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Multi-Modal Remote Surveillance of Localized Terrestrial Processes

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Consortium for Enabling Technologies & Innovation

Multi-Modal Remote Surveillance of Localized Terrestrial Processes

- Participants and contributors
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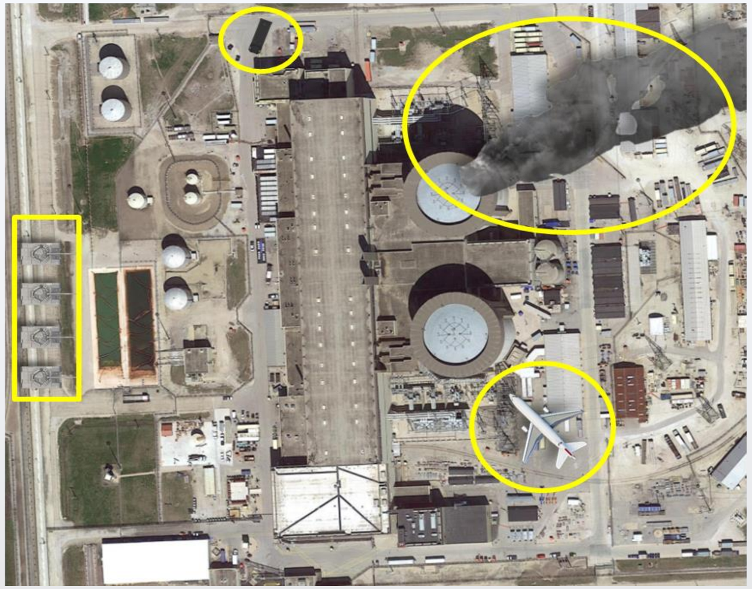
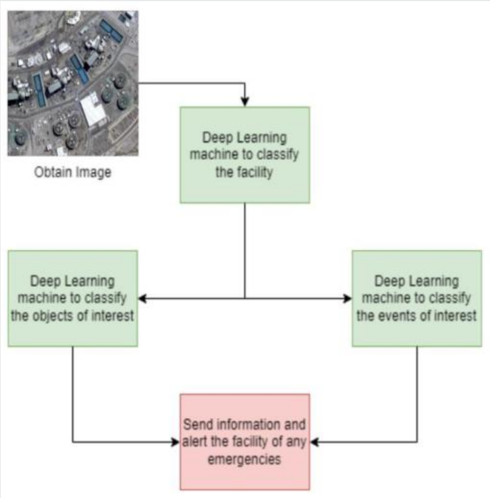
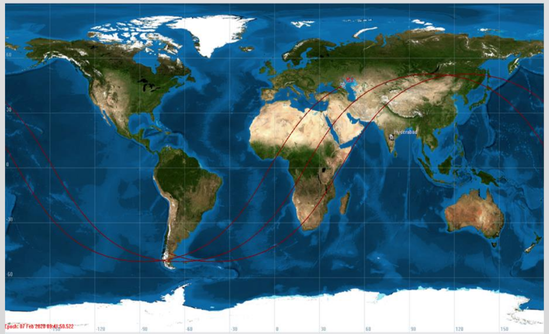
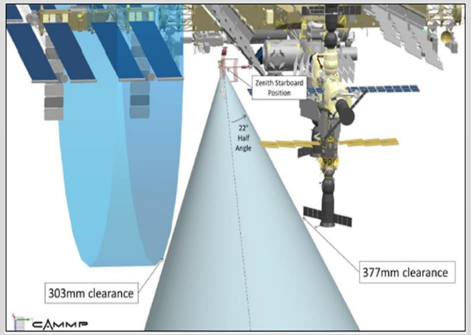
- Project objectives
- Remote surveillance platform
- Data capture and phenomena reconstruction
- Status
- Year 5 and beyond
- ETI impact
- Conclusions









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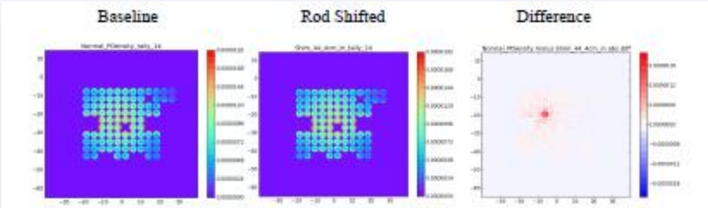

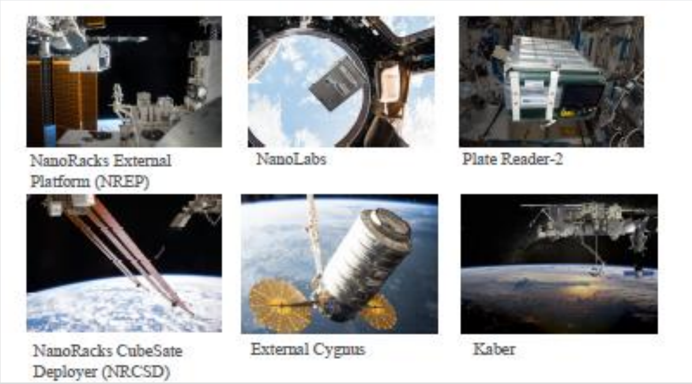

Concept, methods, design and engineering, analysis

- Mario Mendoza, PhD (2022), MS (2020)
- Miguel Avalos, MS (2023)
- Graduate students: Tyler Gates, Scott Walls, James Passmore
- Undergraduate students: Matthew Bowers, Rowan Johnson, Chris Lemke undergraduate student

Cube satellite platform and ISS-based CubeSat launch technology

- Mike Lewis
- Troy Guy

National Laboratories – Advisors:

Sandia National Laboratories

- David Peters
- John Dickinson
- John van der Laan

Pacific Northwest National Laboratory

- Robert Brigantic
- Romarie Morales

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Introduction and Motivation

Cube satellites (CubeSats) provide a unique platform for on-demand evaluating localized processes of potential significance for nuclear security anywhere within the earth's surface or atmosphere:

- Areas of interest can be targeted at times of interest periodically or on-demand.
- CubeSats equipped with adequate sensors and data analytics can provide an autonomous surveillance technology for phenomena of interest.
- **CubeSats are advantageous over the current state-of-the-art conventional satellites because of their high mobility, reduced cost, simplicity.**

Over 2,000 active satellites are currently circulating the Earth

https://www.saab.com/about/innovation/space

https://eospso.nasa.gov/content/nasas-earth-observing-system-project-science-office

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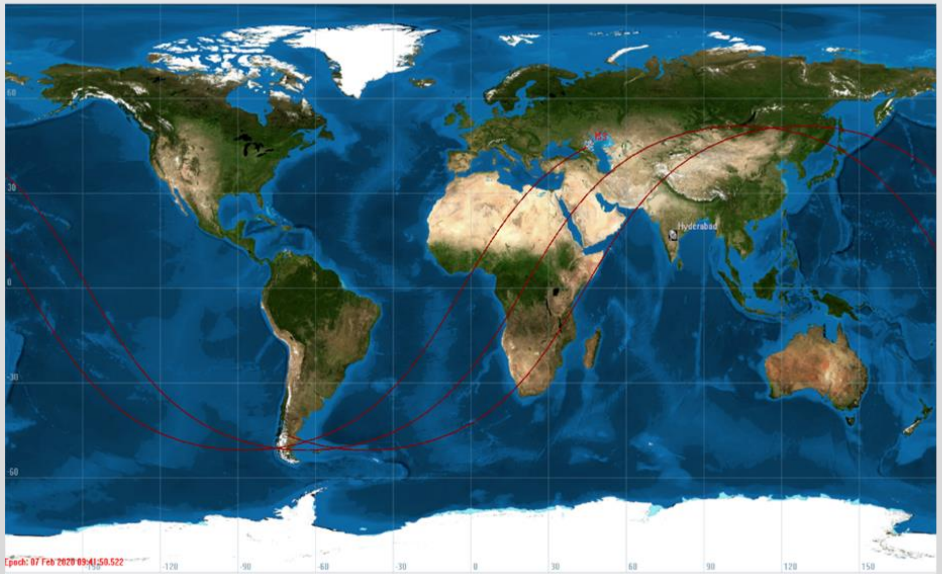
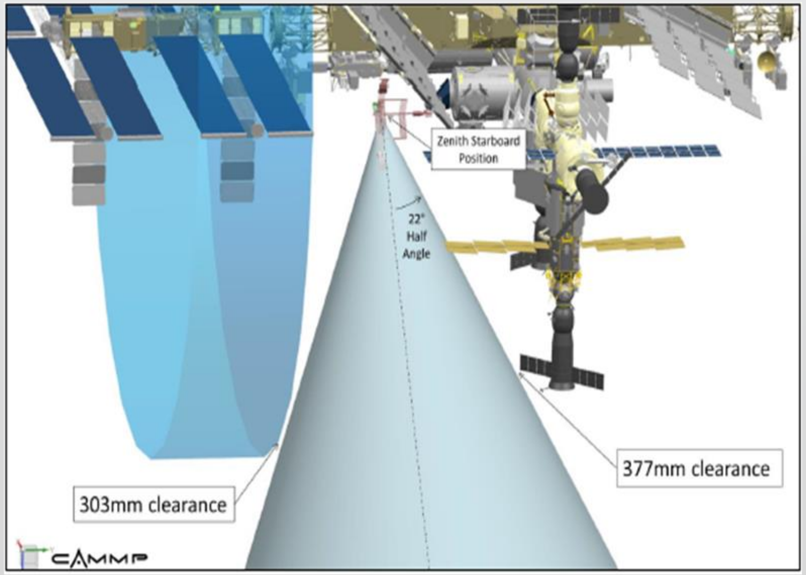
Project Objectives

The effort is focused on the science and technology development for an on-demand characterization of localized processes within atmosphere and on the Earth's surface and subsurface

- Task 1: CubeSat-based global surveyor architecture development
- Task 2: Specification development for a CubeSat-based global surveyor
- Task 3: Computational and experimental program based on surrogate and simulated datasets demonstrating capabilities of the orbital surveyor platform
- Task 4: CubeSat design and data analysis towards a future demonstration launch program





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Mission Relevance

- ***NNSA Mission***

  Preventing nuclear weapons proliferation and reducing the threat of nuclear and radiological terrorism around the world are key U.S national security strategic objectives that require constant vigilance.

  NNSA's Office of Defense Nuclear Nonproliferation works globally to prevent state and non-state actors from developing nuclear weapons or acquiring weapons-usable nuclear or radiological materials, equipment, technology, and expertise.

- **This project contributes to the efforts aimed to reduce the threat of nuclear and radiological terrorism by developing capabilities to survey and automatically characterize phenomena of interest**
  - Offers adaptable technology options supporting constant vigilance
  - Can provide timely and informative data to identify and mitigate threats
  - Offers event-driven reach and global monitoring capability
  - Once established, offers rapid response to anomalies

Mission Relevance

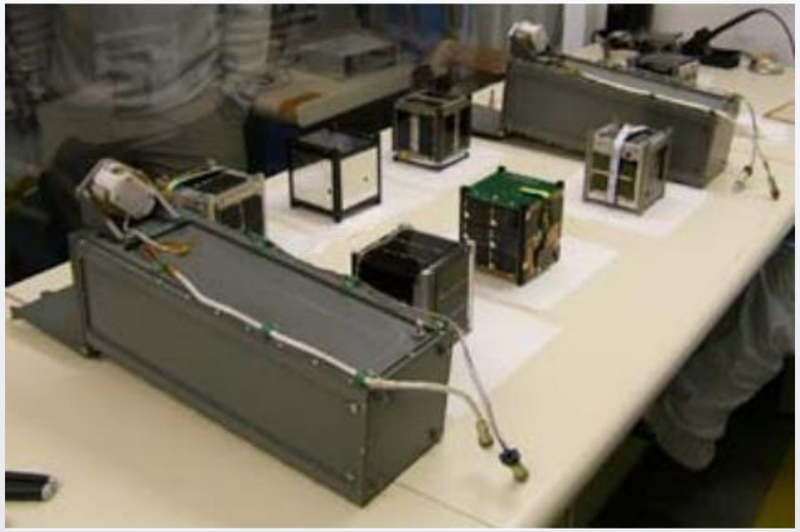
Use of existing and future space platforms to advance global observation and surveillance capabilities

- The use of orbital survey methods offers access options for any location in 3D from subsurface up to upper atmosphere, continuously and over discrete periods of interest
- The project is a synthesis of high TRL observational platforms (cube satellites) with lower TRL sensors and predictive methods including fusion and machine learning to yield a robust multi-modal surveillance and prediction capability
- The process signature development is an integral part of the effort. The results will be widely applicable for all survey programs where signatures are needed to characterize developing local phenomena remotely.
- The Cube Sate surveyor solves the challenge of access to the location of interest.

Remote Surveillance Platform

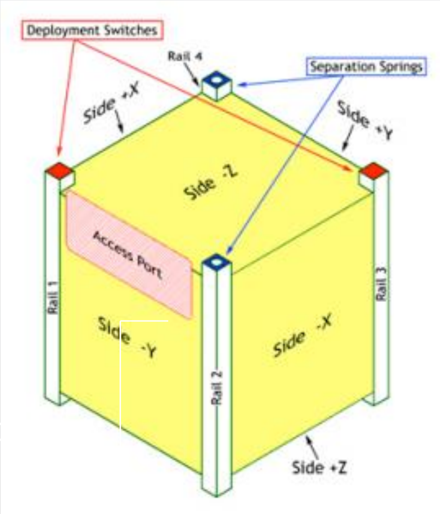
CubeSat architecture

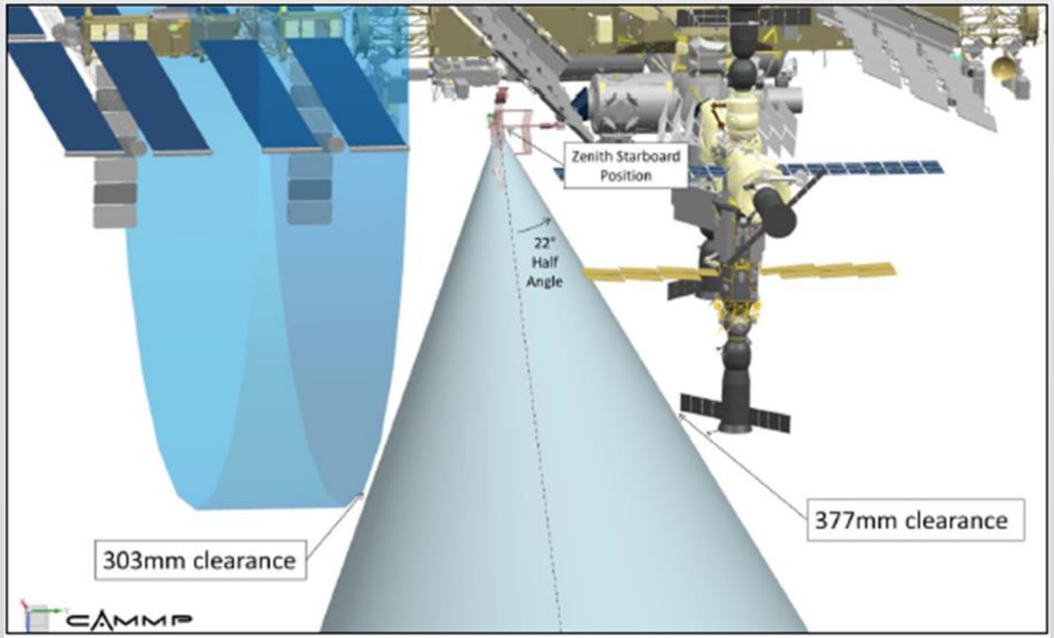
- CubeSats are measured in units of U, 1U is equal to 10 cm x 10 cm x 10 cm cube with a mass close to 1 kg
- Sizes range from 1U to 12U
- Most likely size for including a high-resolution sensor is 3U



High-resolution sensing (spectral and spatial, etc.)

Data analysis and reconstruction methods





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Data Capture and Phenomena Reconstruction

Phenomena Signature Analytics

Feature characterization

- Surveillance
- Data synthesis and reconstruction
- Interpretive analytics
- Use of artificial intelligence methods (smart automation and global 3D interrogation)

Data analytics and reconstruction

- Big Data management
- Characterization and prediction
- Automated (smart) surveillance

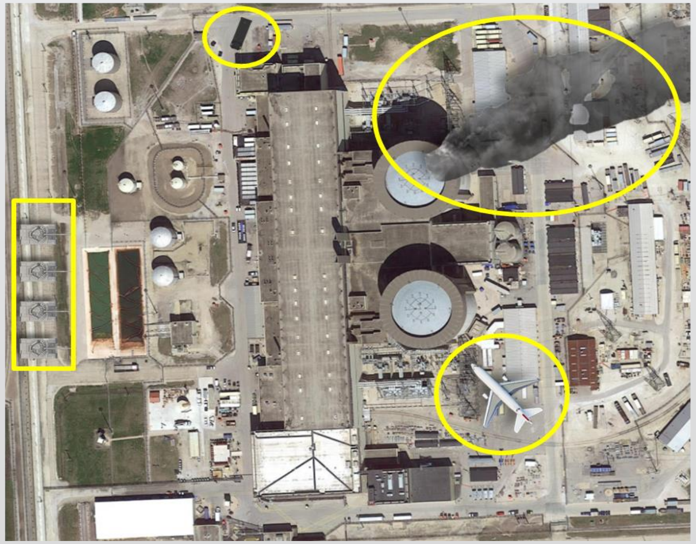
Demonstrations

using available data sets and hi-res. imagery

- Aerial phenomena sensing
- Atmospheric phenomena

Multi-modal spectral interrogation:

- High-resolution remote sensing
- Unique signatures for characterization and identification



Status

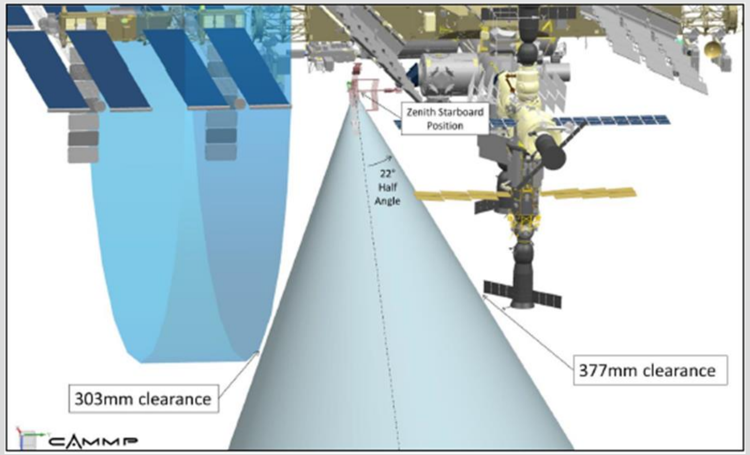
CubeSat Architectures and Deployment Options

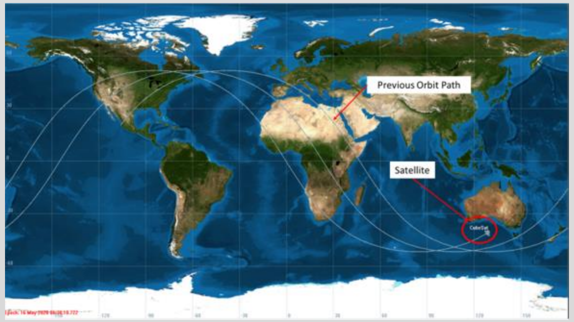
1 CubeSat vs Constellation

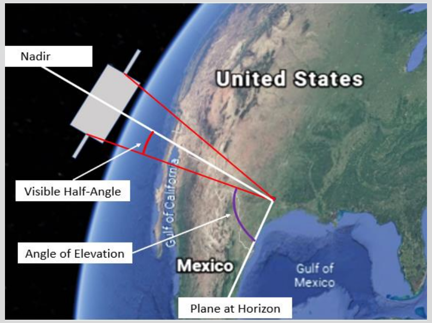
Attribute	1 CubeSat	Constellation of CubeSats
Higher Characterization Accuracy Through Sensor Diversity		✓
Lower Cost	✓	
Increased System Security		✓
Robustness Through Sensor Redundancy		✓
Simplicity	✓	
Longer Overall Access Times to Ground		✓

Communications Options

	Ground Station Only	Inter-CubeSat	Additional Satellite Relay
Operational Complexity	Moderate	High	High
Data Flow Steps	High	Moderate	Moderate
Speed to Surface	Moderate	High	High
Autonomy	Low	High	High
Lifetime	High	Low	High
Cost	Moderate	Moderate	High







Status

Analytics

Characterization

- Surveillance
- Data synthesis and reconstruction
- Interpretive analytics
- Use of artificial intelligence methods (smart automation and global 3D interrogation)

Phenomena

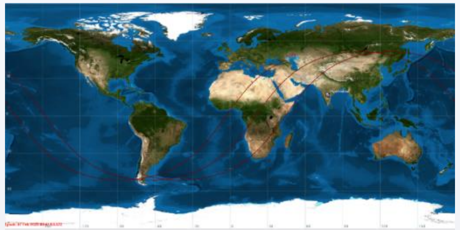
Events, features and objects

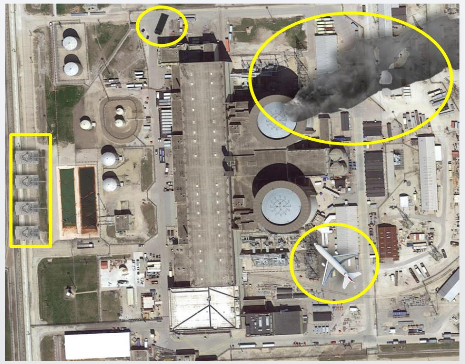
- Automobiles, airplanes, etc.
- Facilities and infrastructure including their performance
- Equipment
- Processes
- Etc.

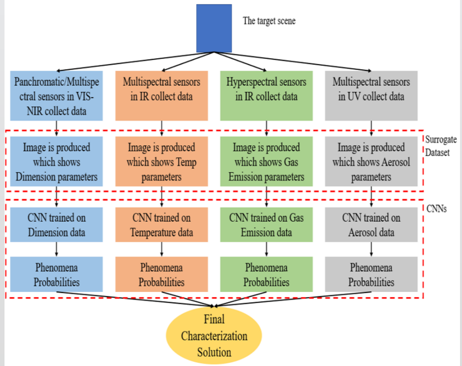
Signatures

Observables

- Dimensions
- Speed (dynamic changes)
- Temperature
- Detectable emissions
- Spectral parameters







Dimensions for medium-sized CAT 320 GC Excavator

Dimension	Value
Height to Top of Cab	3.0 m
Length	9.5 m
Width	3.2 m
Track Length	3.2 m

Type of Fire/Heat Source	Average Temperature
Infrastructural Fire	350-1200°C
Wildfire	800°C
Volcanic Plumes and Lava Flow	600-1200°C

Automobile dimension	Value
Height	1.4 – 2.1 m
Length	2.7 – 5.4 m
Width	1.5 – 2.1 m

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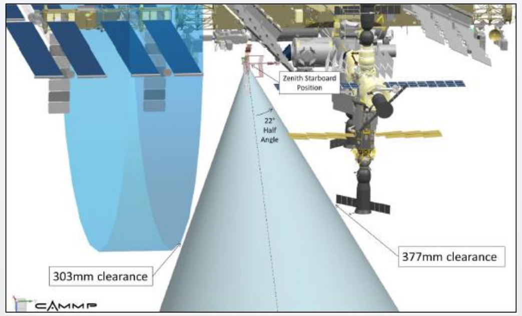
Status

Signature phase space = space (x,y,z), time (t), spectral parameters (E)
event nature (discrete vs. continuous, multiplicity, periodicity)



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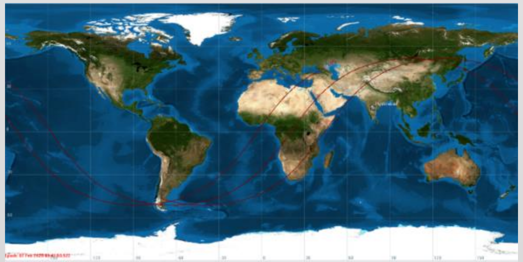
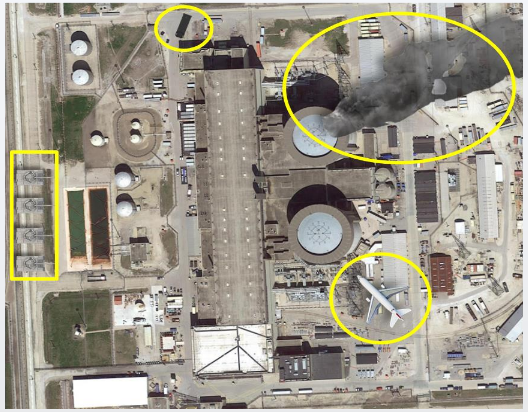
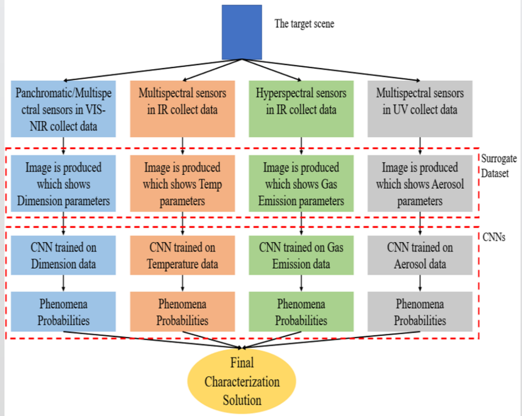


Phenomenon	Parameter	Signature Resolution		
		Spectral (Region)	Spatial	Temporal
Automobiles and Airplanes	Length, Width, Height	Visible and Infrared Light bands	1-1.5 m	Single Sample
	Speed	Visible and Infrared Light bands	1-1.5 m	Multiple Samples
	Temperatures	Infrared Light bands	1-10 m	Single Sample
	Gas Emissions	Infrared Light (Reflectance) bands	10-30 m	Continuous Sampling
Facilities and Emergencies	Length, Width, Height	Visible and Infrared Light bands	10-30 m	Single Sample
	Temperatures	Infrared Light bands	10-30 m	Single Sample
	Gas Emissions	Infrared Light (Reflectance) bands	10-30 m	Continuous Sampling
	Aerosol Index	Ultra-Violet Light bands	10-30 m	Continuous Sampling
Construction and Mining	Length, Width, Height	Visible and Infrared Light bands	1-2 m	Single Sample
	Speed	Visible and Infrared Light bands	1-2 m	Multiple Samples
	Temperatures	Infrared Light bands	1-10 m	Single Sample
	Gas Emissions	Infrared Light (Reflectance) bands	10-30 m	Continuous Sampling
	Footprint	Visible and Infrared Light bands	10-30 m	Single Sample





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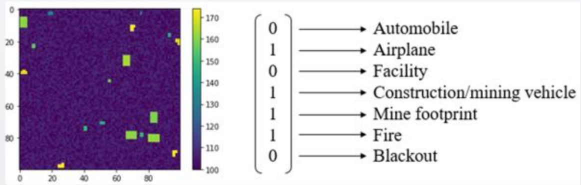
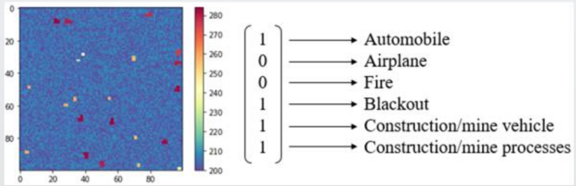
Surrogate Database

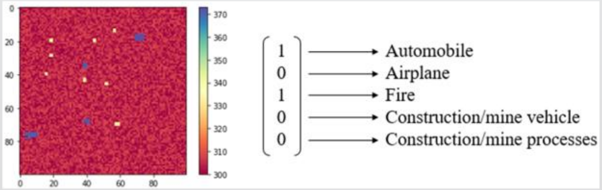
Dimension



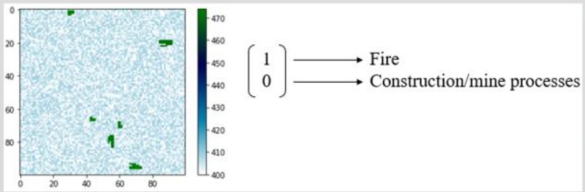
Temperature



Gas

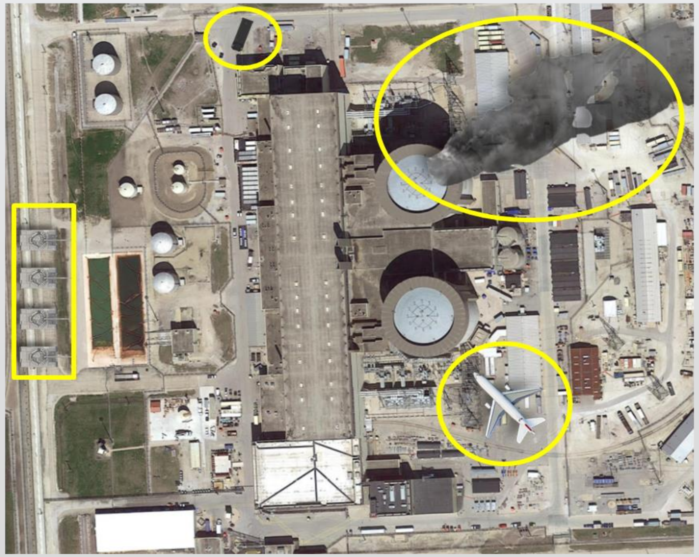


Aerosol



Phenomena and Signature Database

Artificial addition of anomalies



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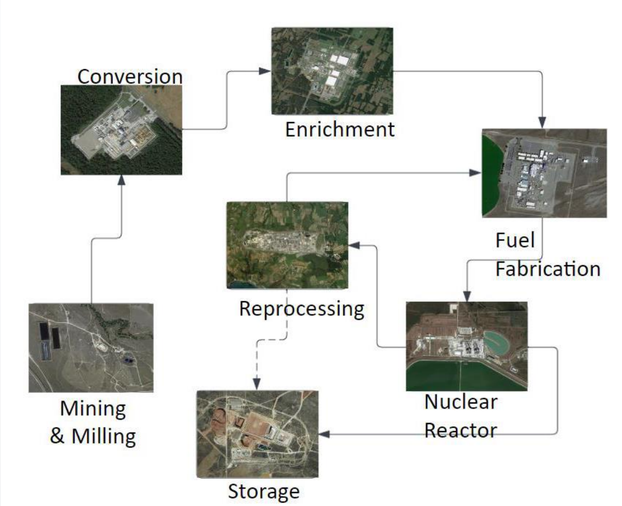
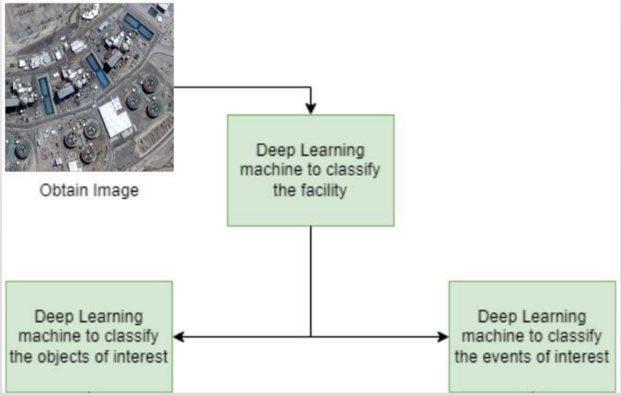
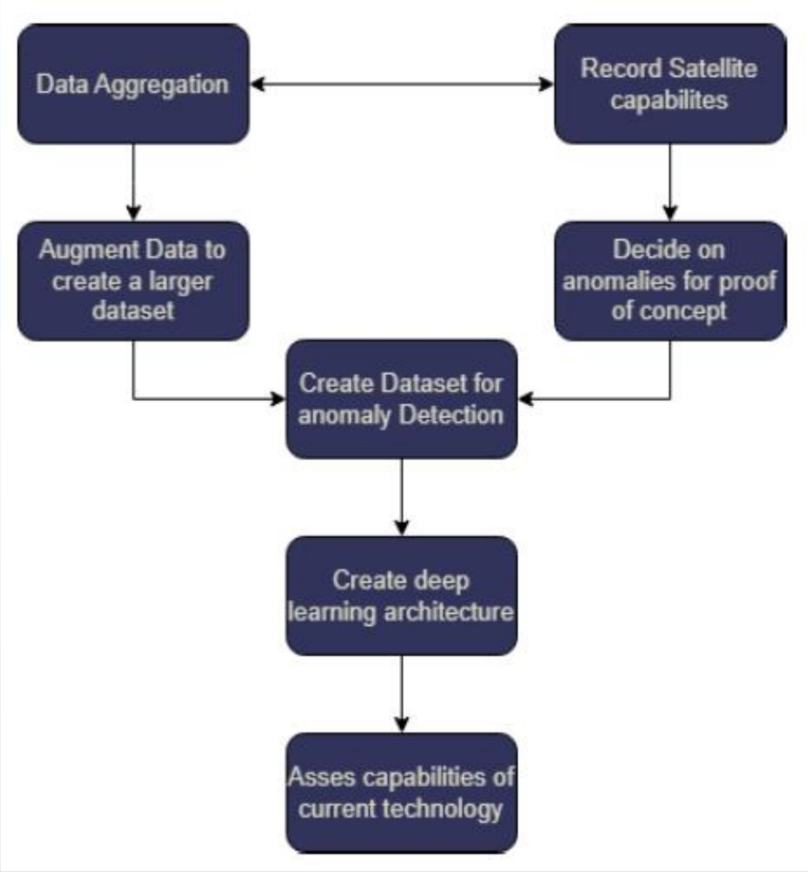






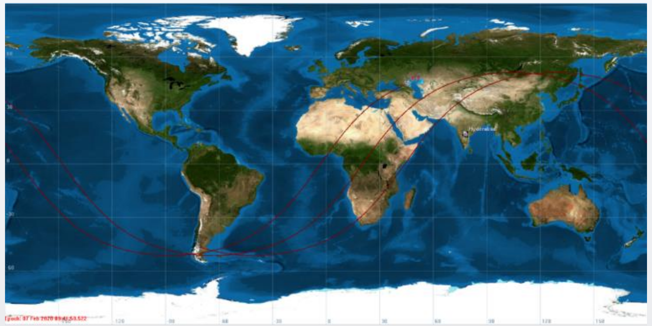
Phenomena and Signature Database

Year 5 and Beyond

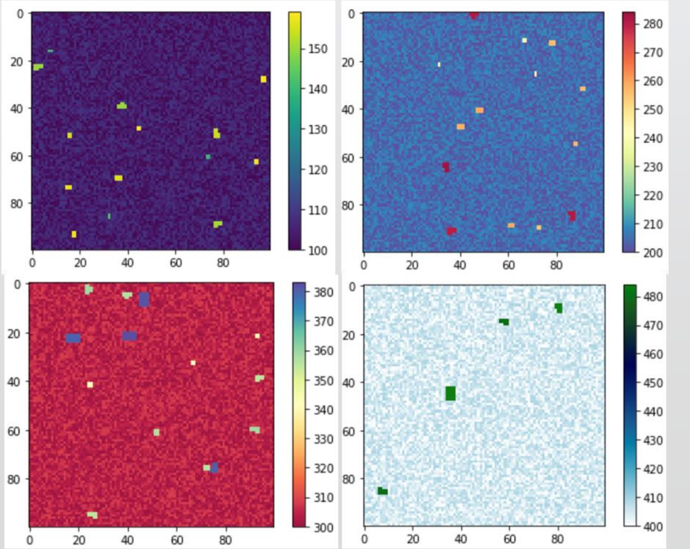
- **Year 1:** CubeSat-based global surveyor applications, options and architectures development
- **Year 2:** Specification development for a CubeSat-based global surveyor
- **Year 3:** Computational and experimental program based on surrogate and simulated data sets demonstrating capabilities of the proposed orbital surveyor platform
- **Year 4:** CubeSat design and data analysis towards a future demonstration launch program
- **Year 5**: Continuation of all efforts

Surveillance

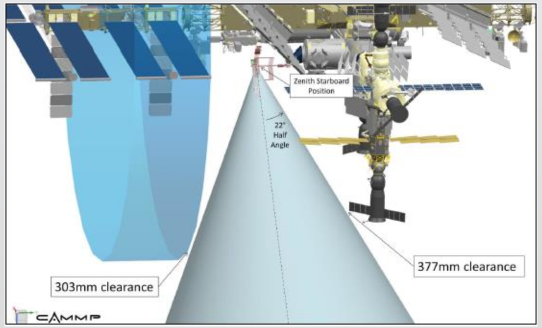
Monitoring and Characterization



Phenomena signature database



CubeSat Deployment



CubeSat

Photo Credits: National Aeronautics and Space Administration (NASA)
https://www.nasa.gov/mission_pages/cubesats/overview

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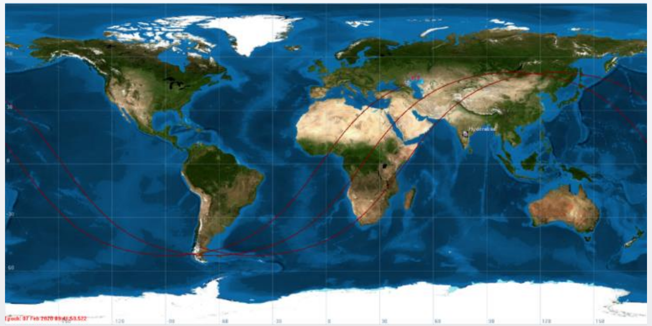

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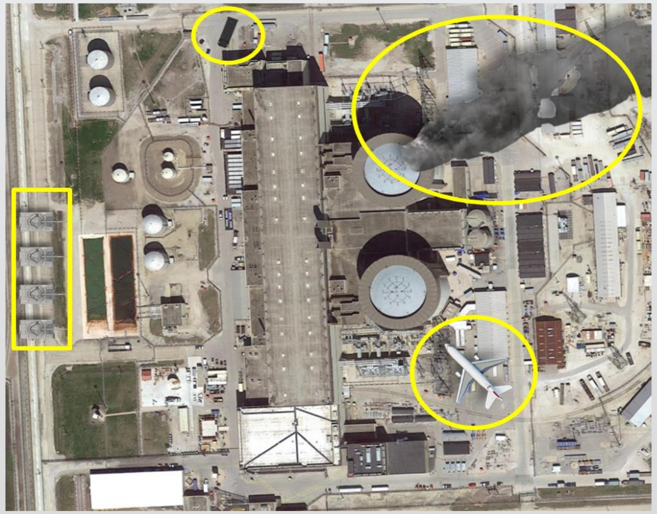

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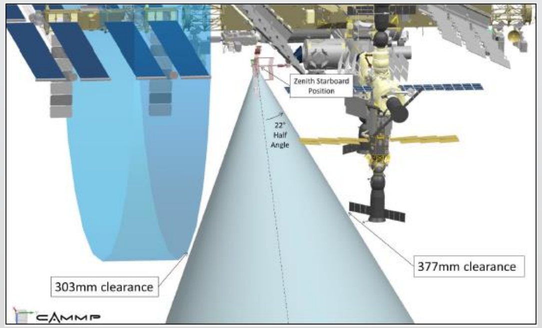

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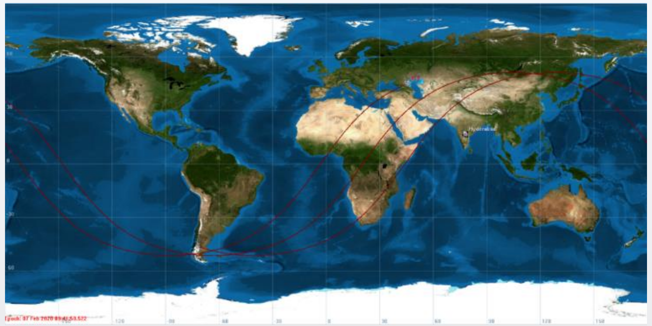
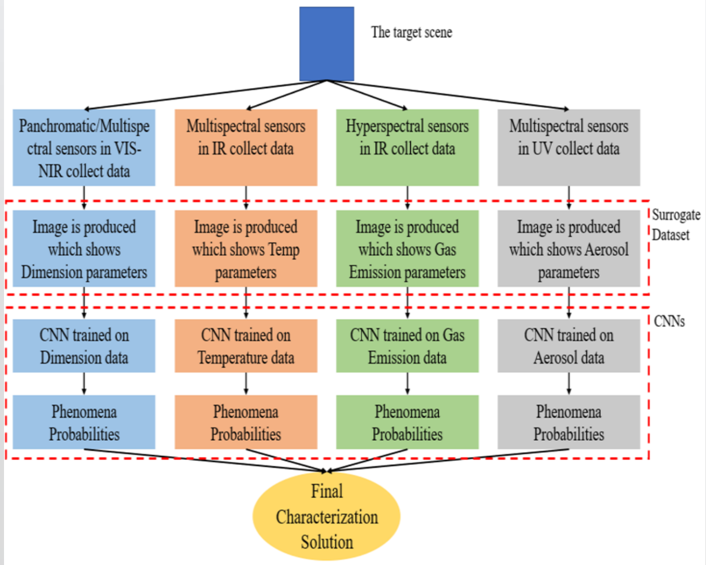
Surveillance

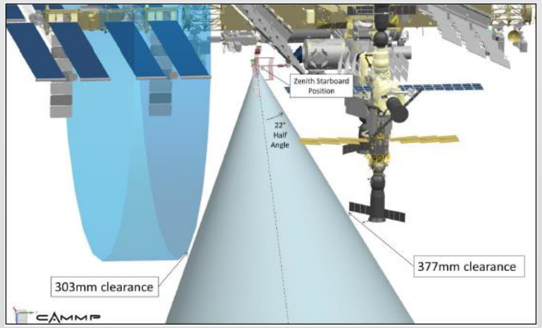
Monitoring and Characterization



Monitoring and characterization method



CubeSat Deployment



CubeSat

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CubeSat-Based Global Surveyor Platform

ETI Impact

Workforce development

- Brought project topics to students and facilitated their engagement and interests
- Facilitated engagements with national laboratories
- Funded student internships at national laboratories

Enabled collaborations

- Nurtured discussions and collaborations towards future engagements

  - Sandia National Laboratories

  - Pacific Northwest National Laboratory

  - Brookhaven National Laboratory

  - Booz Allen Hamilton Inc.

Conclusion

- Developed a foundational signature-based analysis architecture for monitoring and identification of localized phenomena of interest
- Developed specifications and conducted analysis of viable CubeSat architectures, systems, and sensors yielding preliminary design pathways
- Created a high-precision computational method based on surrogate datasets demonstrating capabilities of a CubeSat-based global surveyor
- Developed the phenomena database for further surveillance capabilities studies and methods development
- Developed data analytics architecture for terrestrial and atmospheric phenomena characterization and identification accounting for noisy and incomplete data sets

Accomplishments:

- Phenomena of interest assessed
- Signature sets developed and analyzed
- CubeSat architectures identified and explored
- Orbital capabilities identified
- Developed analysis methods

Year 5:

- Recommendations for sensor selection and architecture design
- Advancing the characterization method through deep learning techniques
- Illustrative applications of the technology towards platform designs

Future efforts:

- Expand characterization method to prototypical real and simulated satellite data
- Further phenomena characterization metrics and signature format development for efficient data processing and identification
- Platform design and demonstration of its prototypic elements
- Sensor development and integration within a surveillance platform designs
- Continue development of CubeSat platform architectures and data analysis methods towards a future demonstration

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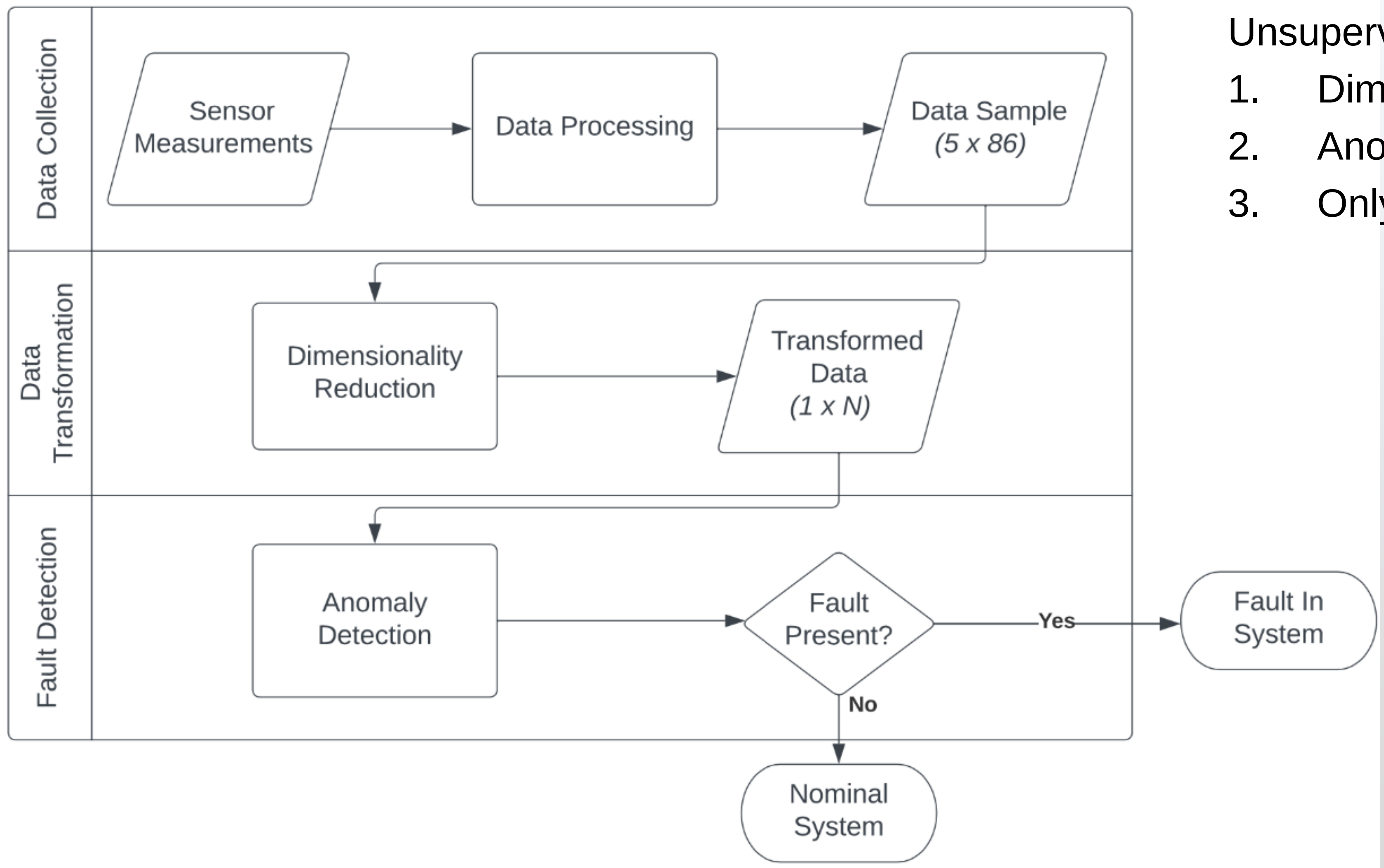
ACKNOWLEGEMENTS

This material is based upon work supported by the Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921.

Backup

Detection architecture



Unsupervised learning fault detection

1. Dimensionality Reduction
2. Anomaly Identification
3. Only train on nominal data

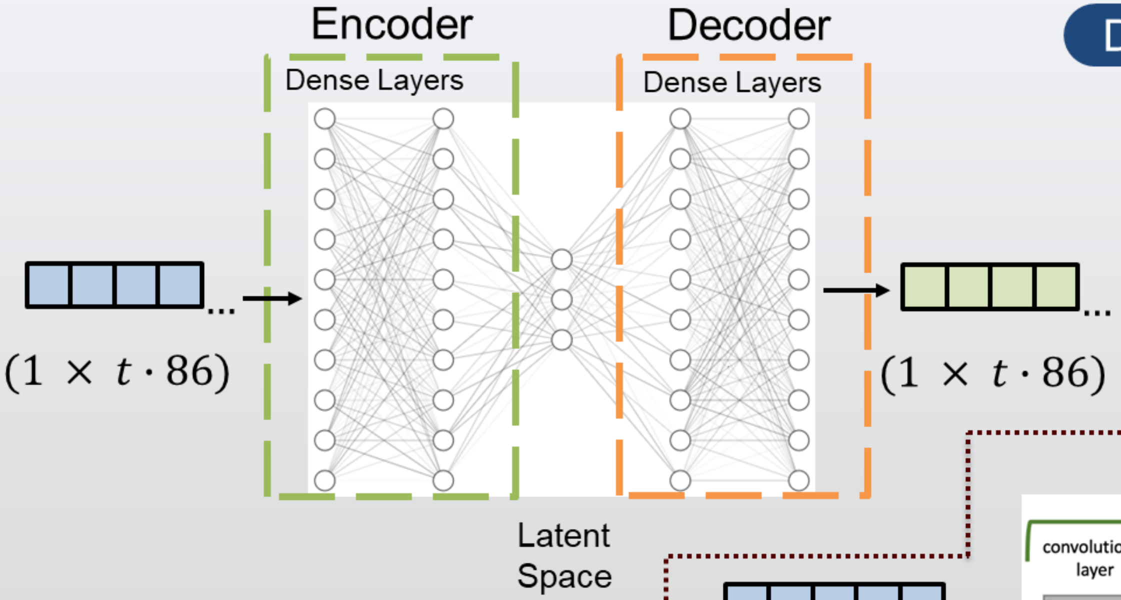
ETI

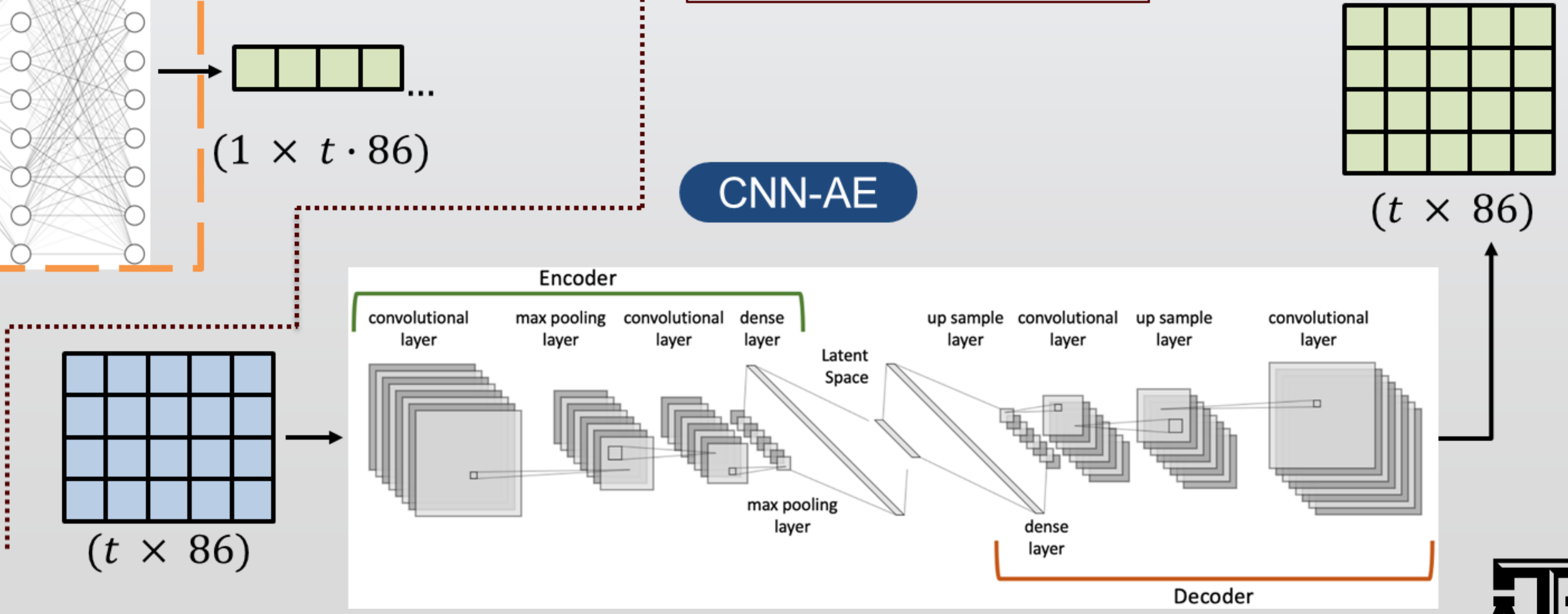
Dimensionality reduction

$(1 \times t \cdot 86)$ → $T_k = XP_k$, $\hat{Y} = T_k P_k$ → Principal Components $(1 \times N)$ → $\hat{X} = \hat{Y} P_k^T$ → $(1 \times t \cdot 86)$

PCA

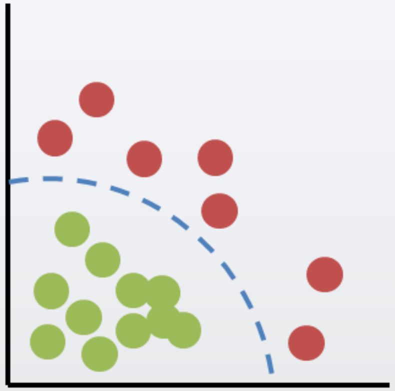
$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(X_i - \hat{X}_i\right)^2$$





Backup

Anomaly identification



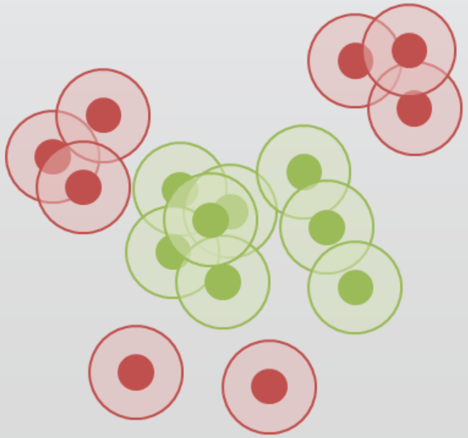
- **Draw decision boundary function to max distance b/n origin and nominal pts**
- User defines factor for kernel function
- Using custom threshold for anomaly decision

$$score(x') = |D(x')| - |\rho|$$

$$\text{Fault:}\quad score(x') = 0$$

$$\text{Nominal:}\quad score(x') > 0$$

Custom Threshold



- Draw Euclidian distance neighborhood around each point
- **Anomalies are pts whose neighborhoods do not overlap the nominal pts neighborhoods**
- User defines minimum distance

$$N_{Eps}(p) = \{q \in D | \text{dist}(p, q) \leq Eps\}$$

$$\text{Fault:}\quad \text{dist}(y, p) > Eps, \forall p \in D$$

$$\text{Nominal:}\quad \text{dist}(y, p) \leq Eps, \forall p \in D$$

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