazard https://ipo.llnl.gov/technologies/national-security-and-defense/drone-based-ground-penetrating-radar-array
Sensor name	GPR – pulseEKKO
Make/model	Sensors and Software
Platform	Aerial – LLNL custom heavy lift drone < 55 lbs
Information provided	Monostatic – have antenna pairs for 250 MHz, 500 MHz, and 1000 MHz. The 250 MHz are only used on ground cart due to size and weight.
TRL	TRL 7
References	https://www.sensoft.ca/products/pulseekkopro/overview-pulseekko/
Sensor name	Methane (CH4) Tunable diode laser absorption spectroscopy (TLDAS) – tunable laser diode absorption spectrometer
Make/model	Purway
Platform	Aerial
Information provided	TLDAS tuned for CH4. From flight tests can detect ~200 g/hr methane release from 30 m altitude at 20 mph flight speeds.
TRL	TRL 6
References	https://purway-innovate.com/uav-ch-4-laser-methane-leak-detector-model-2
Sensor name	Aeries Strato Spectrometer
Make/model	Aeries
Platform	Aerial & Ground
Information provided	Closed cell spectrometer for CH4, thane (C2H6), and water (H2O)
TRL	TRL 6

References	https://aerissensors.com/strato/
Sensor name	Ultris X20 Pluse his
Make/model	Cubert
Platform	Aerial
Information provided	Hyper spectral camera between 350-1000 nm, 164 bands. Light field technology, figure below illustrates sensor/filter setup for light field. For each spectral band you get a 400 x 400 pixel image
TRL	TRL 6
References	https://cubert-hyperspectral.com/en/ultris-x20-plus/

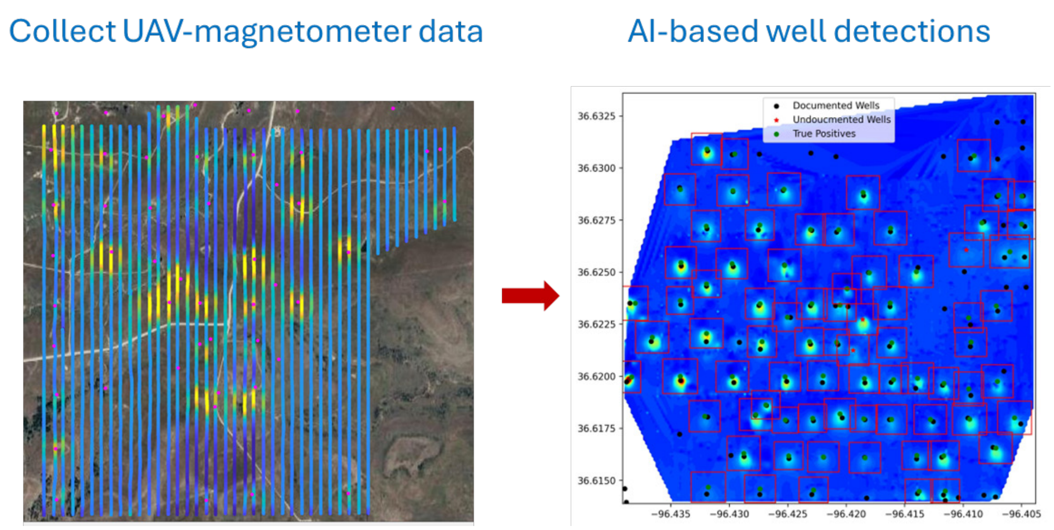

Figure C- 1. LLNL's capability of collecting UAV-based magnetometer and associated AI based pipeline to automate its processing to detect wells

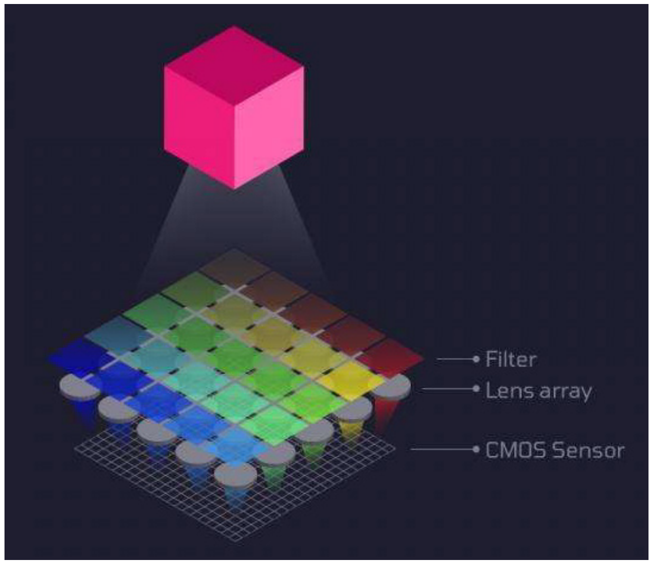

Figure C- 2. Sensor field setup for light field technology used by Ultris X20 Pluse HSI

Appendix D. Laboratory Capabilities: Savannah River National Laboratory

Savannah River National Laboratory (SRNL)	
Drone Fleet Summary	
Summary	The SRNL UAS Program currently has fifteen UAS aircraft (rotary and fixed-wing) in its fleet and four FAA Part 107 certified pilots. Types of missions include: R&D activities for Government teams and equipment (Light Detection and Ranging (LiDAR), sensors, etc.), application of herbicide to rooftops with a UAS, training, virtual tours and inspections of waste units for Site and environmental regulators, infrastructure inspections (rooftop inspections, facility inspections, etc.), and general aerial photography and videography.
Primary point(s) of contact	Troy Lorier, troy.lorier@srnl.doe.gov, (803) 645-2193
Core competencies	• UAS payload research and development (R&D) • LiDAR surveys, general aerial photography/videography • Testing and training with other government agencies (OGAs)
Sensors/Detectors	
Sensor name	LiDAR
Make/model	YellowScan Mapper+
Platform	LiDAR is remote sensing technology that uses laser light to create high-resolution 3D models of objects and environments (Figures D-1 and D-2)
Information provided	Creates topographic mapping information (detailed terrain information), creates elevation models, and good for environmental monitoring.
TRL	9
References	www.yellowscan.com/products/mapper-plus/
Sensor name	Sprayer
Make/model	Custom-built in UAS lab
Platform	Hexacopter, ~72” diameter, tank holds ~3 gallons
Information provided	Sprayer UAS is used to dispense herbicide on reactor rooftops that contain unwanted vegetation
TRL	8

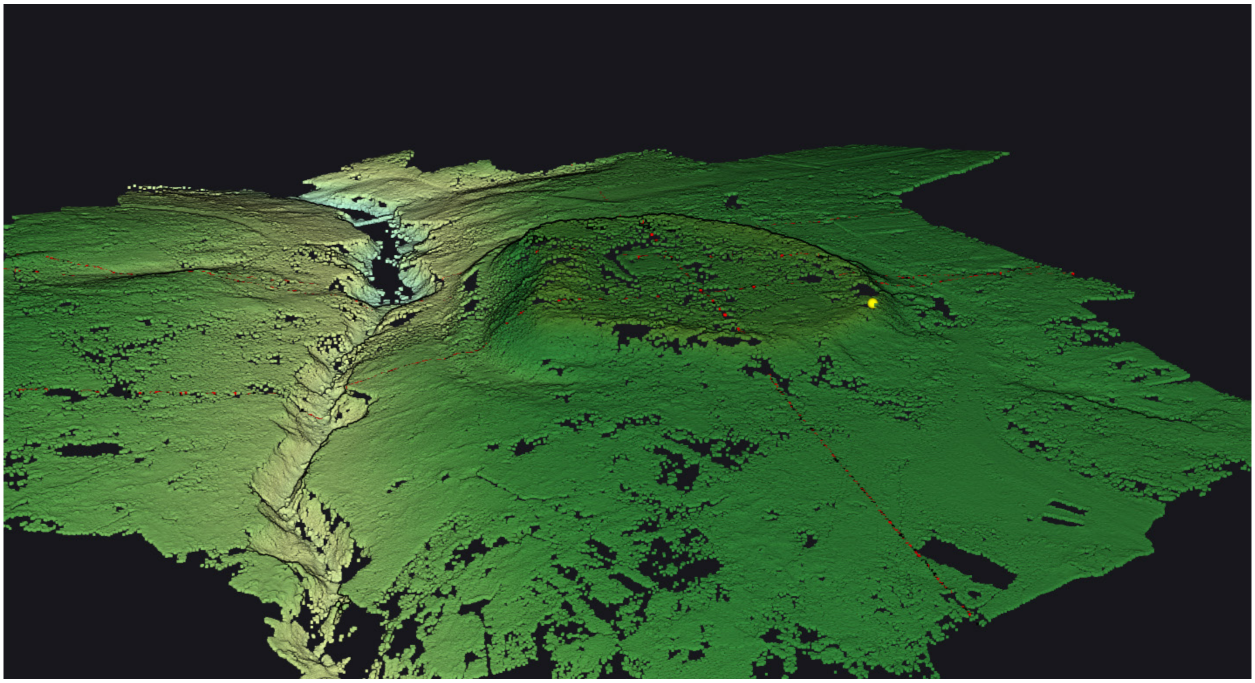

Figure D- 1. LiDAR survey, example 1

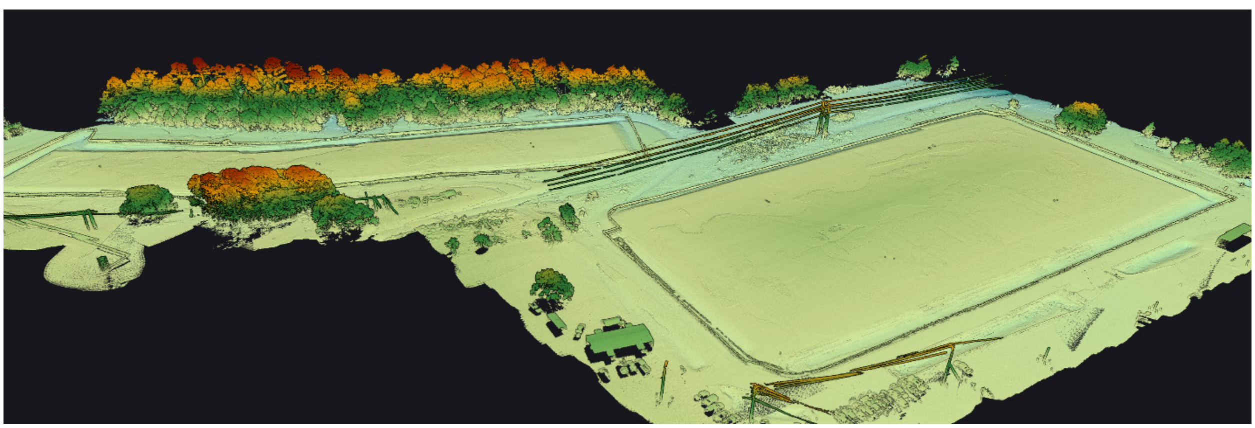

Figure D- 2. LiDAR survey, example 2

Appendix E. Laboratory Capabilities: Pacific Northwest National Laboratory

Pacific Northwest National Laboratory	
Drone Fleet Summary – July 2025	
Summary	The PNNL Robotics and Autonomous Systems Laboratory (RASL) operates 25 small UAS in support of national security, environmental, and physical science studies. Payload capacities range from 1 to over 25 pounds. PNNL draws on experienced experts in autonomous systems to engineer, program, and integrate advanced science payloads on UAS to achieve cutting edge results in environmental characterization surveys and other missions. Sensors and environmental sample collection experience includes; electro-optical (EO)/IR imaging, multi-spectral imaging, aerial radiation mapping, aerial radionuclide particulate detection and collection, aerial chemical detection and sample collection, whole air sampling, ground debris sampling, water sampling, marine transducer placement, radar reflective payloads, edge computing payloads, object recognition on the edge, live streaming communications to the cloud, advanced communication relays, satellite communication and control links, co-robotic operations with ground and marine assets, tethered aerial operations, subsurface imaging payloads, and autonomous 3-D surface model generation. PNNL RASL staff also develop and operate ground-based and marine autonomous systems.
Primary point(s) of contact	John E. "JES" Smart; je.smart@pnnl.gov Office: 509-375-1989
Core competencies	• DOE and FAA compliant professional UAS flight operations • Development and integration of unique sensors and sample collection payloads of every variety in any venue. • Development of autonomous and cooperative robotics involving AI/machine learning (ML) guided operations.
Sensors/Detectors [See image gallery below]	
Sensor name	**Drone based frequency-domain electromagnetic ground conductivity sensor**
Make/model	PNNL Laboratory Development
Platform	"Aurelia X-8 MAX" Octocopter – Remote Controlled UAS
Information provided	This PNNL developed drone-based frequency-domain electromagnetic ground conductivity sensor and associated software uses transmitter and receiver units with no wired connection between them, allowing for deployment on two or more drones. Rich datasets with enhanced sensitivity to 3D subsurface heterogeneity can be acquired. Inversions in 1D are done in real-time using a new machine learning algorithm. Data and models are sent to the cloud immediately, where they can be viewed by remote users through a web interface.

TRL	5-6
References	• Bowles-Martinez E.J., M.S. Taubman, P. Jaysaval, P.D. Royer, A.S. Sinkov, J.E. Smart, and E.D. Shapiro, et al. "New drone-based electromagnetic instrumentation and AI-based processing for rapid subsurface characterization and monitoring for critical-mineral and environmental applications." In internal review for submission to *The Leading Edge* • Matthew Taubman, Anton Sinkov, Esteban Bowles-Martinez, Luke Placzek, Lisa Newburn, Amoret Bunn, John Smart, Frederick Day-Lewis. August 2024. *Modular Subsurface Sensors and Integrated Software for Advanced Subsurface Characterization and Monitoring using Unoccupied Vehicles*. PNNL-36436. Richland, WA: Pacific Northwest National Laboratory. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-36436.pdf
Sensor name	**Radiation Detectors and Sampling Devices**
Make/model	Various customized detector implementations developed at PNNL
Platforms	Multirotor UAS, Fixed Wing UAS, and Ground Based Robots
Information provided	Gamma, Beta, and Neutron Radiation can be detected using a number of COTS and government off the shelf (GOTS) sensors. Ground-level Dose Rates of concern to human health can be mapped. Some implementations will provide spectroscopy information for isotope identification. Other implementations provide near real-time dose rate from airborne or waterborne radionuclides.
TRL	5-6
References	• Bunn A.L., K.A. Wagner, D.K. Fagan, H. Gadey, T.A. Ikenberry, K.E. Markham, and M.Y. Obiri. 2022. *Drones for Decommissioning*. PNNL-32519 Rev. 1. Richland, WA: Pacific Northwest National Laboratory. Available at: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32519Rev1.pdf and at the NRC site: https://www.nrc.gov/docs/ML2219/ML22196A040.pdf • Overview of NRC project: https://www.pnnl.gov/news-media/drones-fly-low-and-slow-radiation-detection?utm_campaign=Web%20Feature&utm_medium=email&_hsmi=258908541&_hsenc=p2ANqtz-90sRKd1_QIBrEJ09G_pNkjFQYLmgBAT8Lea_g_337FKAnW7xyiiWEV6Ok2WJSF1lpXCfSYTM-zwZL-skJoToFV6WolEA&utm_content=258908541&utm_source=hs_email • Bunn A.L., K.A. Wagner, D.K. Fagan, H. Gadey, T.A. Ikenberry, K.E. Markham, and M.Y. Obiri. 11/16/2023. "Comparison of UAV and Human Surveys for Decommissioning." Presented by A.L. Bunn at RemPlex, Richland, Washington. PNNL-SA-186475. Available at:

	https://www.pnnl.gov/sites/default/files/2023-11/Remplex%20Submission%2058%20%20437.pdf • Smart J.E., Metz L.A, et al "*Fast Retrieval of Ground Samples*." PNNL-32041. Richland, WA: Pacific Northwest National Laboratory.
Sensor name	**Edge Computing with AI/ML**
Make/model	PNNL developed routines that employ NVIDIA and other high performance processor brands.
Platforms	Several models of Airborne, Ground, and Marine Based Autonomous Vehicles capable of carrying more than 5 pounds of payload
Information provided	AI/ML applications can provide object recognition and allow vehicles to "self-navigate" to achieve desired missions.
TRL	3-5
References	• https://www.pnnl.gov/projects/cloud-high-performance-computing-and-edge-science-and-security/project-thrusts • https://www.pnnl.gov/adaptive-autonomous-systems

Figure E- 1. PNNL UAS capable of transitioning from VTOL to horizontal fixed wing flight. This embodiment can transport samples from the field to locations where sample analysis can be conducted. Other payloads include ground sample collections and wide area radiation detection sensors.

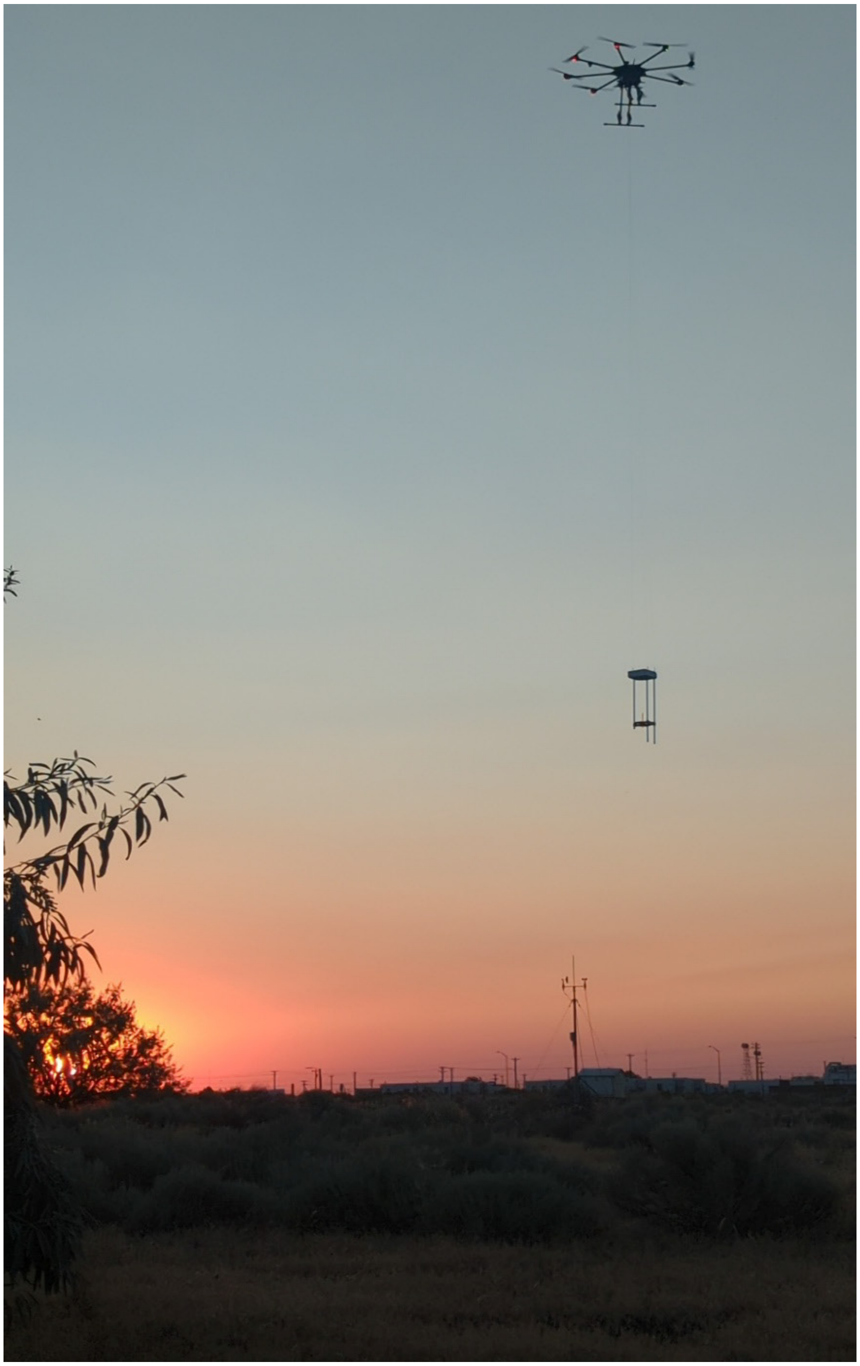

Figure E- 2. PNNL "X-8" Octocopter carries a custom-built sub-surface imaging payload suspended several meters below the vehicle

Figure E- 3. PNNL "Alta-X" quad copter capable of carrying 10 pounds of payload for over 30 minutes (or up to 35 pounds for about 11 minutes) is shown performing AI/ML augmented object recognition with onboard edge computing resources

Figure E- 4. A PNNL training drone is flown by students to gain skills required to become PNNL Certified UAS Pilots. Pilots at PNNL are trained and certified by instructors on each airframe that they fly. The PNNL Remote and Autonomous Systems Lab operates several of these small drones and makes them available to projects with payloads under two pounds. PNNL has procedures that allow multiple drones to fly simultaneously in the same general airspace.

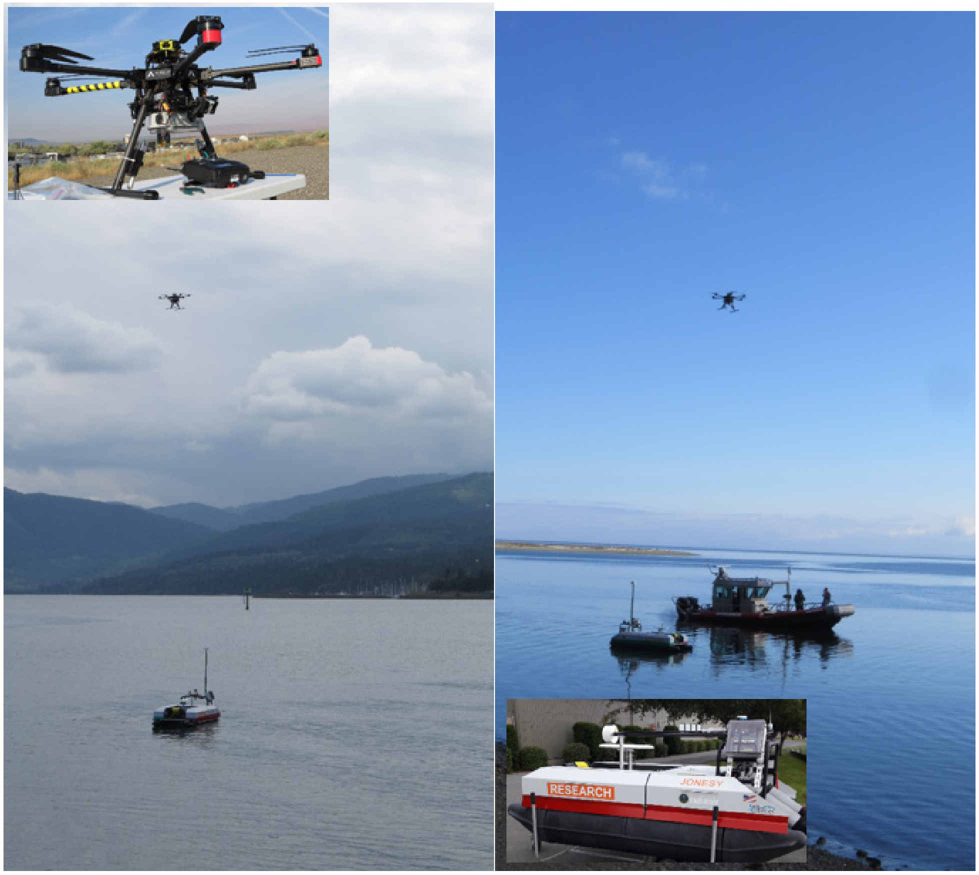

Figure E- 5. PNNL Operates surface and underwater autonomous systems at the PNNL Marine Science Laboratory located on the shore of Sequim Bay, WA. The images show one of our "X6" hexacopters interacting with an Unmanned Surface Vehicle (left) and the manned vessel (right) during a demonstration of autonomous collaborative behavior and communications capabilities. Inset images show the multirotor "X-6" UAS and the Autonomous Surface Vehicle.

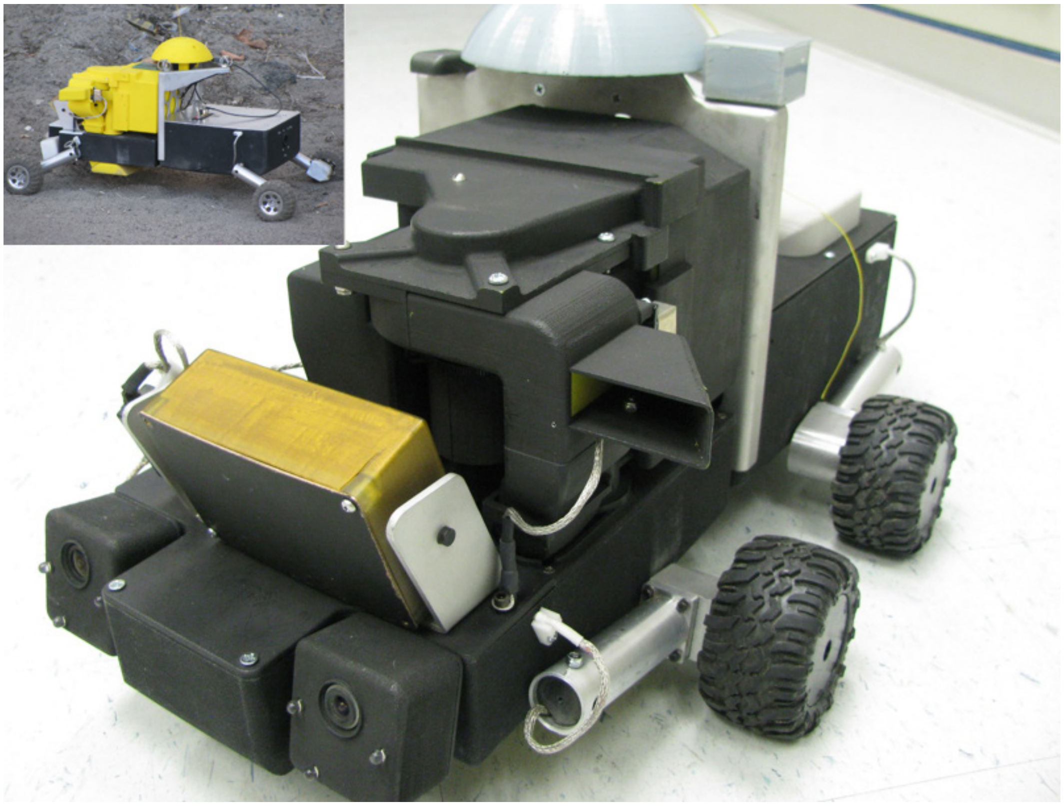

Figure E- 6. One of many PNNL developed "co-robots" designed for deployment by Unmanned Airborne Systems winch lines. This vehicle features stereo cameras, radiation detection, ground sample collection, and onboard computing and communications capabilities. This type of vehicle can be delivered and retrieved by PNNL UAS to accomplish remote high fidelity ground characterization missions that are difficult for humans to access.

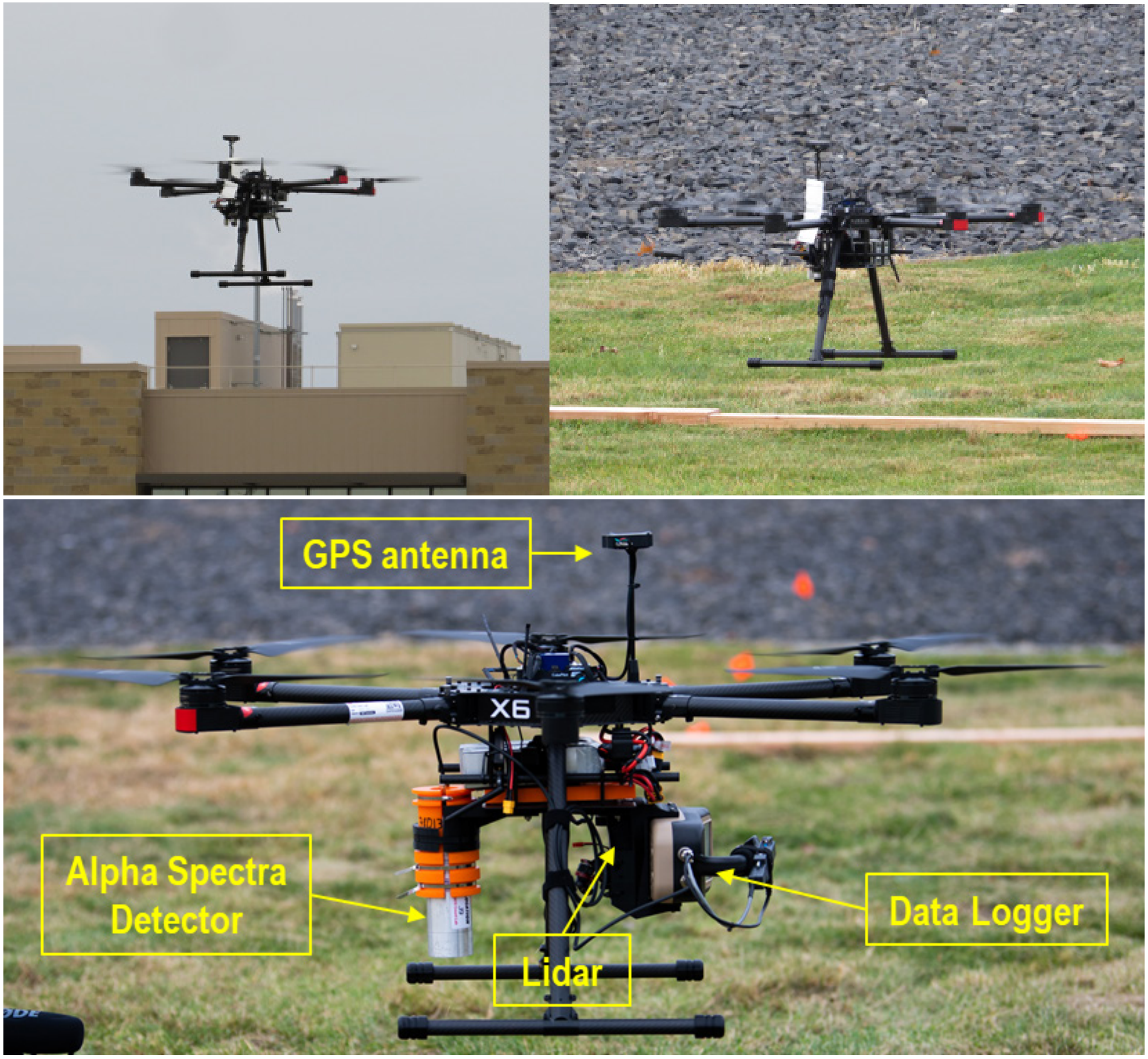

Figure E- 7. Above - PNNL "X-6" multirotor UAS exercises low altitude control and (below) carries a sodium iodide radiation detection sensor to survey sources on the ground

Figure E- 8. A small "Skydio S2" drone with a gimbaled 4K HD camera collects video imagery of a new PNNL building interior

Figure E- 9. 3D photogrammetry video of a paint ball course generated by the PNNL "Skydio S2" drone

Figure E- 10. PNNL flies the FLIR 30Hz "Duo Pro R" - Electro Optic / Infrared camera mounted on a "Gremsy S1" gimbal system on the "X-6" multirotor UAS

Figure E- 11. PNNL X-6 UAS attached to the "Blue Vigil" powered tether system. This allows the UAS to stay aloft indefinitely while powered by the ground-based power source

Figure E- 12. PNNL "Harris Carrier H6 Electric" UAS is equipped with the "Phoenix miniRanger" LIDAR and Camera system. The H6 will lift a 17.6 pound (8 kg) payload and will fly for 48 minutes when empty.

Figure E- 13. PNNL "Boxbotix" 3-D printed drone with insulated radiation detection sensor payload (top left inset image)

Appendix F. Laboratory Capabilities: Lawrence Berkeley National Laboratory

Lawrence Berkeley National Laboratory	
Drone Fleet Summary	
Summary	LBNL geophysics team owns multiple electrical, and hybrid Blue UAS certified drones capable of 20+ lbs payload, up to 3 hours of single flight time, and 20+km radio link range. Routine payloads include Lidar, hyperspectral camera (350 – 1000nm with 160+ bands), magnetometer, EM sensor, infrared and RBG cameras with full gimbal functionality. The system is used for critical minerals and orphaned wells research, as well as general inspection and survey in infrastructure, geographic, and geological studies. The LBNL applied nuclear physics (ANP) program owns several electrical drones and ground robots and has coupled radiation and contextual sensing payloads with those platforms as well as the LBNL geophysics teams' drones. The ANP payloads are called radiological Localization and Mapping Platforms (LAMPs) and provide platform-agnostic data products, but can autonomously control some platforms through robotic application programming interfaces. LAMPs comprise radiation and contextual sensors and onboard data processing algorithms that are well-suited for challenging environmental, contamination, and radiation localization search scenarios.
Primary point(s) of contact	Yuxin Wu, ywu3@lbl.gov Kenneth H. William, khwilliams@lbl.gov Brian J. Quiter, bjquiter@lbl.gov
Core competencies	• Multiple high function drone platforms • Multiple state-of-the-art payloads • Multiple Part107 pilots with rich field experience • Advanced ML and analytical skills for data analysis and integration • Spectroscopic and imaging radiometry
Sensors/Detectors	
Sensor name	Hyperspectral camera, magnetometer, Lidar, Infrared camera, EM61, High Res RGB cameras, NG LAMP, Chanderlier LAMP, M400 LAMP gamma and gamma-neutron spectroscopic radiation detector and imaging systems.

Make/model	Cubert Gmbh (Germany), Geometrics, Rock Robotics, Sierra Olympia, Geonics
Platform	Skyfront P8 MRS (U.S. drone manufacturer in California), Dronebase X1000 (Italian drone manufacturer), Theiss (U.S.), Aurelia (U.S.), Inspired Flight (U.S.), Boston Dynamics Spot (U.S./South Korea),
Information provided	Collectively, the acquired datasets from the multiple payloads provide detailed digital terrain model, surface visual and hyperspectral imageries, and subsurface magnetic and conductivity properties, which can be combined into a comprehensive datasets for 3D digital earth (twin) model for various purposes, such as the identification of metallic objects, critical mineral prospectivity and thermal and conductivity anomalies. Radiometric data has been coupled with geophysics datasets but has been provided separately as a per-isotope near-surface volumetric activity map.
TRL	9 (geophysics) 6-9 (radiometric)
References	Dafflon, Baptiste et al., "Advanced monitoring of soil-vegetation co-dynamics reveals the successive controls of snowmelt on soil moisture and on plant seasonal dynamics in a mountainous watershed." Frontiers in Earth Science 11 (2023): 976227. Jayson R Vavrek et al., “Surrogate distributed radiological sources III: quantitative distributed source reconstructions.” arXiv preprint arXiv:2412.02926 2024/12/4 K Vetter et al., "Advances in nuclear radiation sensing: Enabling 3-D gamma-ray vision" Sensors 19 (11), 2541, 2019 doi:10.3390/s19112541

Figure F-1. Photographs of LAMP systems and uses on robotic platforms. (Left) Chandelier LAMP, a NaI(Tl) based gamma-ray detector designed to be slung below UAVs. (Left-center) Chanderlier being carried by a UAV in a remediation excavation at the Deepwater FUSRAP site. (Top-right) The neutron and gamma-sensitive NG LAMP system mounted to a Theiss UAV. (Bottom-right) NG LAMP carried on a Boston Dynamics Spot quadruped robot.

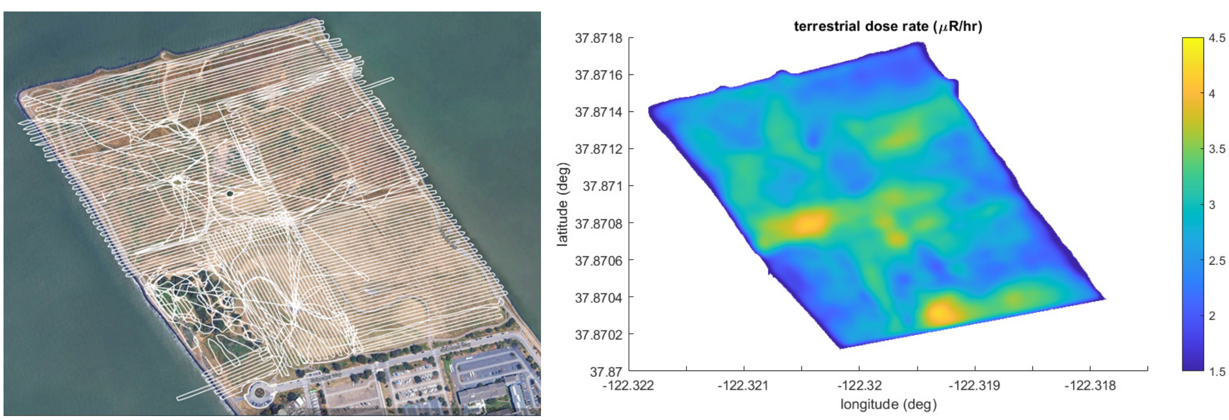

Figure F-2. (left) Autonomous UAS survey flight tracks over Cesar Chavez park and former landfill in Berkeley, CA. (right) Reconstructed gamma dose rate from Cesar Chavez park surveys using LAMP system.

Appendix G. Blank Questionnaire of Surveyed Laboratories

<Lab Name>	
Drone Fleet Summary	
Summary	3-5 sentences describing size of fleet, routinely used sensor payloads, common application areas
Primary point(s) of contact	Name, email address
Core competencies	• Key area of expertise 1 • Key area of expertise 2 • Key area of expertise 3
Sensors/Detectors **<focus on advanced or unique capabilities>**	
Sensor name	Sensor name or physical property being measured
Make/model	Manufacturer details
Platform	Aerial/ground/platform and brief manufacturer details if pertinent
Information provided	Brief statement (several sentences) about what information the data provide or how they can be used. Cite figures as needed.
TRL	See level descriptions
References	Papers, reports, web sites, etc.
Sensor name	Sensor name or physical property being measured
Make/model	Manufacturer details
Platform	Aerial/ground/platform and brief manufacturer details if pertinent
Information provided	Brief statement (several sentences) about what information the data provide or how they can be used. Cite figures as needed.
TRL	See level descriptions
References	Papers, reports, web sites, etc.
Sensor name	Sensor name or physical property being measured
Make/model	Manufacturer details
Platform	Aerial/ground/platform and brief manufacturer details if pertinent
Information provided	Brief statement (several sentences) about what information the data provide or how they can be used. Cite figures as needed.
TRL	See level descriptions
References	Papers, reports, web sites, etc.
Sensor name	Sensor name or physical property being measured
Make/model	Manufacturer details
Platform	Aerial/ground/platform and brief manufacturer details if pertinent

Information provided	Brief statement (several sentences) about what information the data provide or how they can be used. Cite figures as needed.
TRL	See level descriptions
References	Papers, reports, web sites, etc.

Figure 1. (optional)

Figure 2. (optional)

Figure 3. (optional)