Autonomous Ground-Penetrating Radar Robot for Subsurface Mapping and Monitoring of Hazardous Waste Repositories

REMPLEX

From Earth to Orbit: Autonomous Measurements and Remote Sensing

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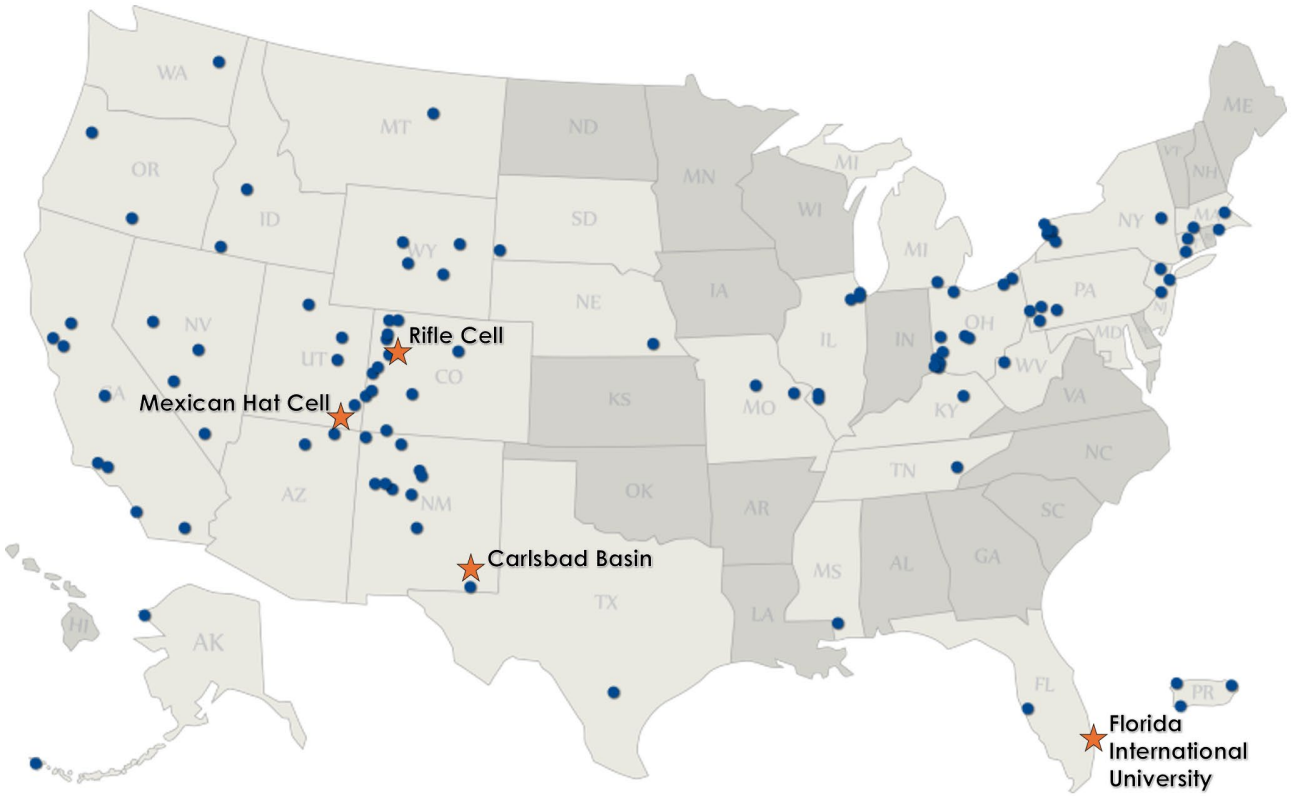
DOE Disposal Cells

Critical Infrastructure for Nuclear Waste Management

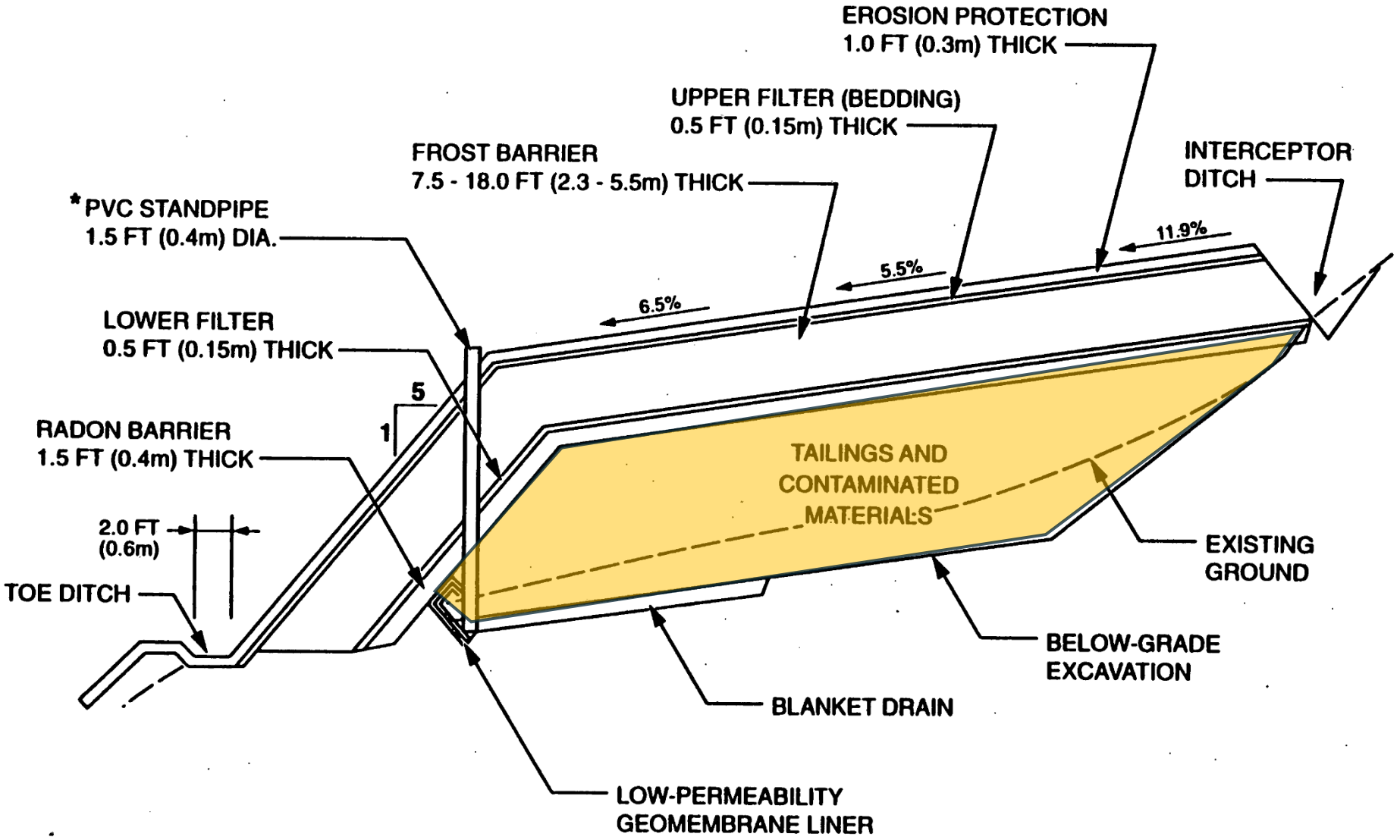
- 28 engineered disposal cells across the US
- Regular inspection and monitoring required

Safely containing hazardous and radioactive waste in DOE disposal cells is crucial to environmental protection, public health, and trust.



U.S. DEPARTMENT OF ENERGY
Legacy Management

Engineered Layered Repositories



DOE Long-Term Surveillance Plan

- Designed to contain millions of cubic yards of radioactive material
- Expected stability: 200 – 1,000 years
- Routine maintenance
- Emergency measures protocols

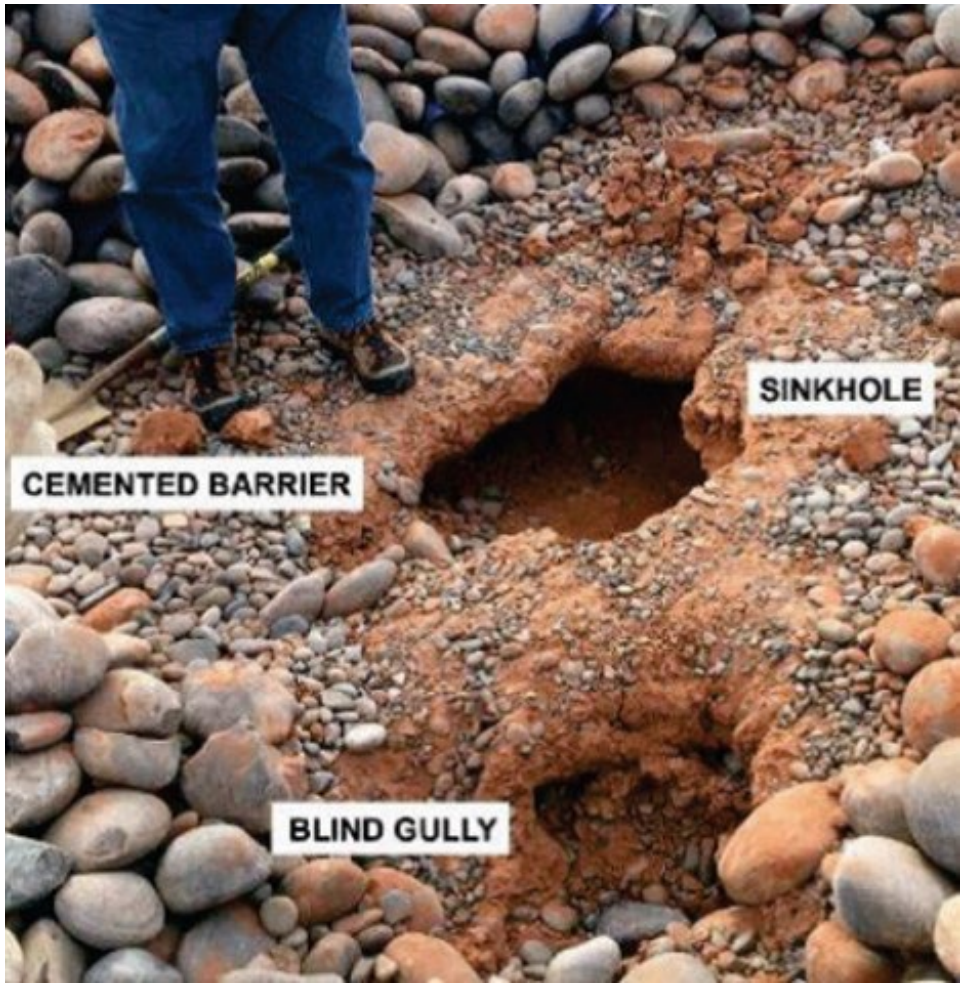
Field records are vital to managing and maintaining cell structural integrity and regulatory compliance

Current Challenges

Emerging Issues in Long-Term Surveillance

- Premature subsurface erosion discovered
- Climate change impacts on cell stability

Mexican Hat Disposal Cell, 2017



Premature Subsurface Erosion

30

200

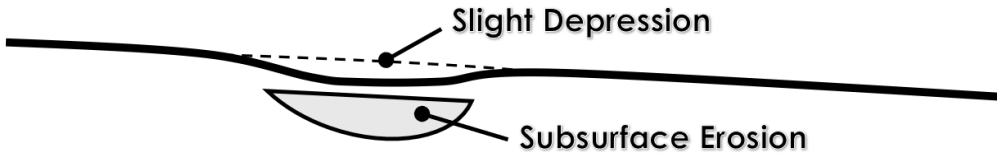
Long Term Surveillance

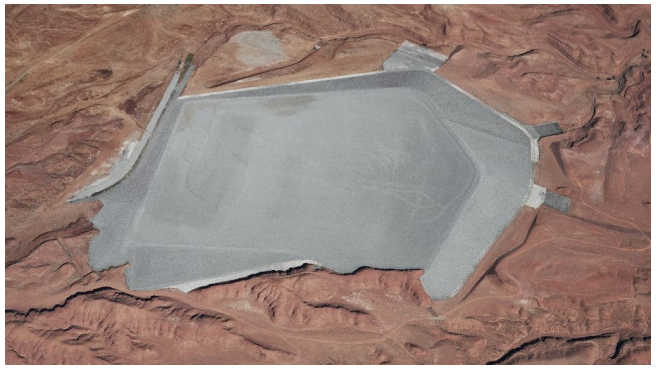
1,000 **Uranium Mill Tailings**

DOE-LM site managers and scientists suspect that climate patterns are a contributing cause.

Despite a severe drought in the southwest US, climate change projections indicate more intense precipitation events, confirmed by meteorological records.

During intense rainfall events, rock covers are ineffective in slowing runoff, leading to potential problems with subsurface erosion and the long-term stability of disposal cell cover systems.

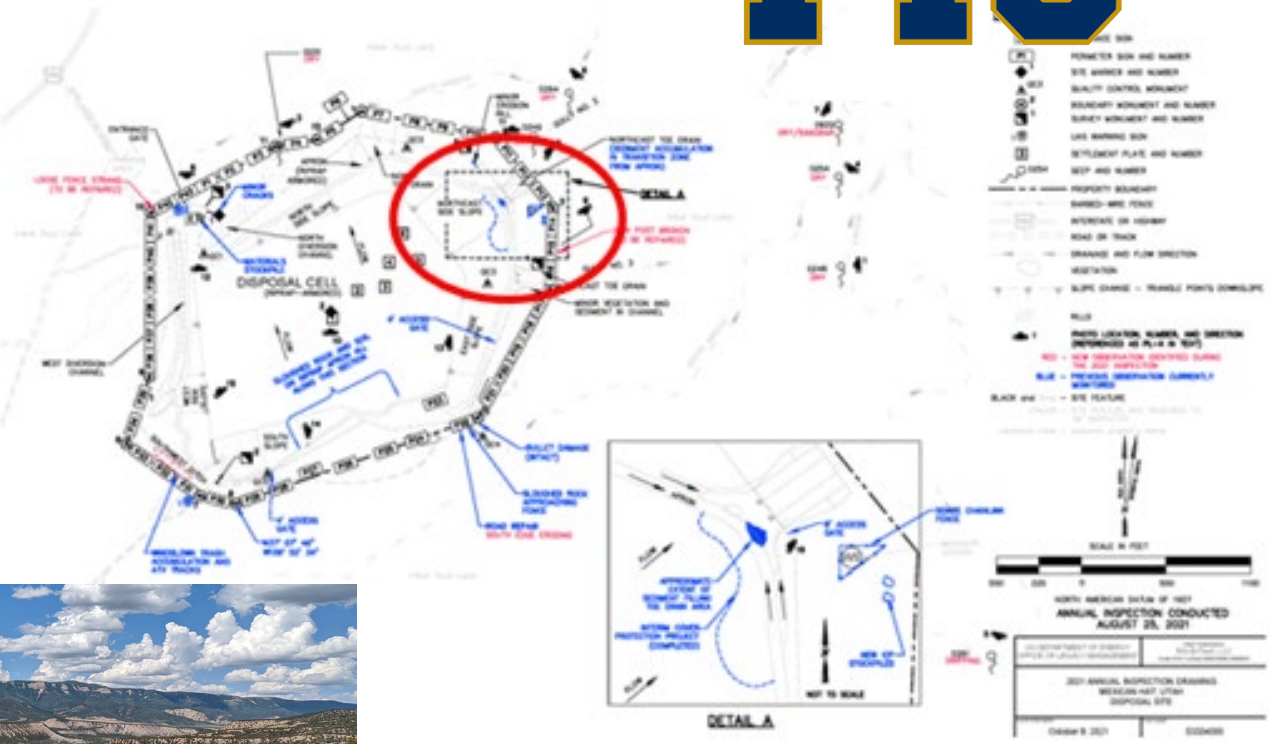


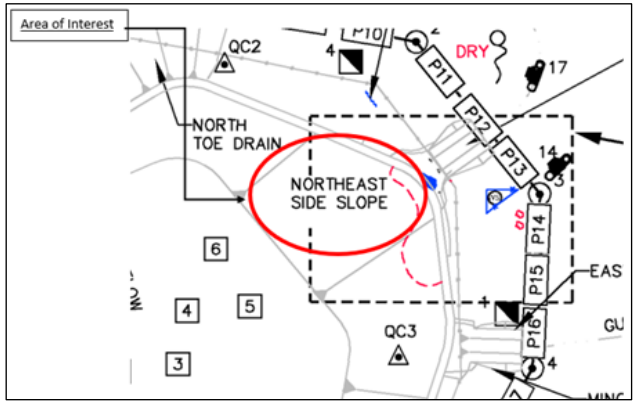


Mexican Hat Disposal Cell

Long-Term Surveillance Plans

DOE annual site inspections

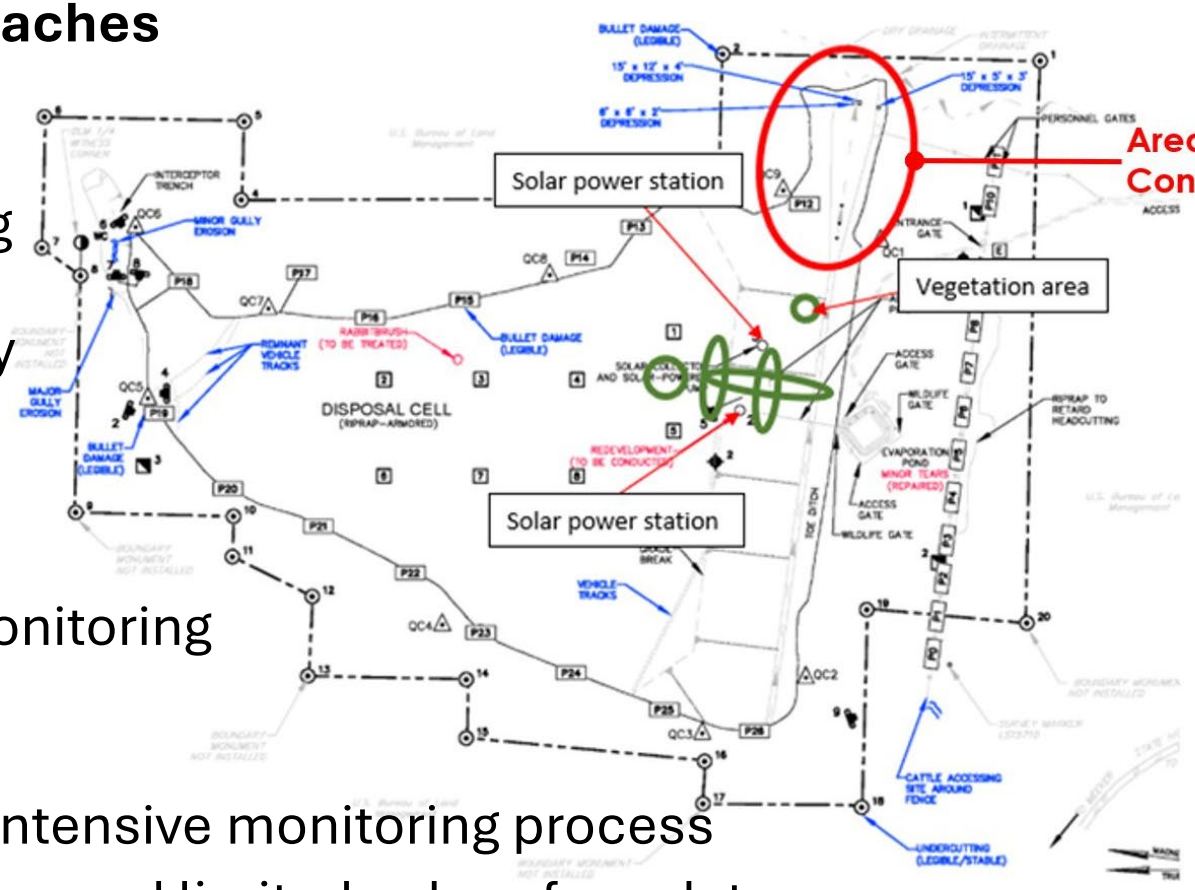


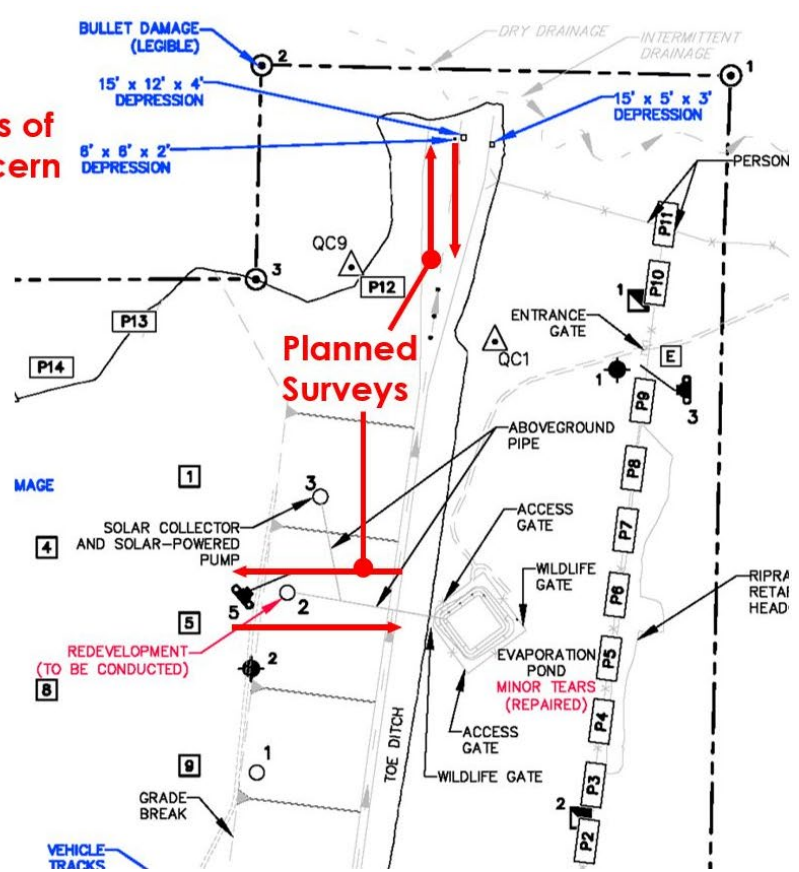


Current Monitoring Methods

Traditional Approaches

- Annual visual inspections
- Satellite Imaging
- Aerial photogrammetry
- Aerial lidar
- Radiological surveys
- Groundwater monitoring



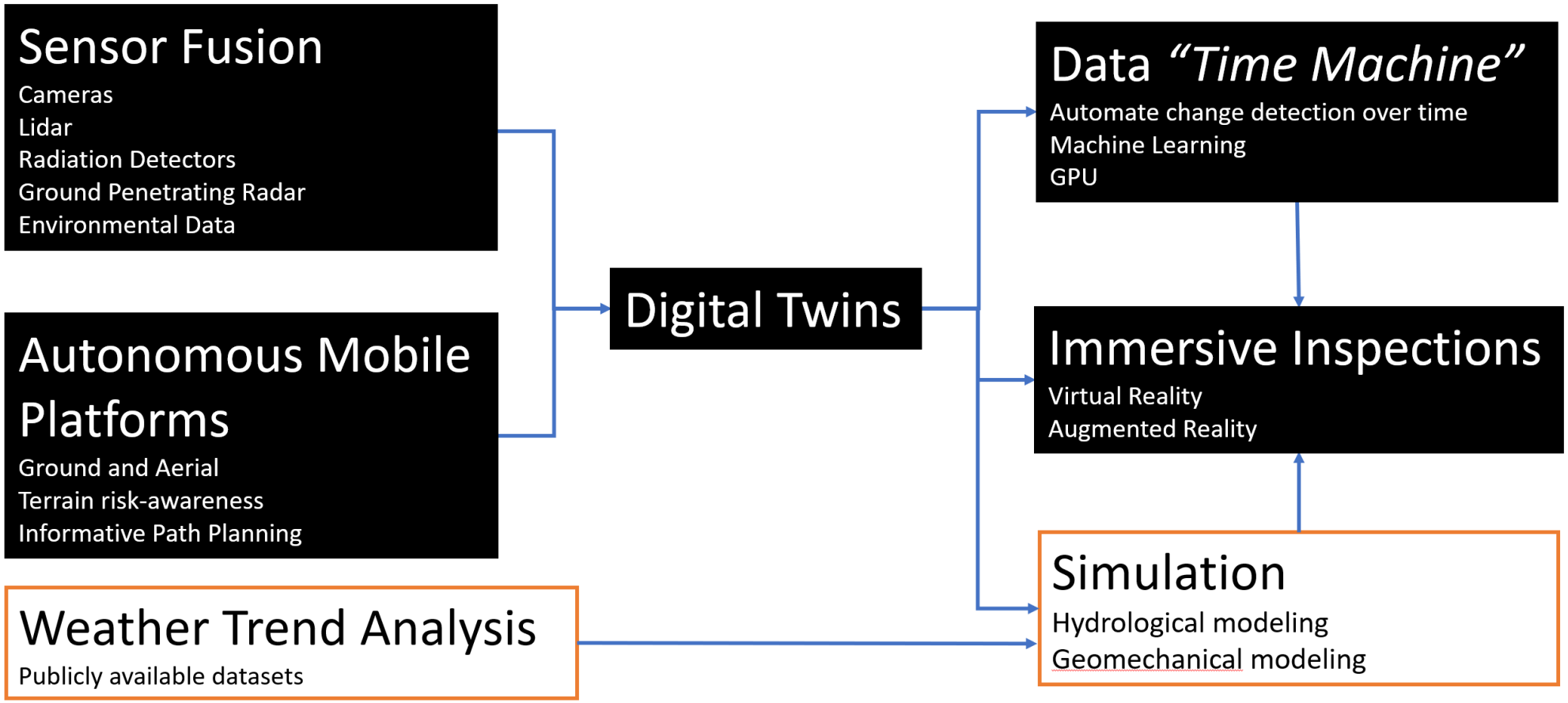


Survey maps

Limitations

- Time and labor-intensive monitoring process
- Visual inspections and limited subsurface data
- Operational burdens
- Safety concerns and potential radiological exposure risks

Noninvasive Evaluation Framework

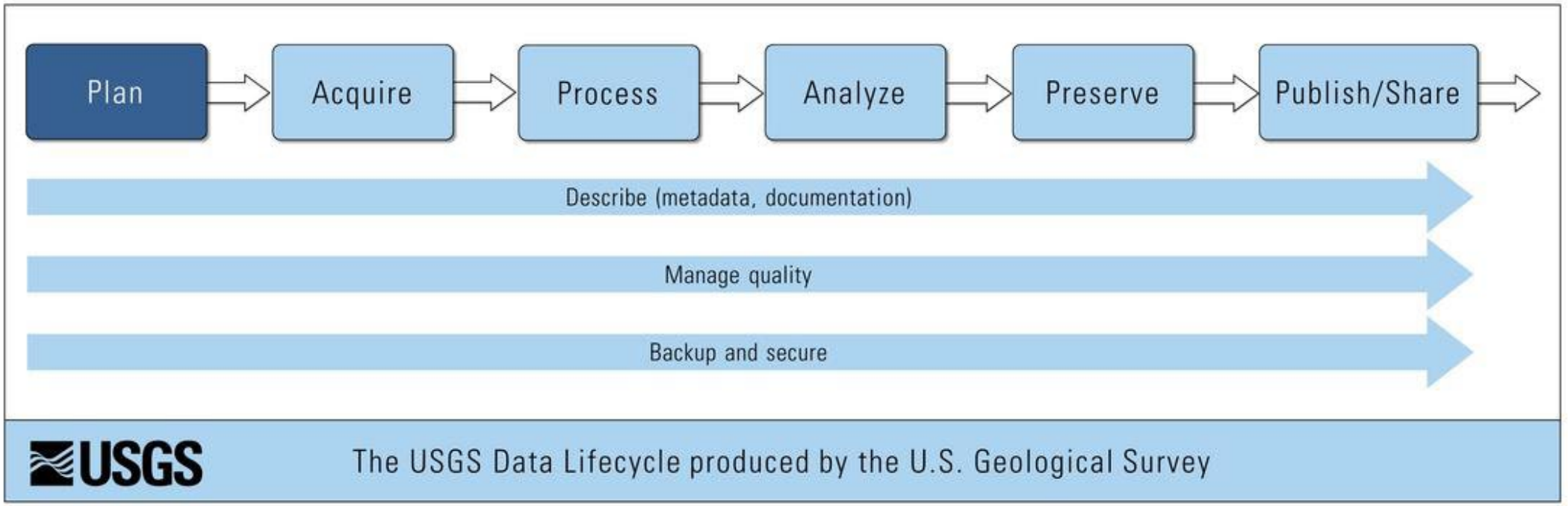


"Assess potential erosion features using minimally invasive inspection methods to avoid disturbing additional material, as erosion of the radon barrier could create potential radiological exposure risks."

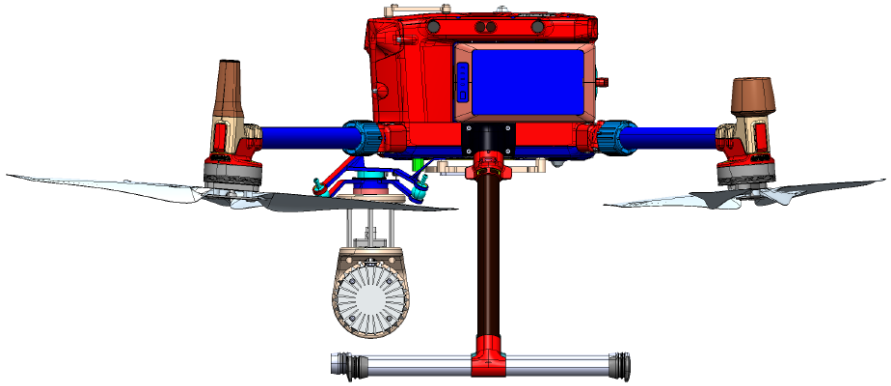
Onsite Autonomous Surveys

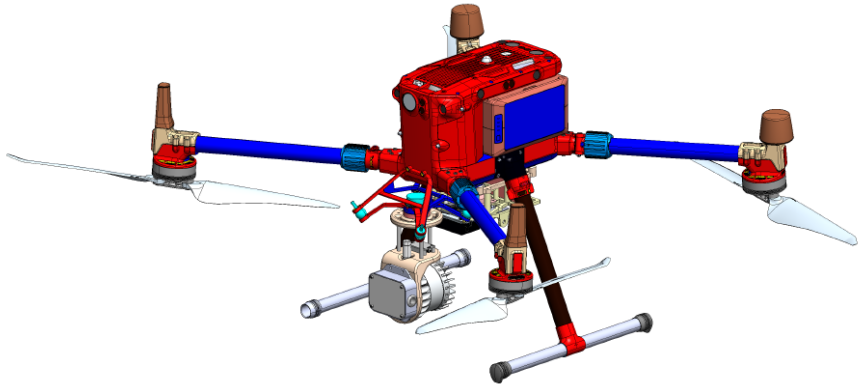
- Centimeter-level precision
- Cost-effective
- Meaningful data at your disposal
- Broad custom-built sensory
- See beneath the surface

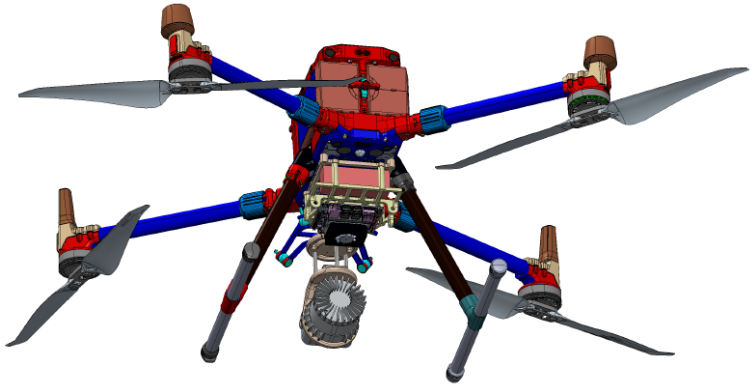
- Automated data collection
- Machine Learning historical change
- Data-driven decision-making



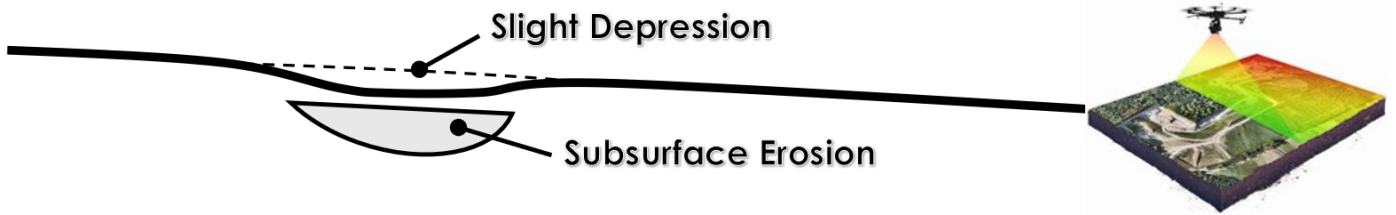
2021 FIU Aerial Survey





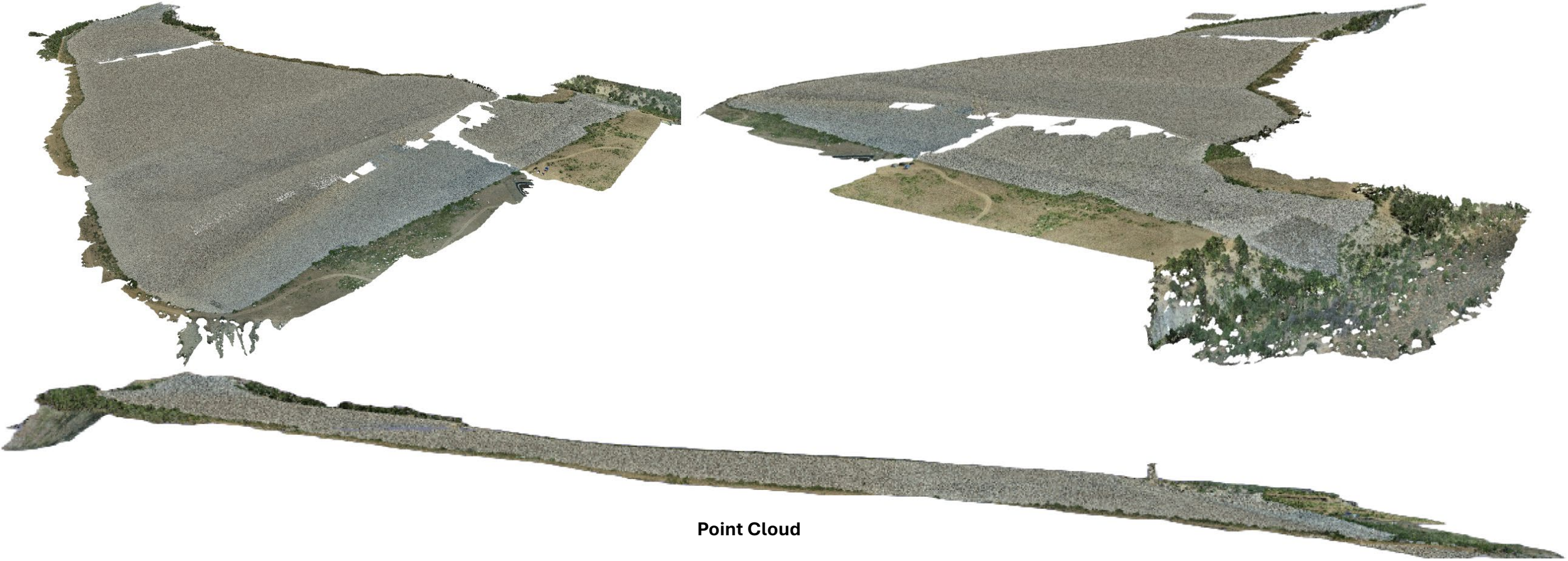


FIU in-house aerial lidar system



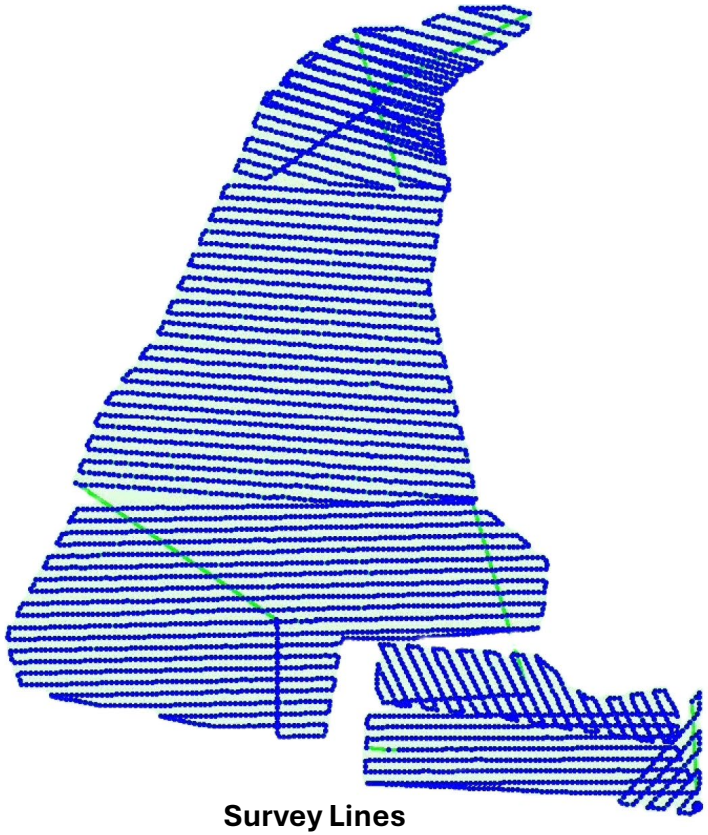
2021 Rifle Cell Deployment

Rifle Cell Survey



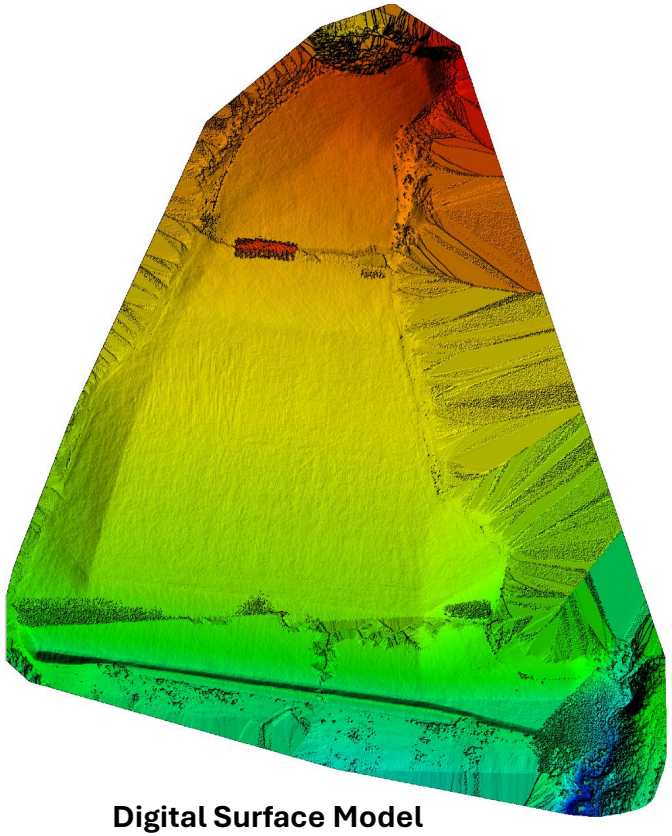
Point Cloud

Rifle Cell Digital Elevation Model



Survey Lines

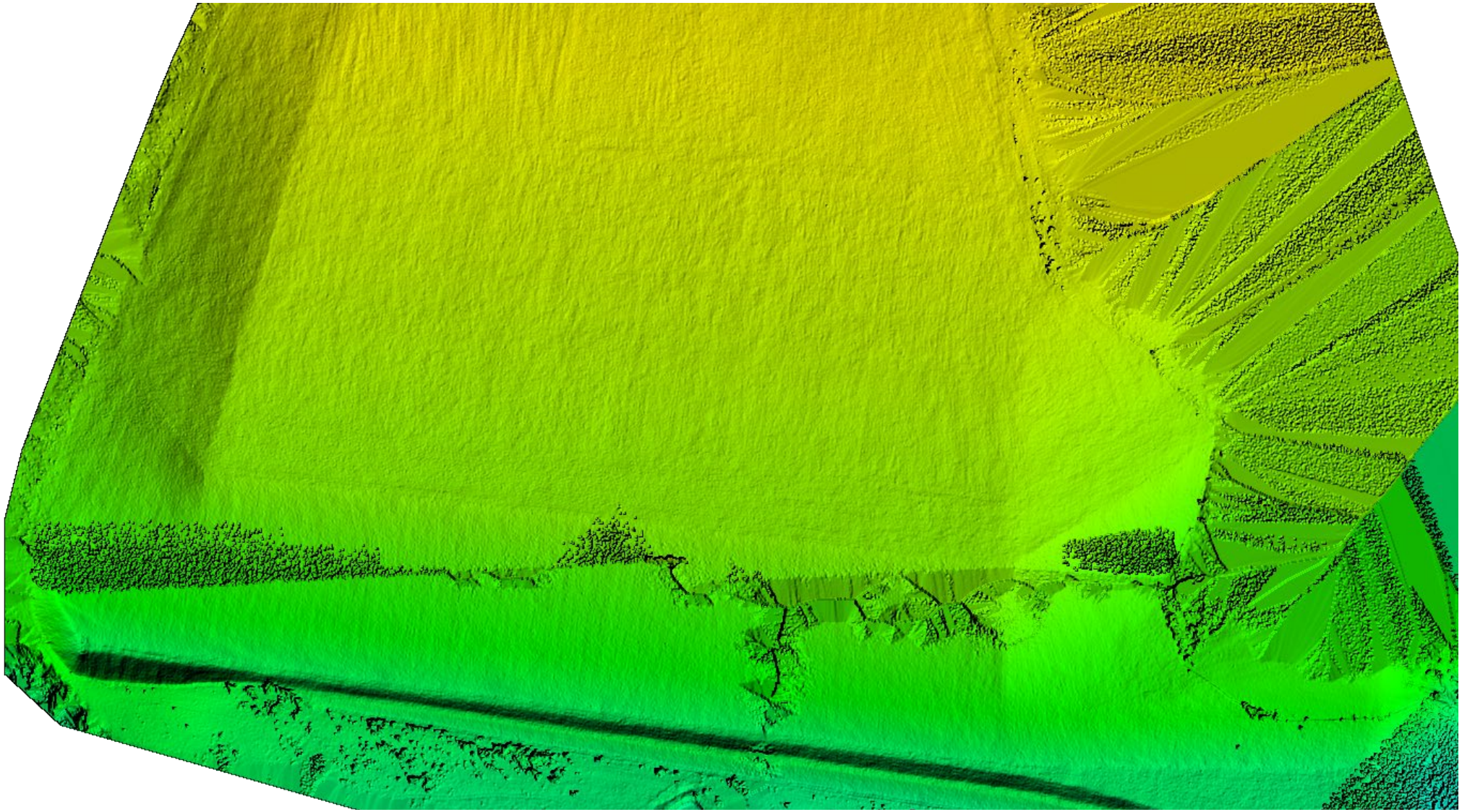
Orthomosaic Map



Digital Surface Model

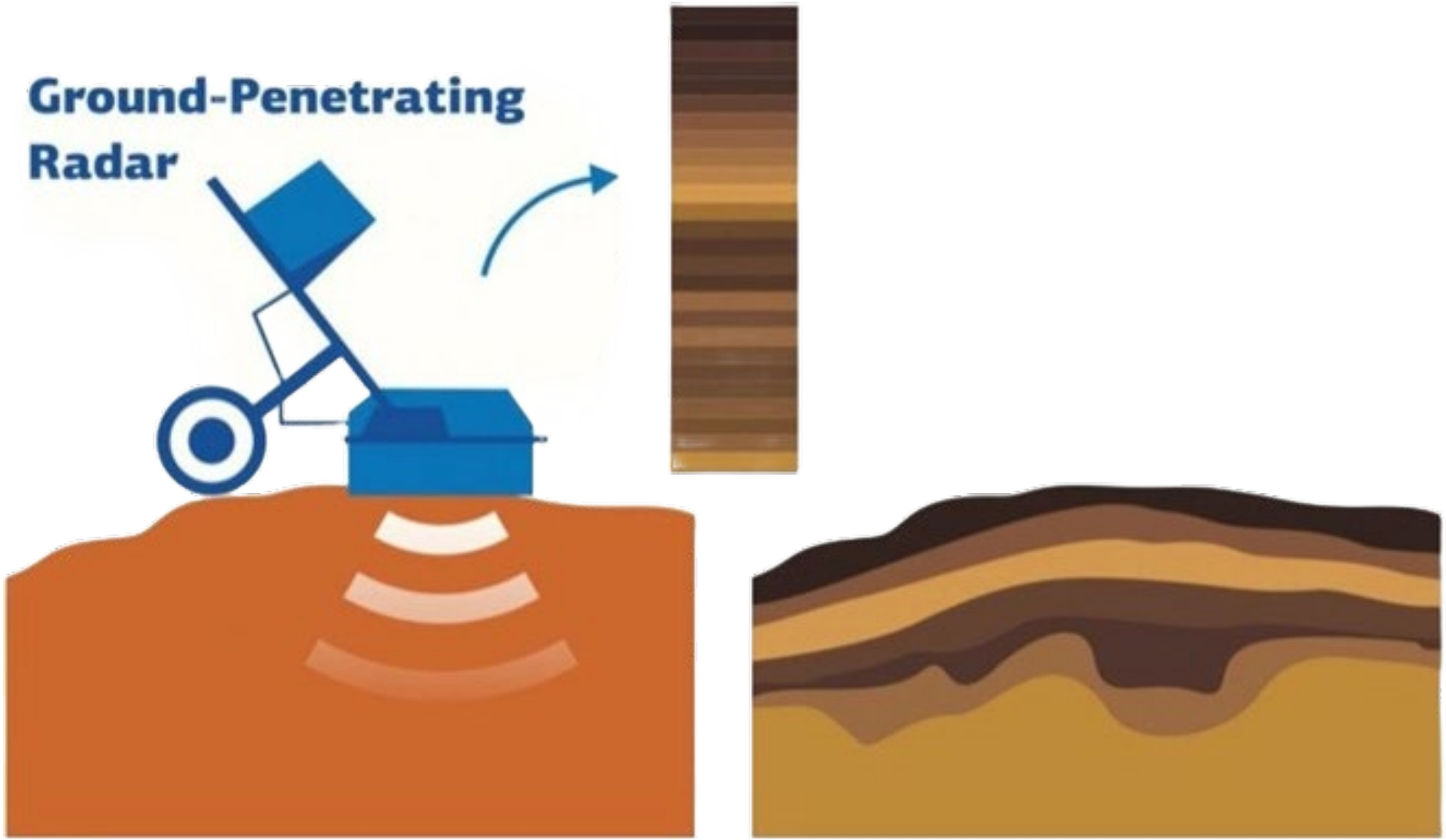
- 5,266 high-resolution aerial images
- 6 inches terrain resolution
- 5 days survey.
- 16 Batteries
- Crew intensive
- Mandatory DOE Officials Supervision
- High liabilities
- Restrictive FAA regulations
- Weather constraints
- Extreme heat

Rifle Cell Digital Elevation Model



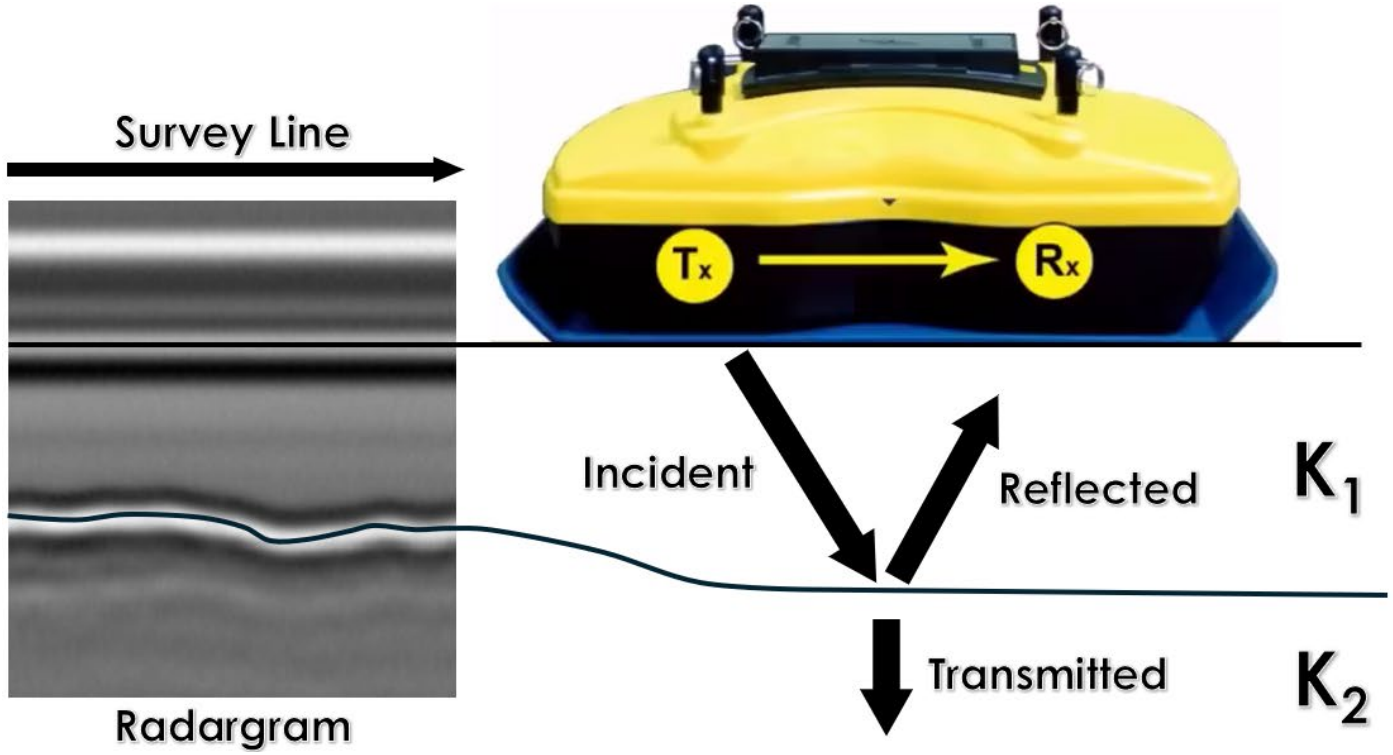
Erosion Features

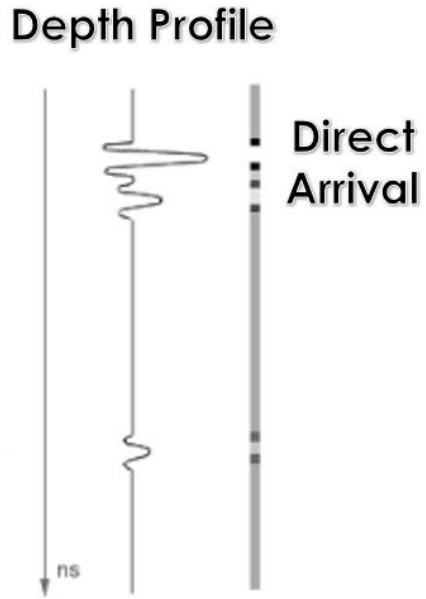
Ground Penetrating Radar (GPR)



Ground Penetrating Radar (GPR)

- GPR is a non-invasive subsurface imaging tool
- Mature technology for Applications in landfill management





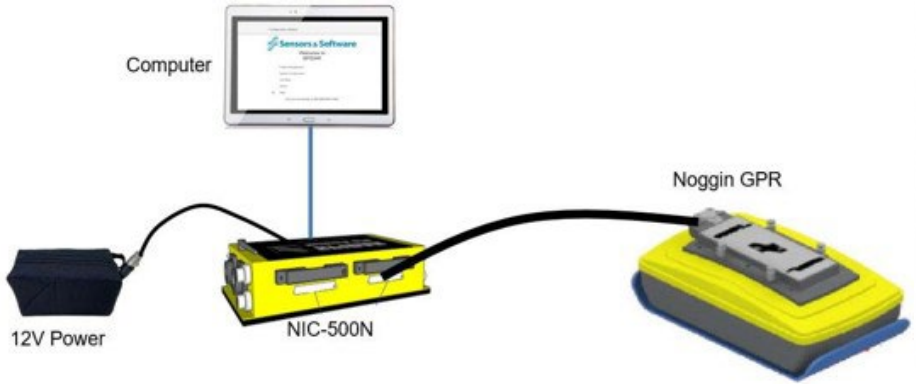
Material	Dielectric Constant (K)
Air	1
Ice	3 - 4
Sand (dry)	3 - 5
Soil (dry)	3 - 5
Clays (dry)	2 - 6
Granite	4 - 6
Riprap	4 - 9
Limestone	4 - 8
Shales	5 - 15
Silts	5 - 30
Sand (wet)	20 - 30
Soil (wet)	3 - 40
Clays (wet)	5 - 40
Fresh Water	80
Metal	∞

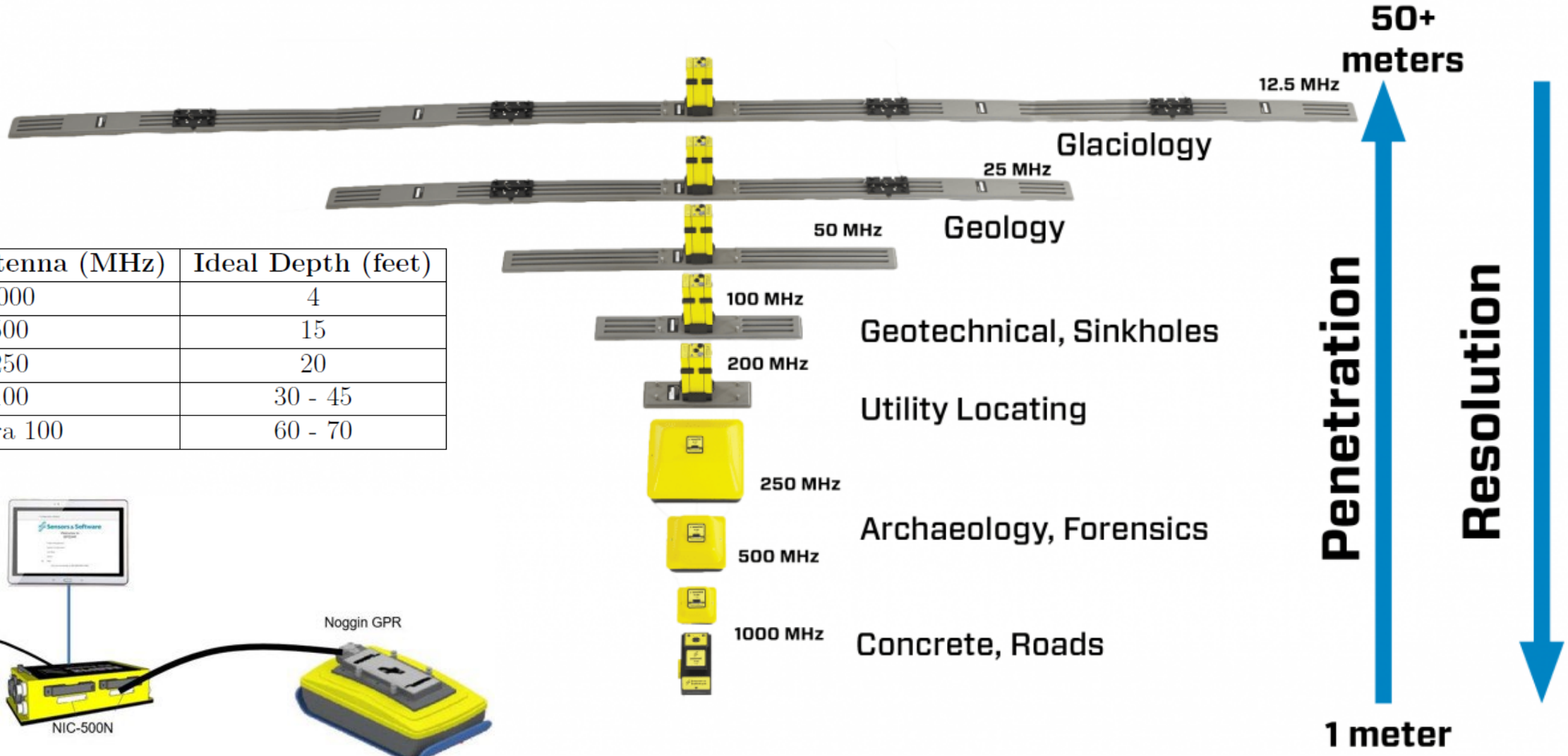
Fresnel's equations $R = \dfrac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}}$

Material	K_1	Material	K_2	R (%))
Soil (dry)	3 - 5	Air	1	27 - 38
Soil (wet)	3 - 40	Air	1	27 - 73

Ground Penetrating Radar (GPR)

Noggin Antenna (MHz)	Ideal Depth (feet)
1000	4
500	15
250	20
100	30 - 45
Ultra 100	60 - 70





Ground Penetrating Radar (GPR)

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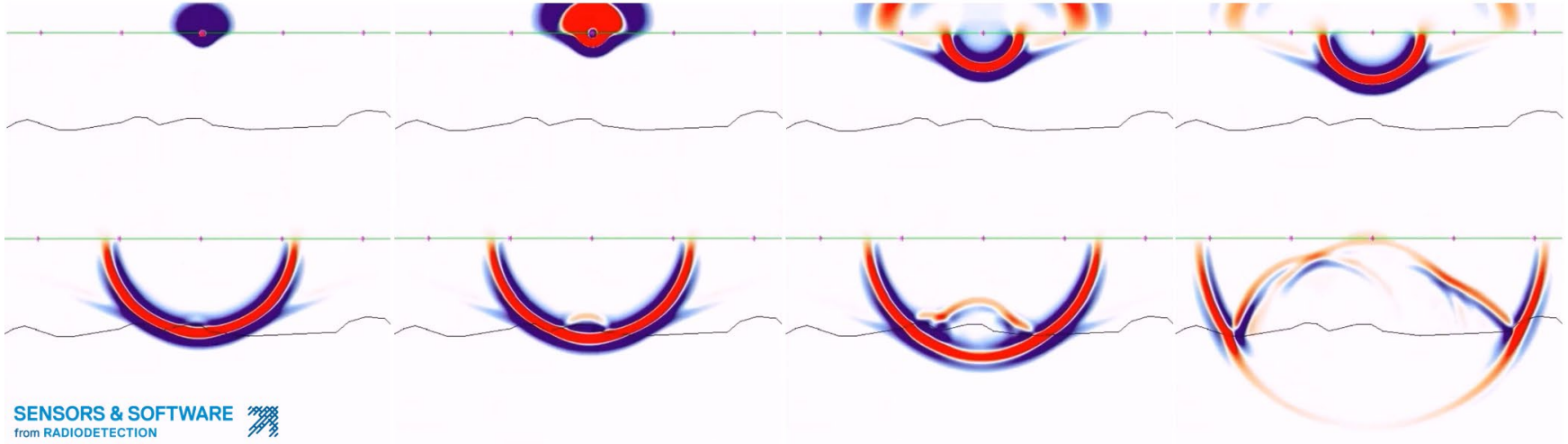
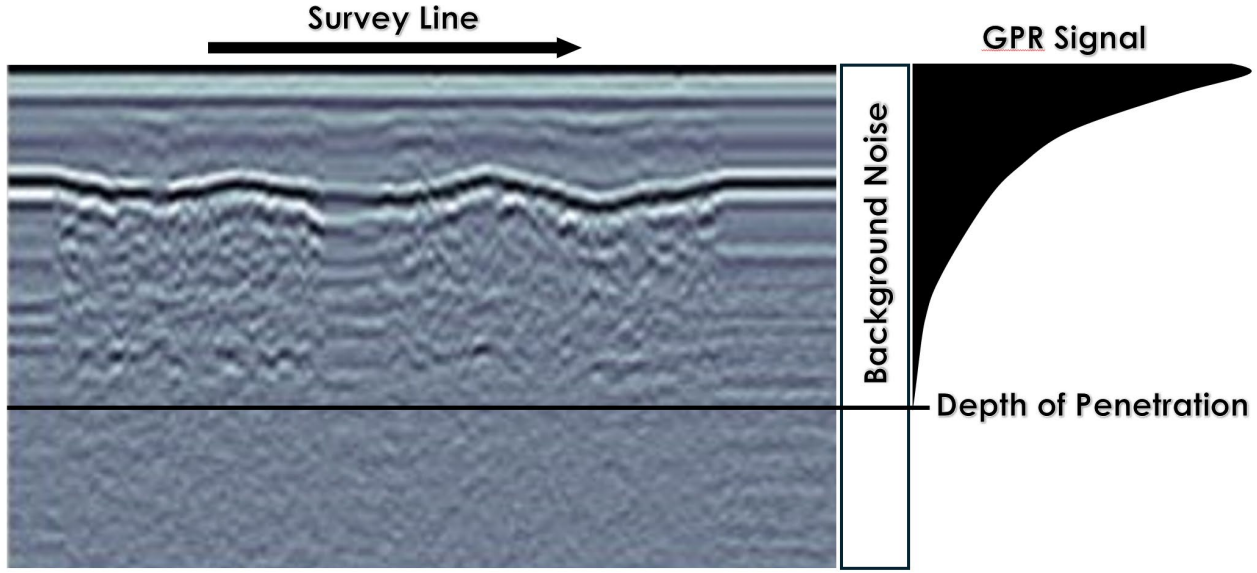
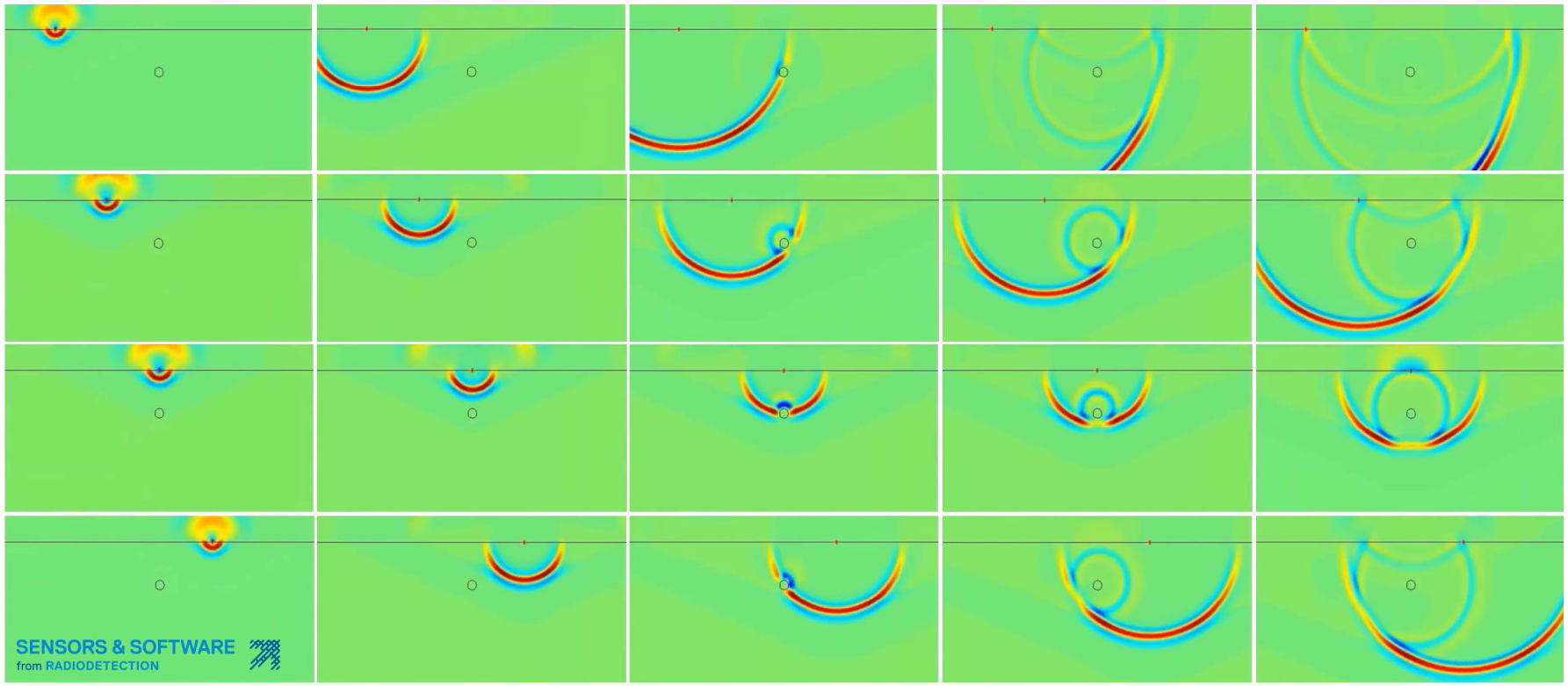


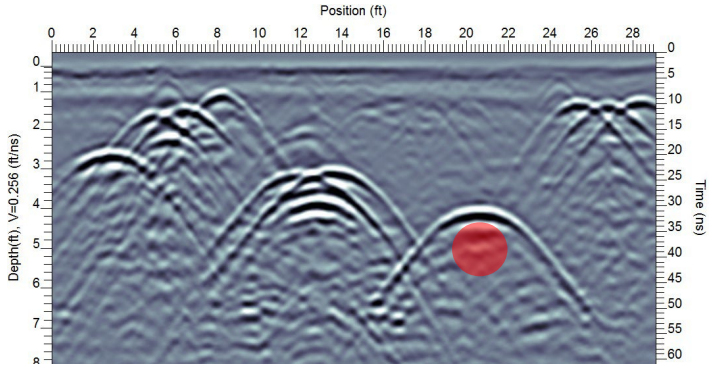
"GPR does not detect material composition but rather subsurface interfaces," and context is crucial for accurate interpretation.



Ground Penetrating Radar (GPR)

Survey Line

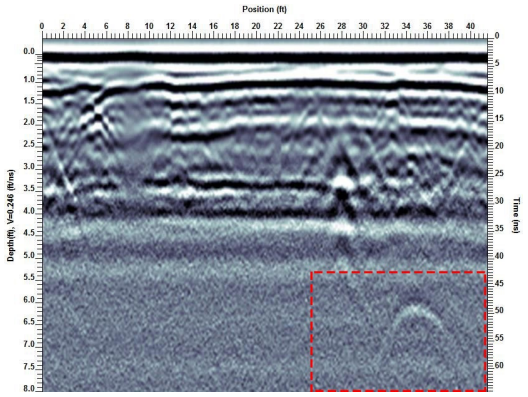


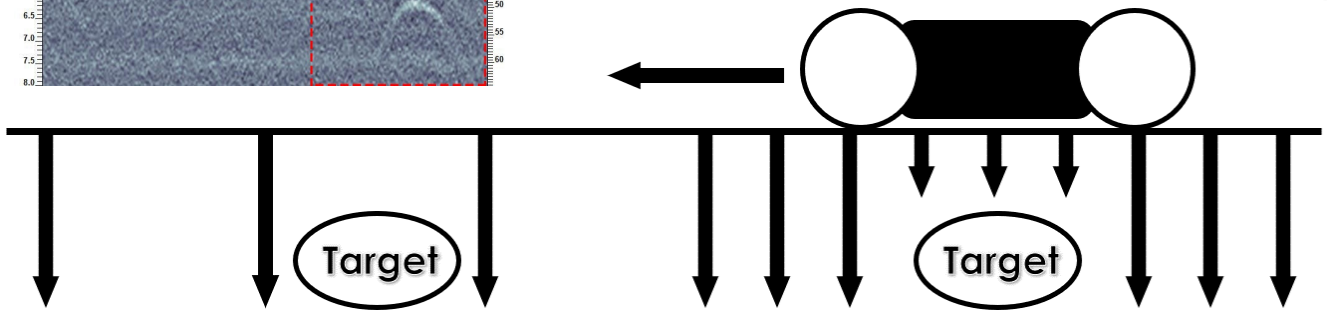


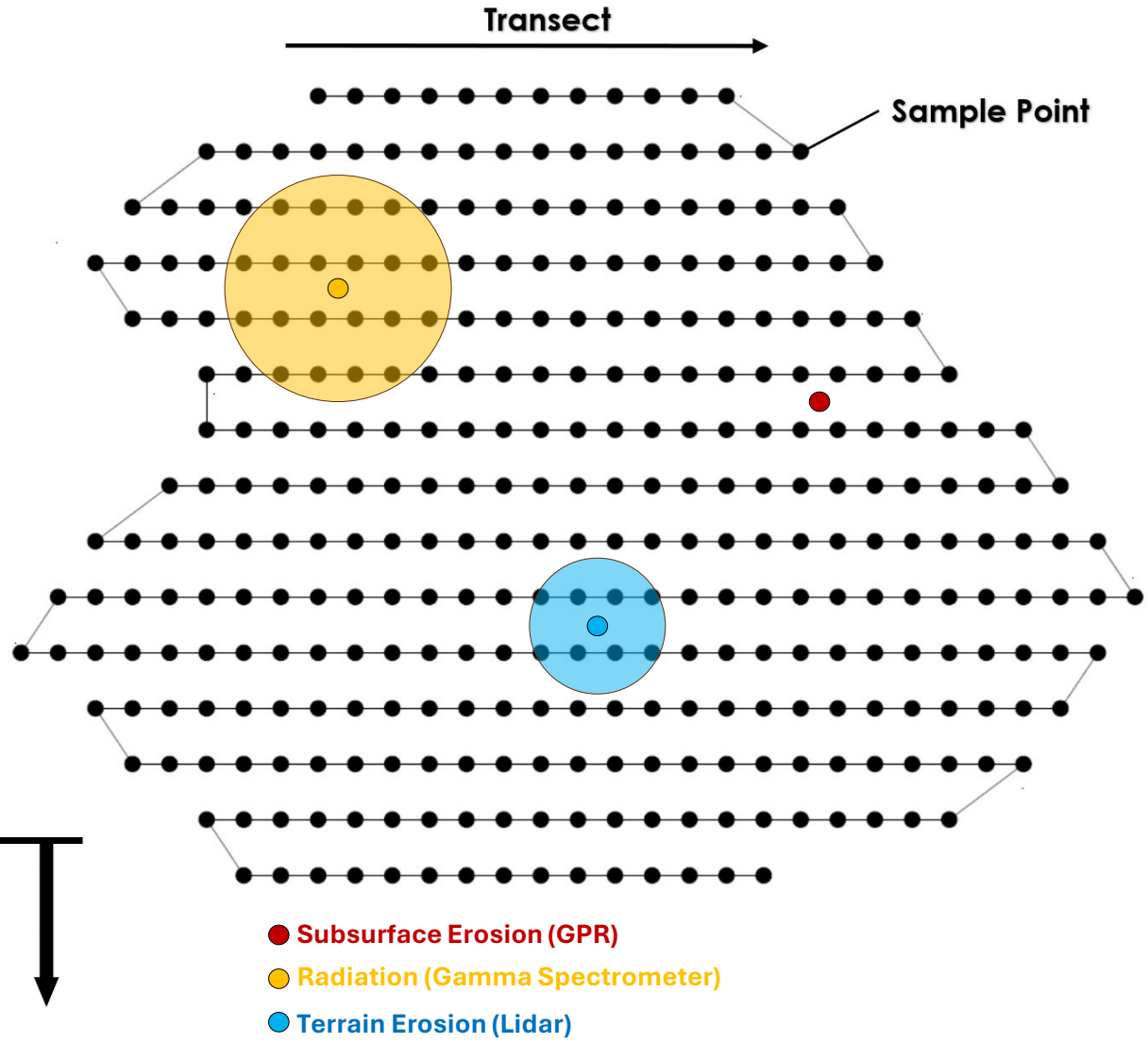
"Ghost reflections!"

Autonomous Ground Robots
for Environmental Monitoring

- Automate manual sampling
- GPS autonomously navigation
- Perform obstacle avoidance
- Data postprocessed

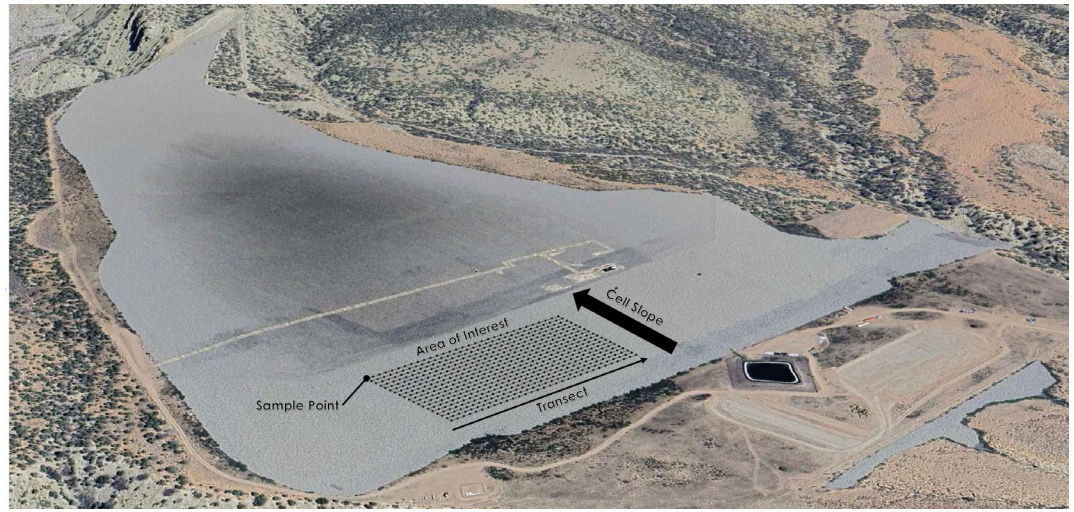






Active Mapping

“The sensing system functions as an intelligent agent, using environmental perception to inform and guide its actions.”



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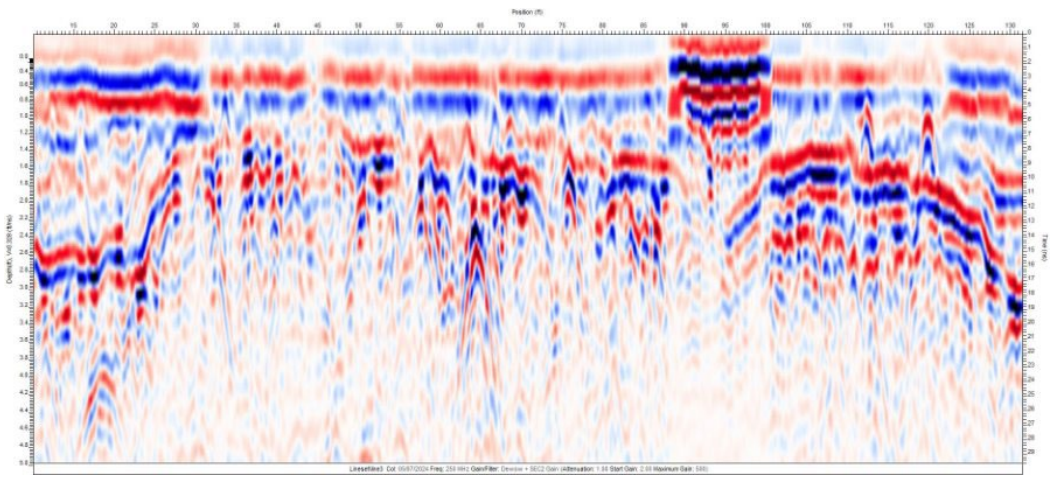
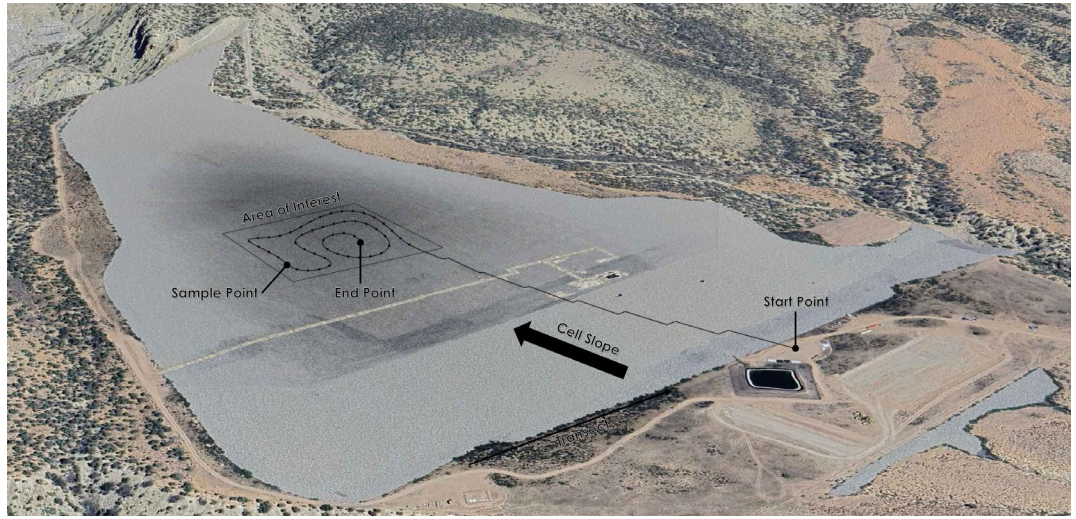


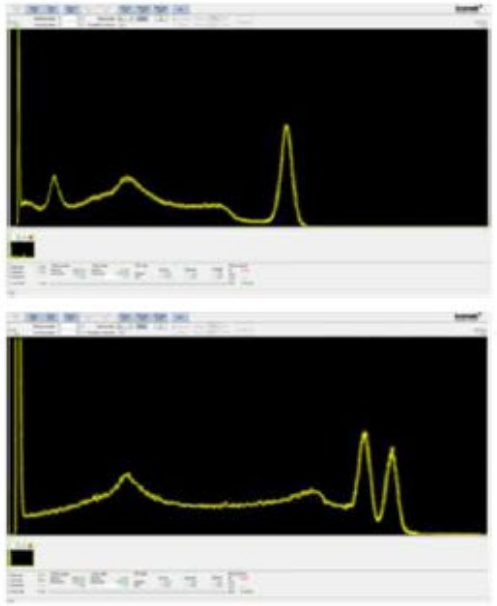


Radiation Mapping
for Environmental Monitoring

- Gamma radiation field
- Contaminated high-dose areas

Sigma 50
Omnidirectional
(broad field)

GR1
Collimated
(isotope Identification)

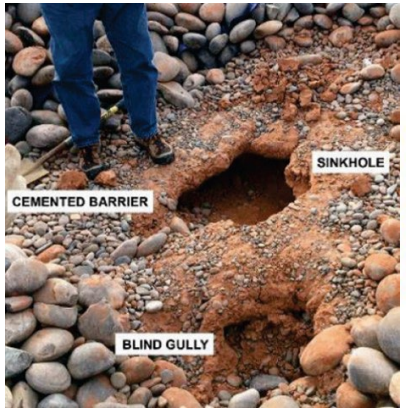


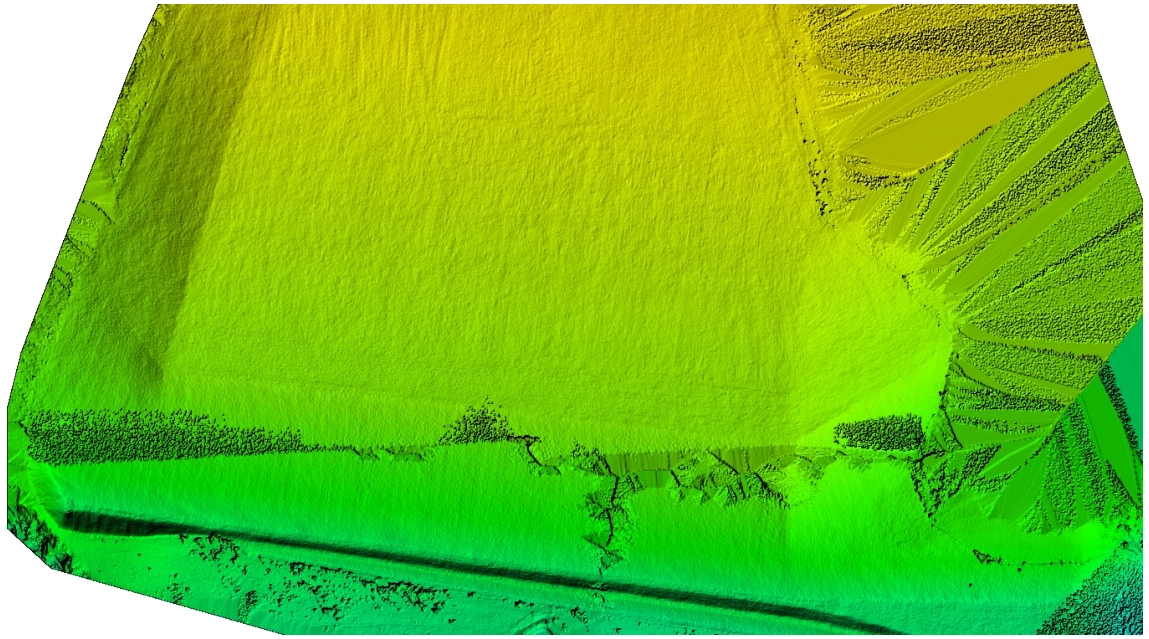
Radiation Field + Isotope Identification

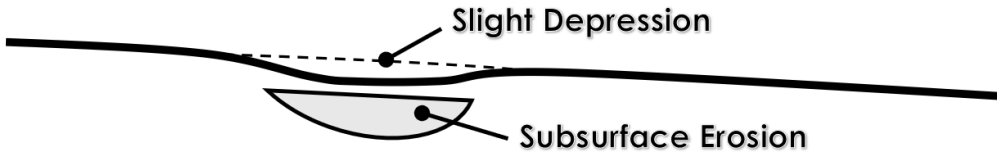
High	Low	:	**Sensitivity**
Low	High	:	**Accuracy**

Lidar Mapping for Guiding Subsurface Erosion Detection

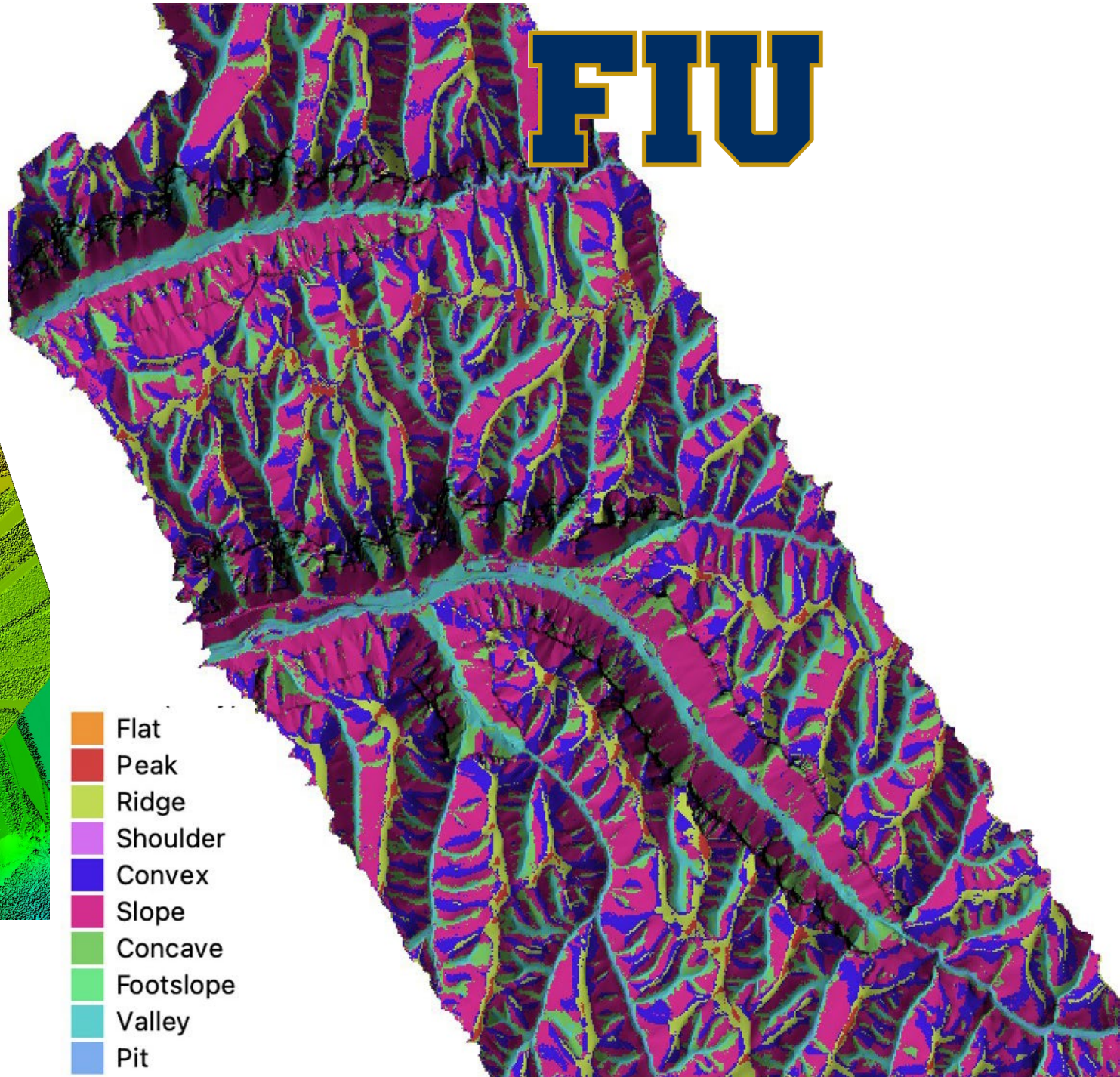
- Rain erosion
- Flow routing on terrain



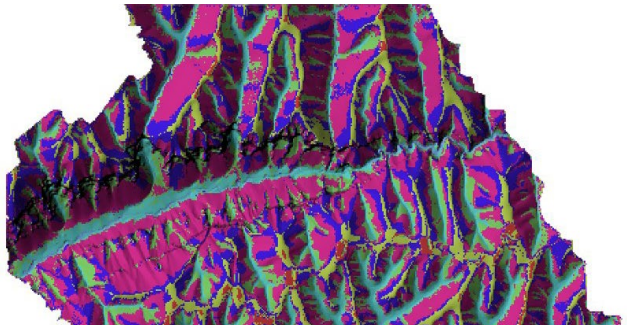


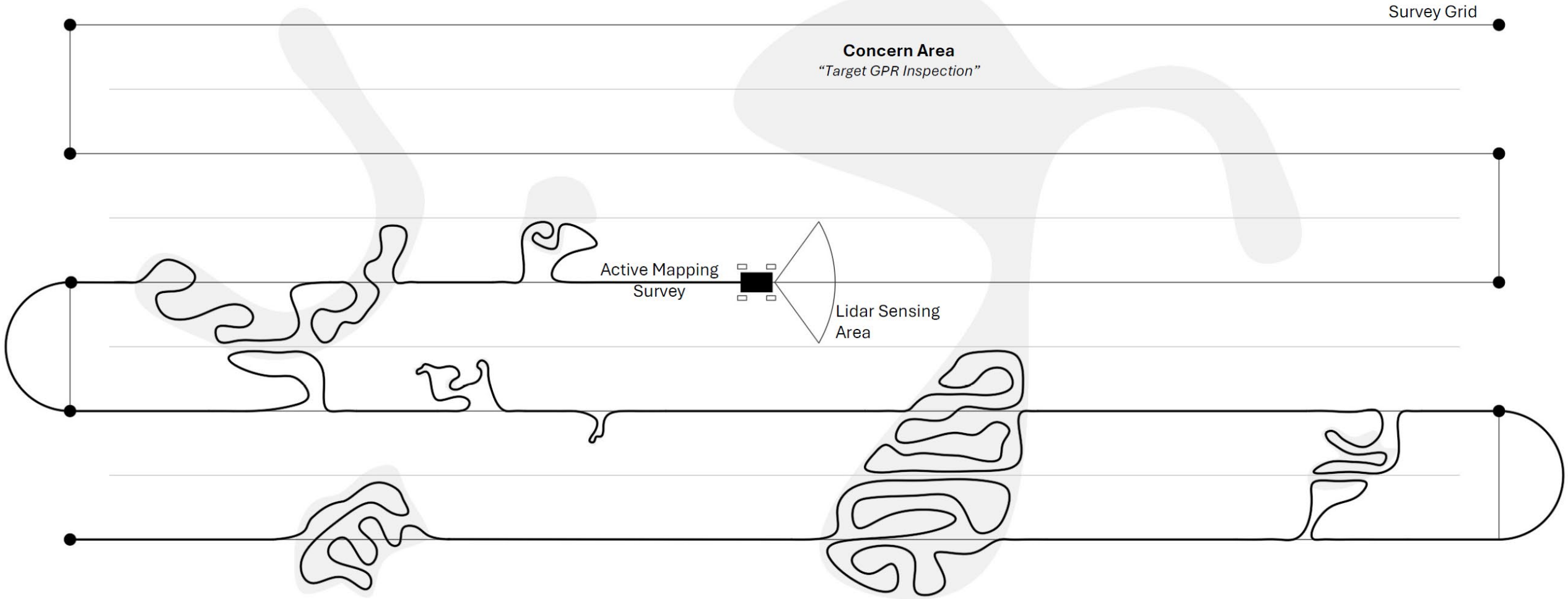


FIU



Active Mapping





Methodology

2022

Phase I: Robot Development

- GPR robot design and prototype construction
- Remote-controlled testing in lab environments for core functionality
- The prototype is deployed in the disposal cell and other DOE sites
  - Evaluate the performance of the hardware
  - The accuracy of the GPR data
  - Provide preliminary subsurface conditions to the DOE for consideration of technology.

2024

Phase II: Automation

- Upgraded prototype with enhanced perception and navigation
- Autonomous navigation and sensor integration tests in field settings

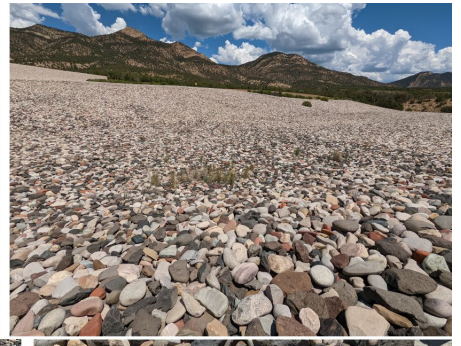
2025

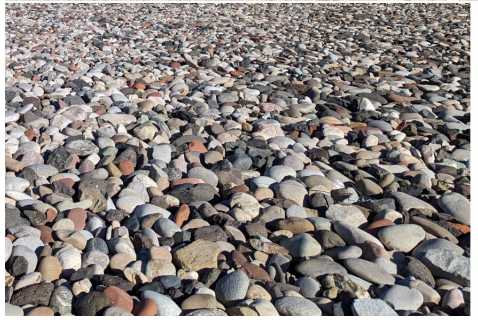
- Redeploy at DOE sites

Phase III: Full Autonomy

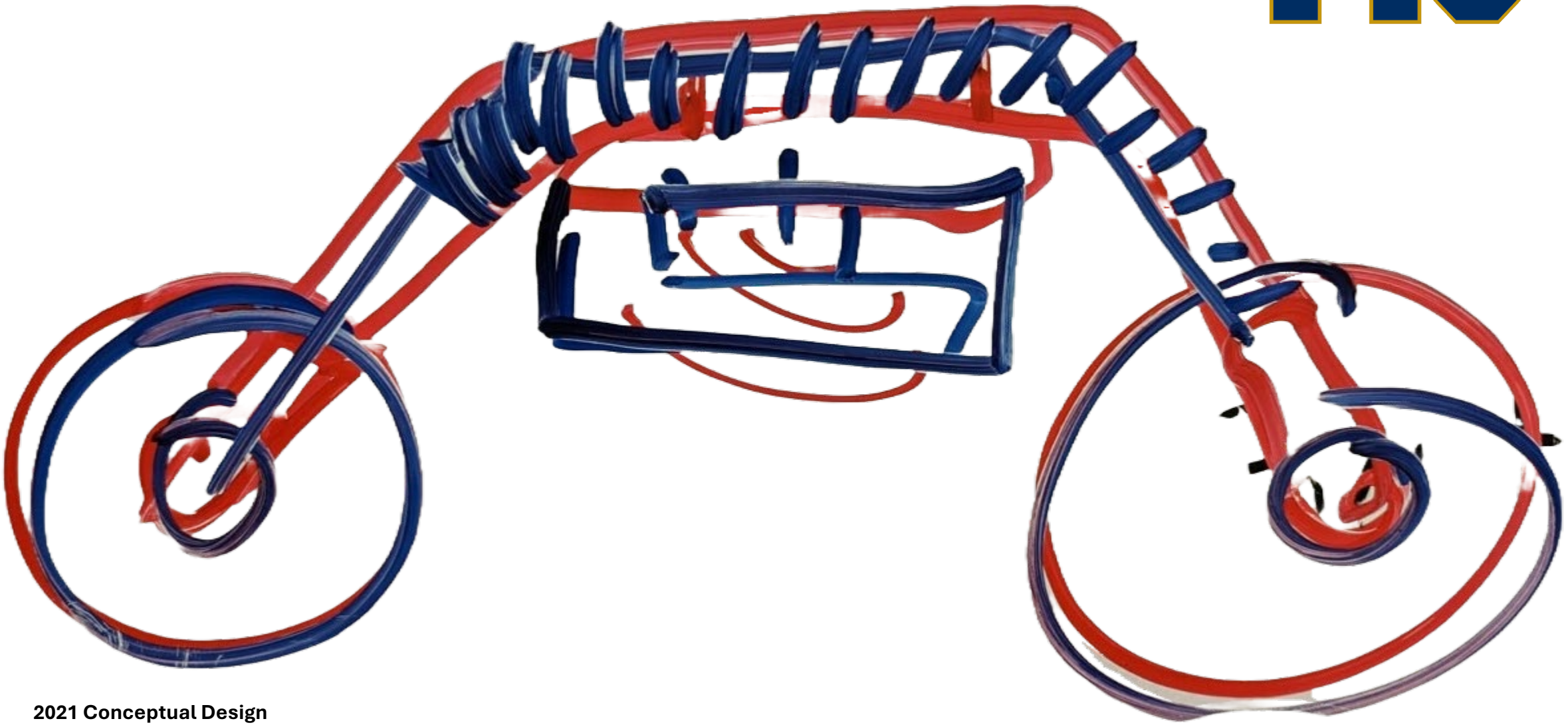
- Fully autonomous GPR surveys and data processing
- Goal: complete site coverage with minimal human intervention
  - Deploy a final system at DOE sites and demonstrate technology potential
  - Finally, transfer technology to DOE

2026



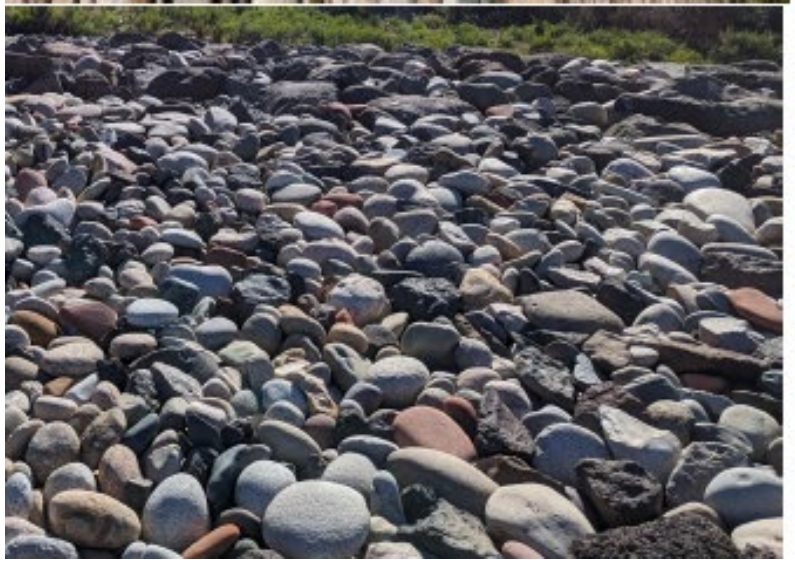
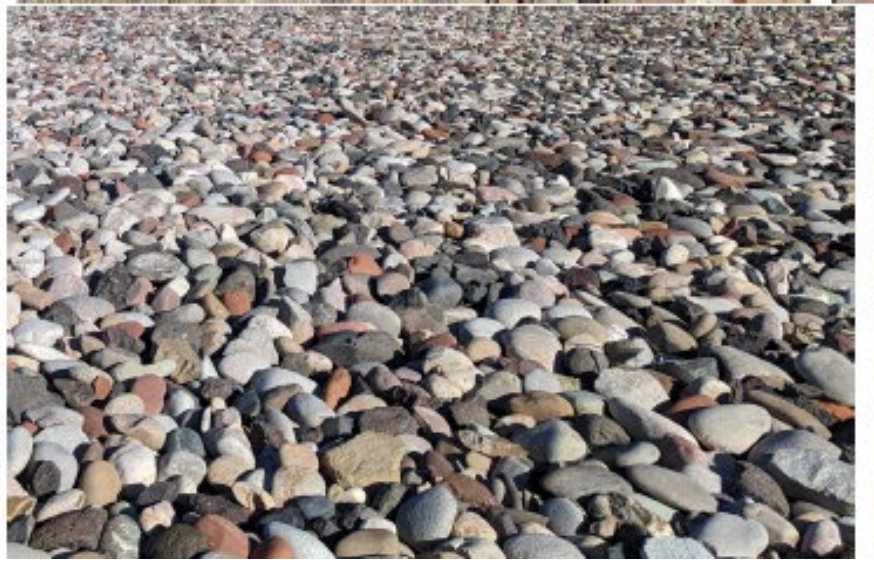


Phase I: Robot Development



2021 Conceptual Design

Phase I: Robot Development

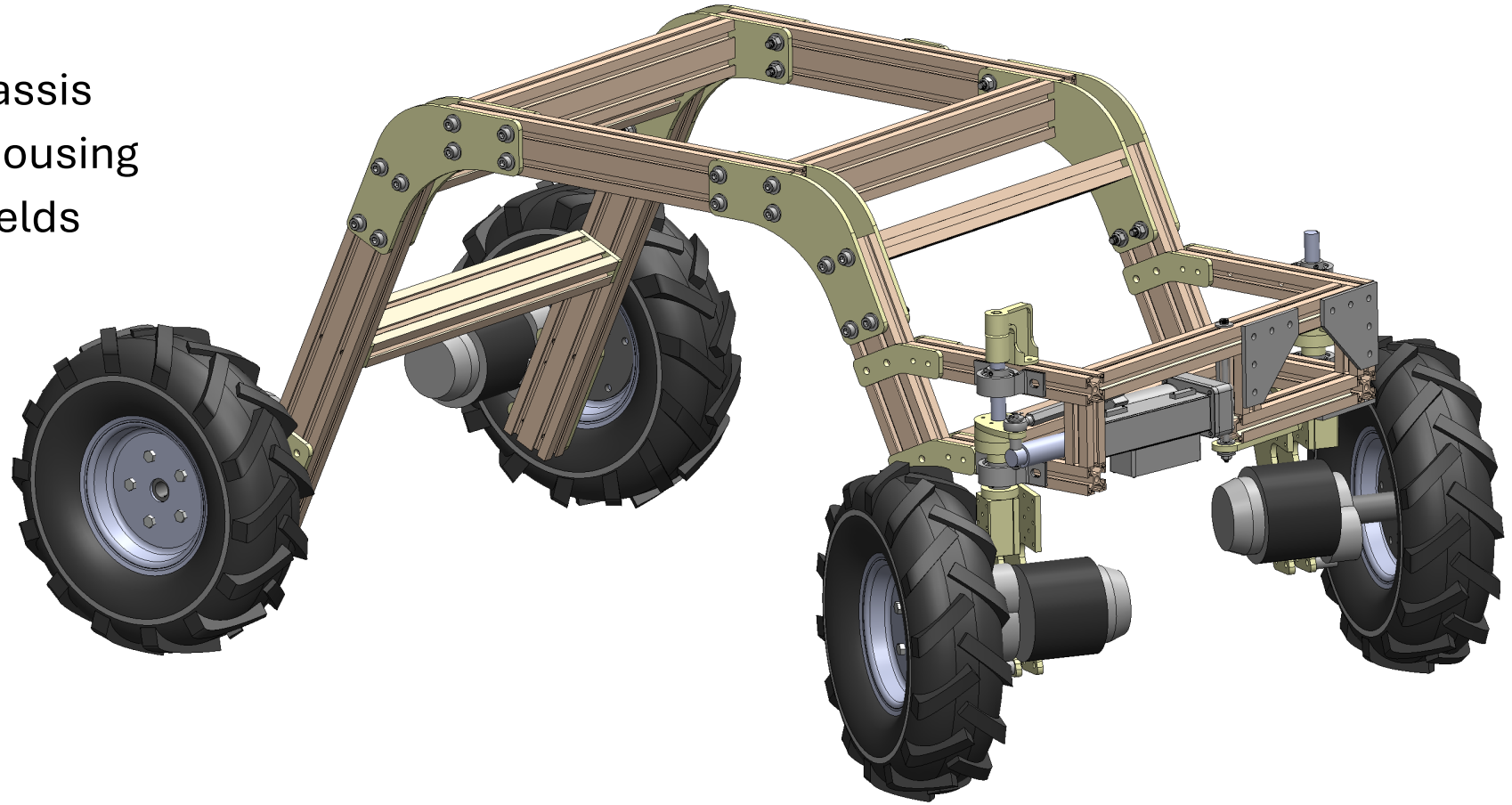
Ground Platform

Platform Frame

- Dimensions: 66" x 44" x 32“
- Weight: 250 pounds
- Custom aluminum extrusion chassis
- Saddle-shaped design for GPR housing
- Modular construction without welds

Drive System

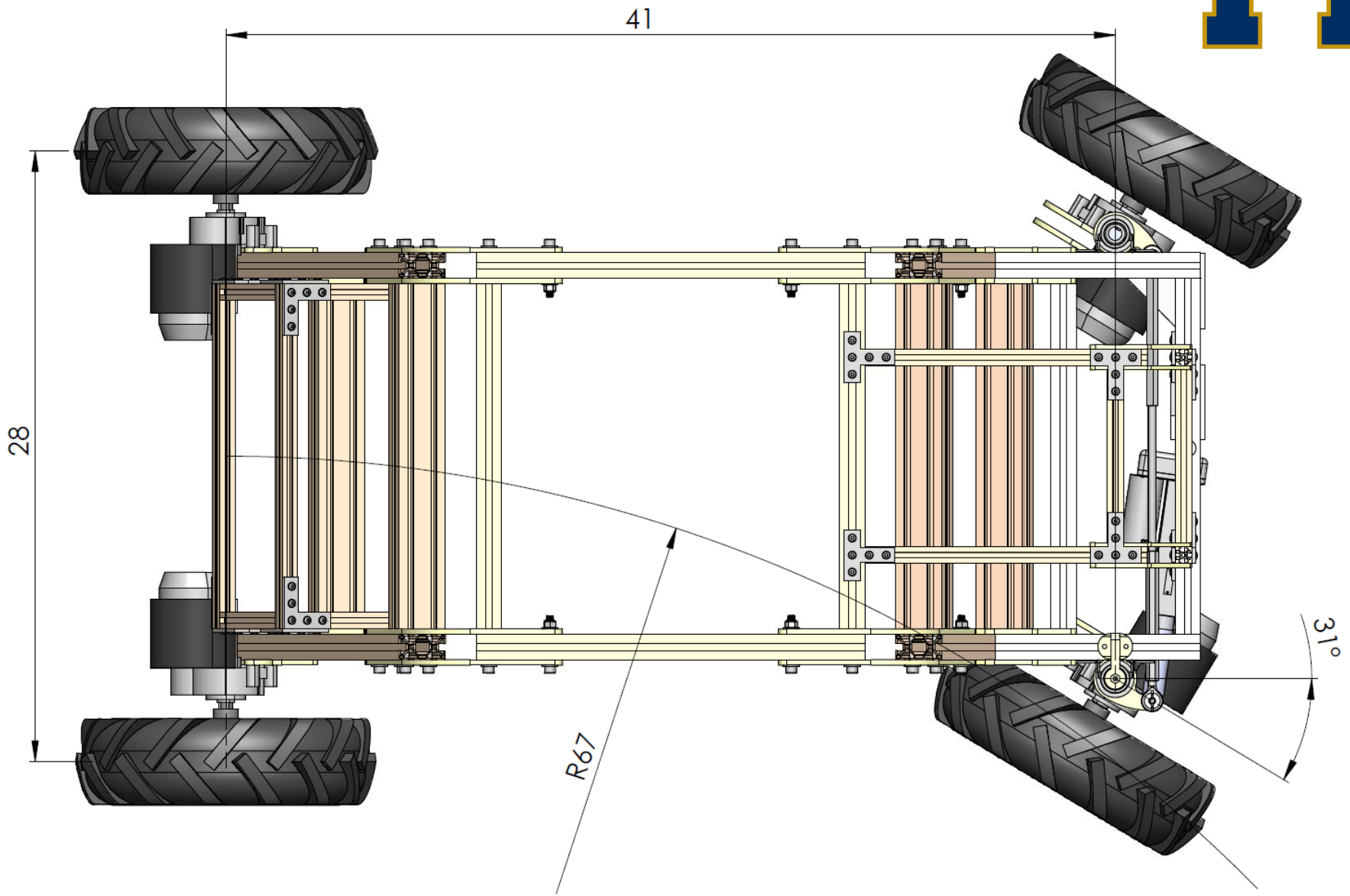
- 4 All wheel drive
- 4 x 250W gear DC motors (24V)
- 13" heavy-duty pneumatic tires
- 318 lb-in torque per wheel
- 31° parallel steering mechanism
- 67“ turning radius
- 2.90 mph maximum speed



Transport

The chassis shape considers the SUV’s cargo volume for deployment.

Drive System



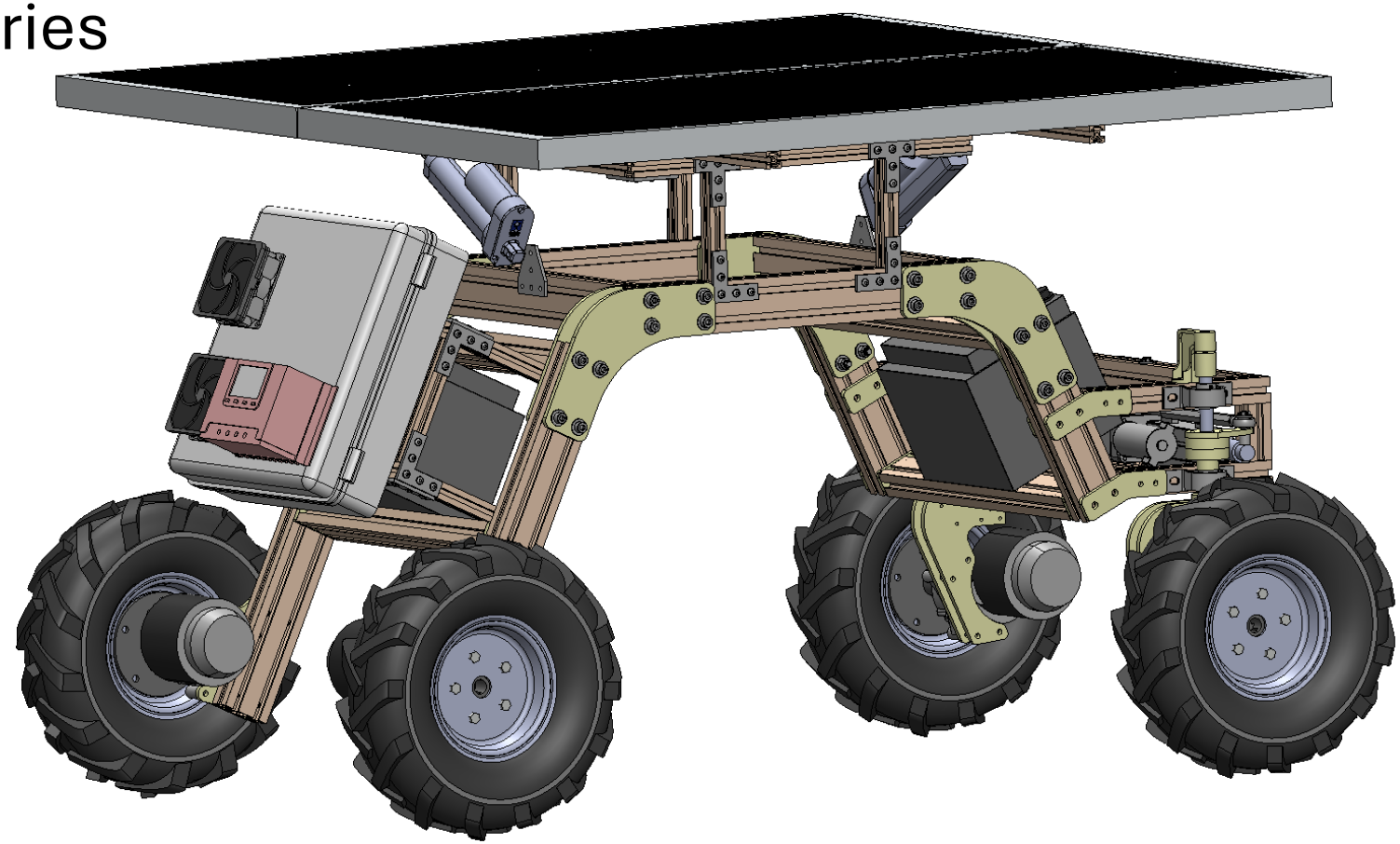
Solar-Powered Sustainability

Power Sources

- Dual 100W monocrystalline solar panels
- Two 24V 25Ah LiFePO4 batteries
- MPPT charge controller

Safety Features

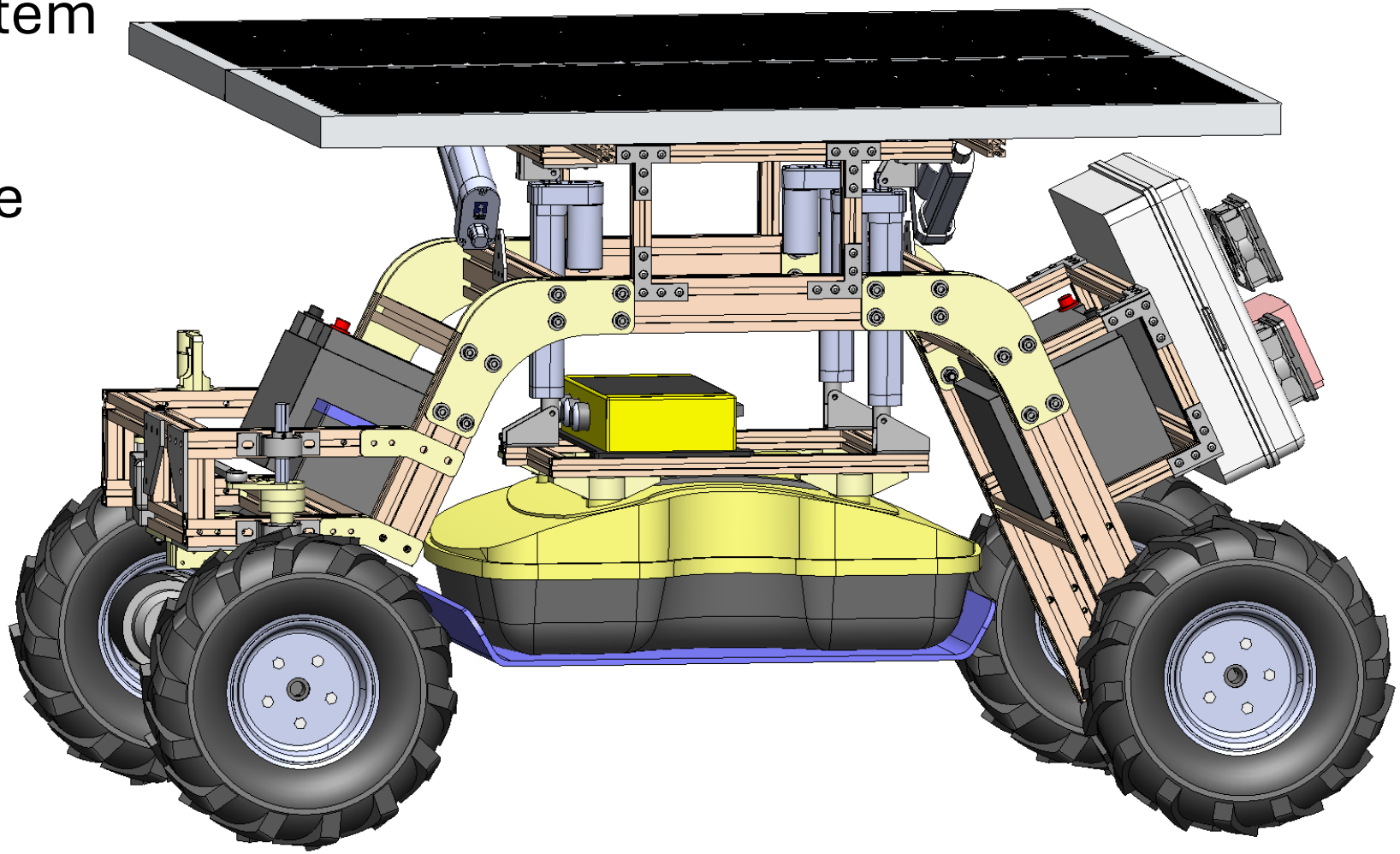
- Built-in battery protection
- Voltage spike management
- Thermal regulation
- Emergency power cutoff



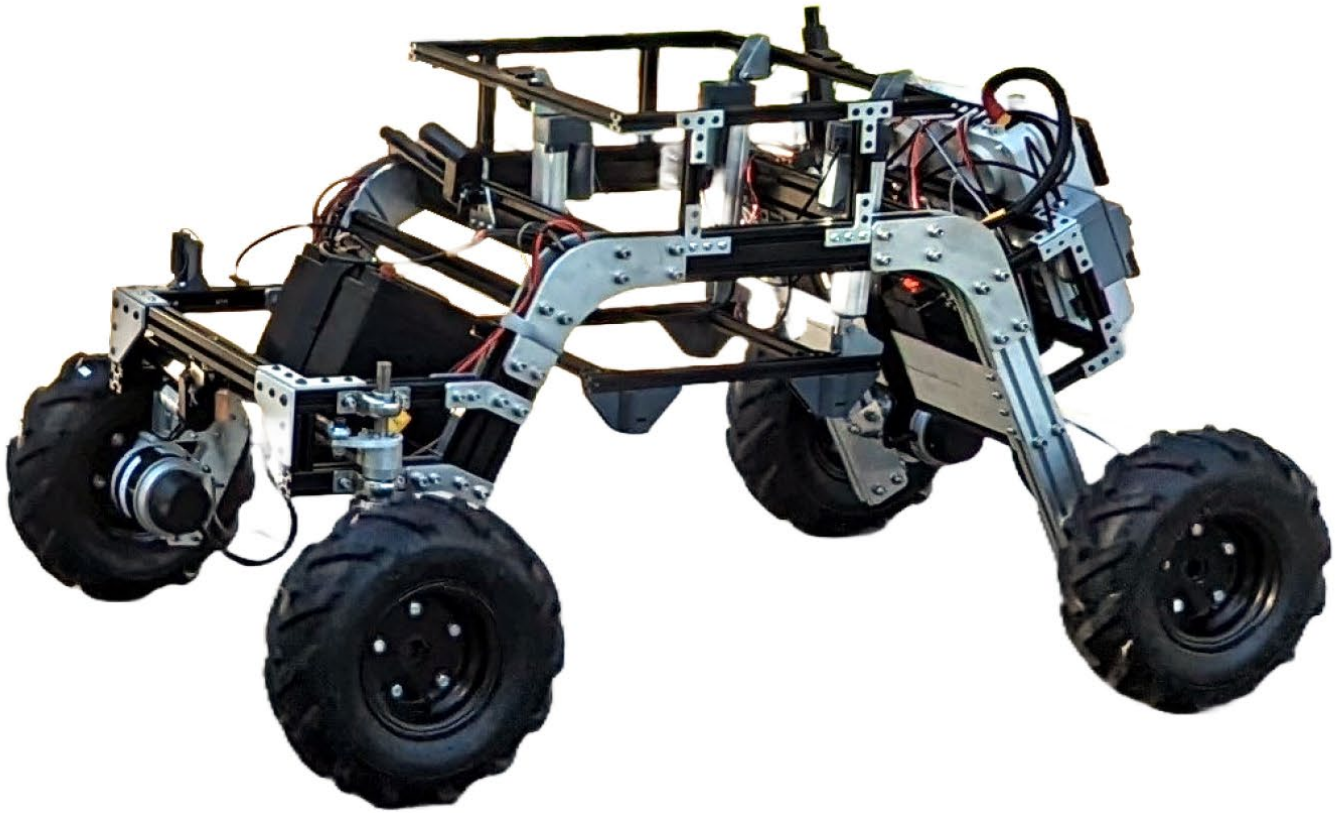
Subsurface Imaging

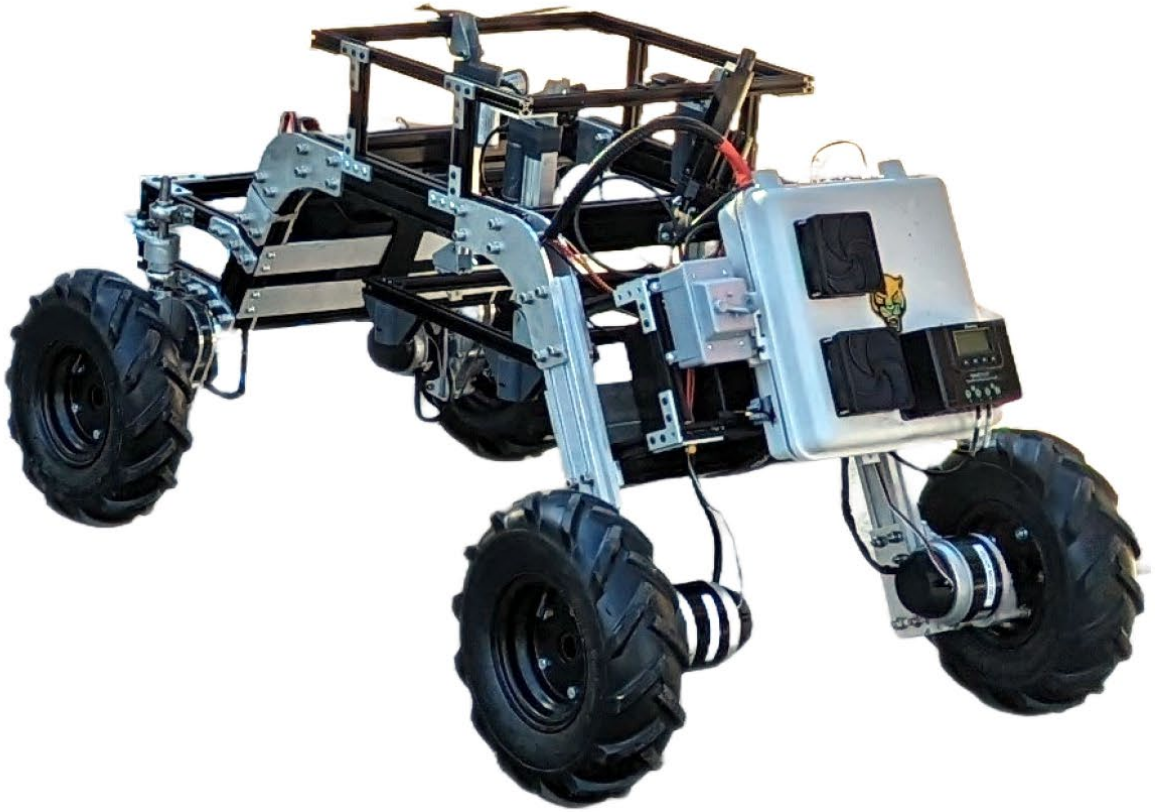
Ground Penetrating Radar

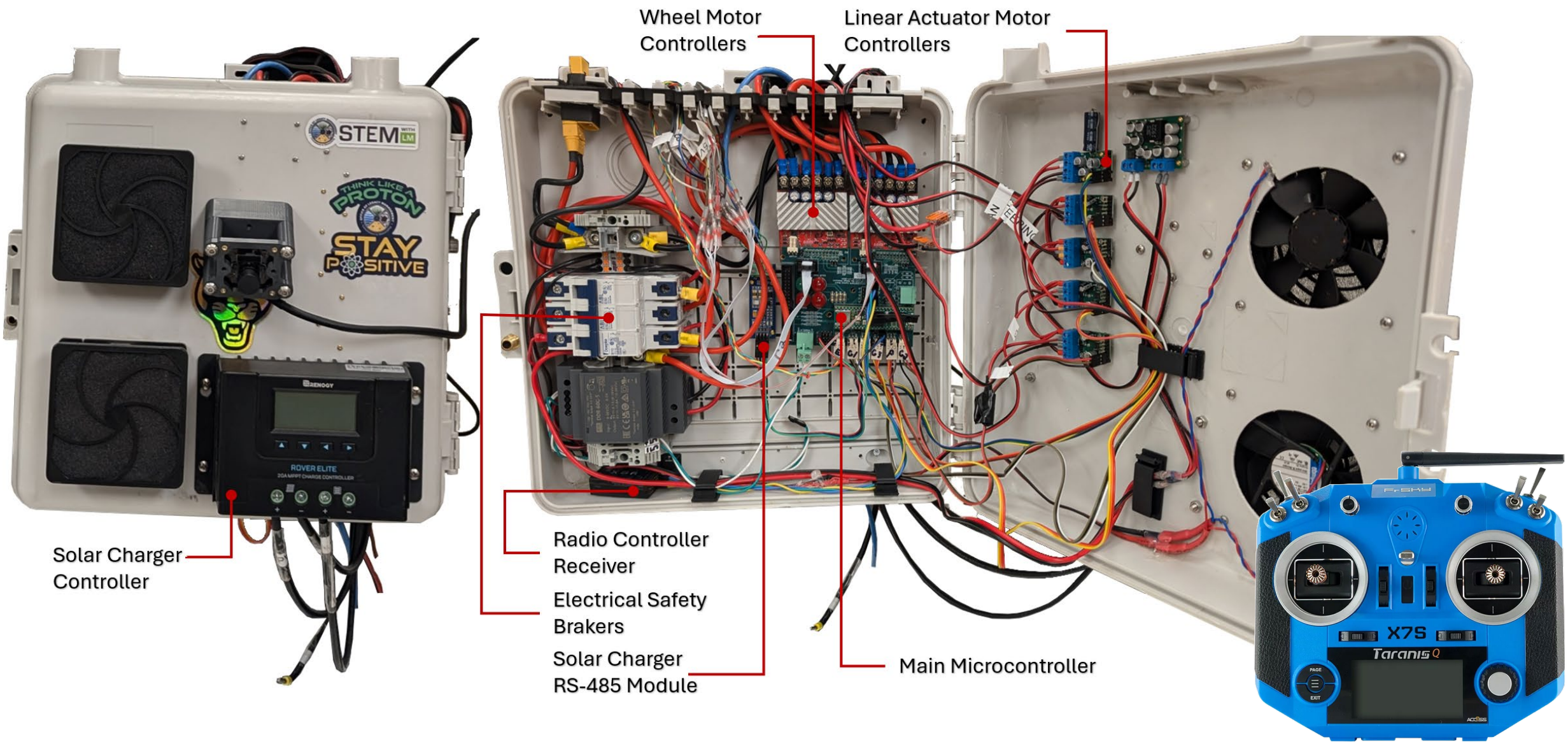
- Self-contained GPR system
- A 250 MHz antenna
- Data acquisition module
- Dedicated battery pack



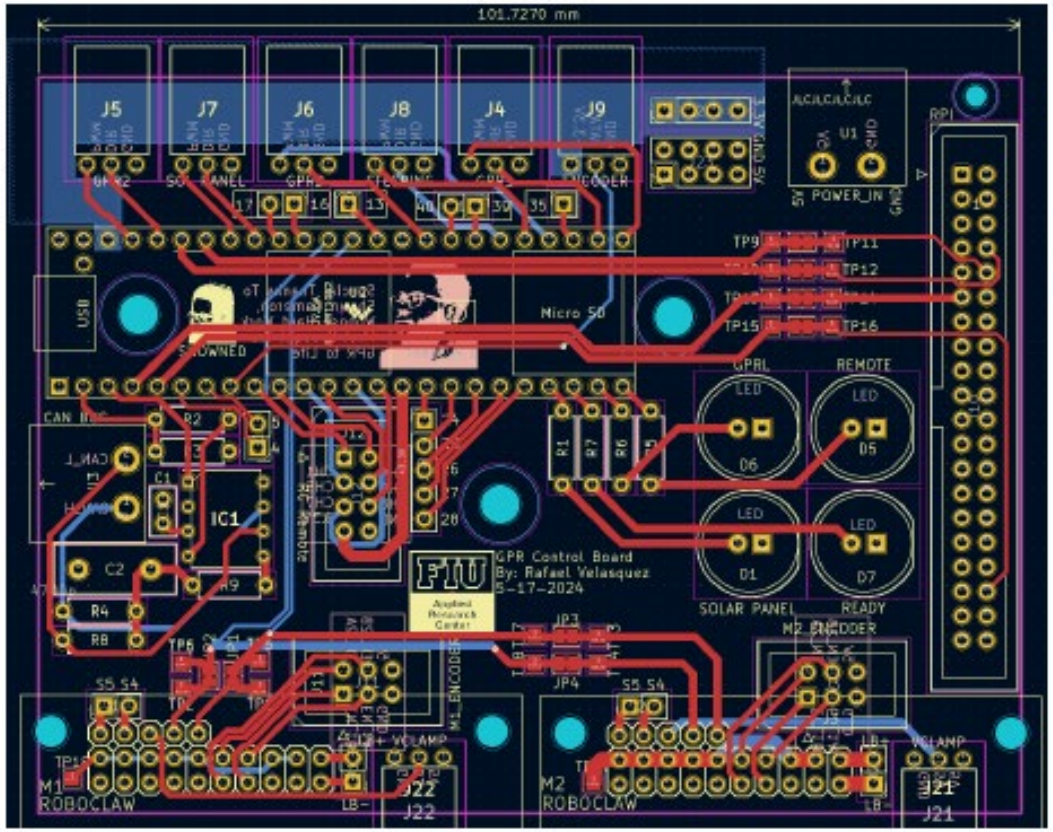
Prototype

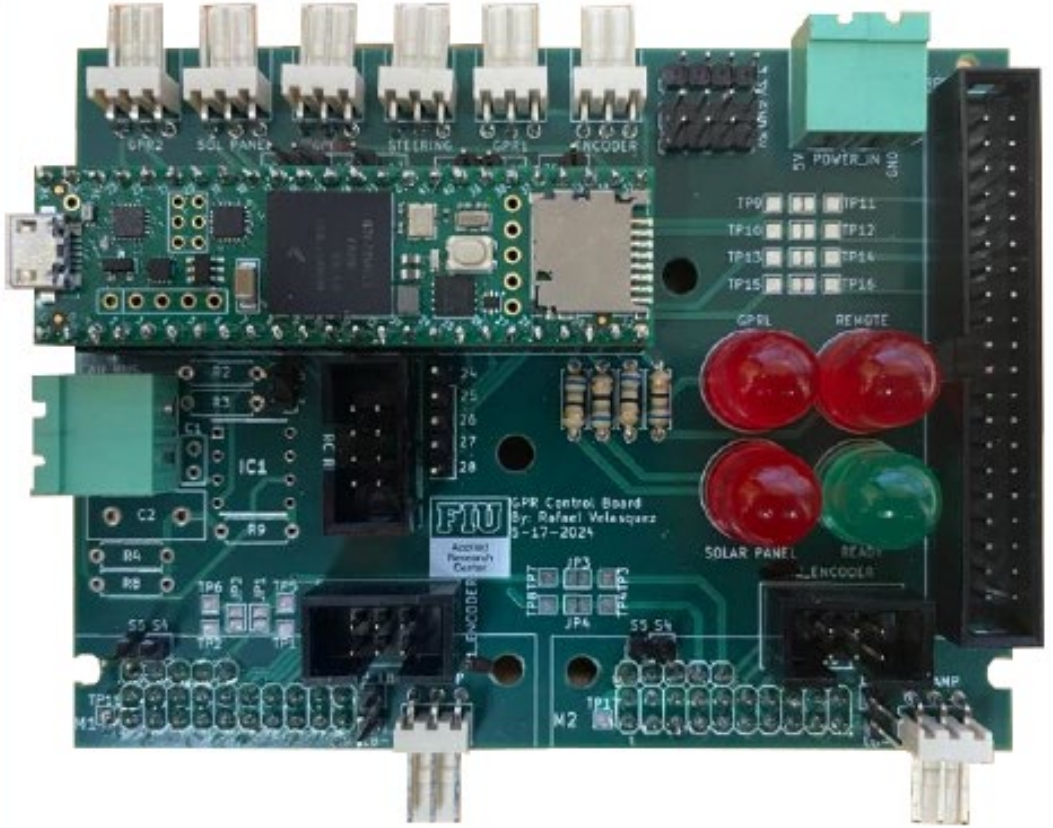





Wheel Motor Controllers
Linear Actuator Motor Controllers
Solar Charger Controller
Radio Controller Receiver
Electrical Safety Brakers
Solar Charger RS-485 Module
Main Microcontroller
STEM
THINK LIKE A PROTON
STAY POSITIVE
ROVER ELITE
X7S
Taranis Q

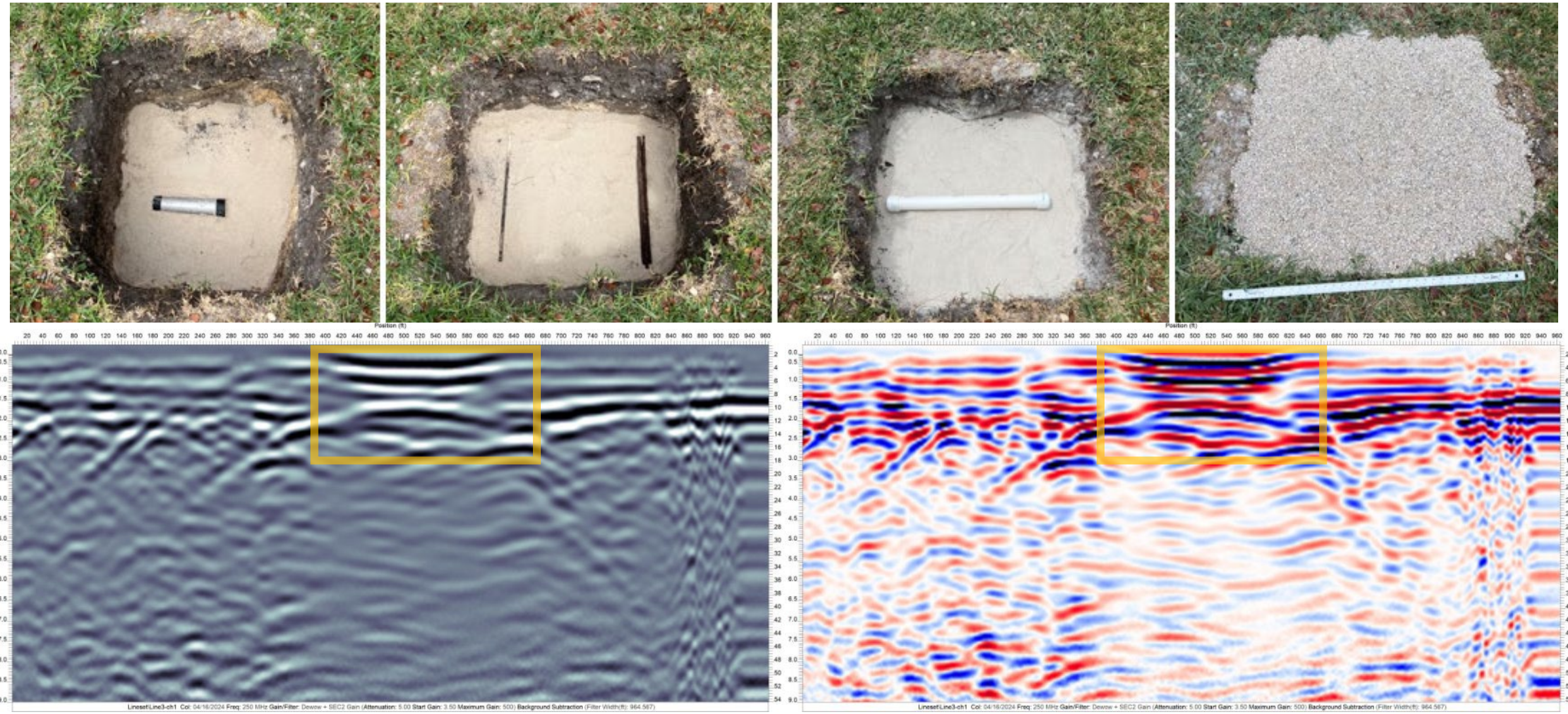
Main Microcontroller





Loading Test
“Easy deployment”

GPR Evaluation

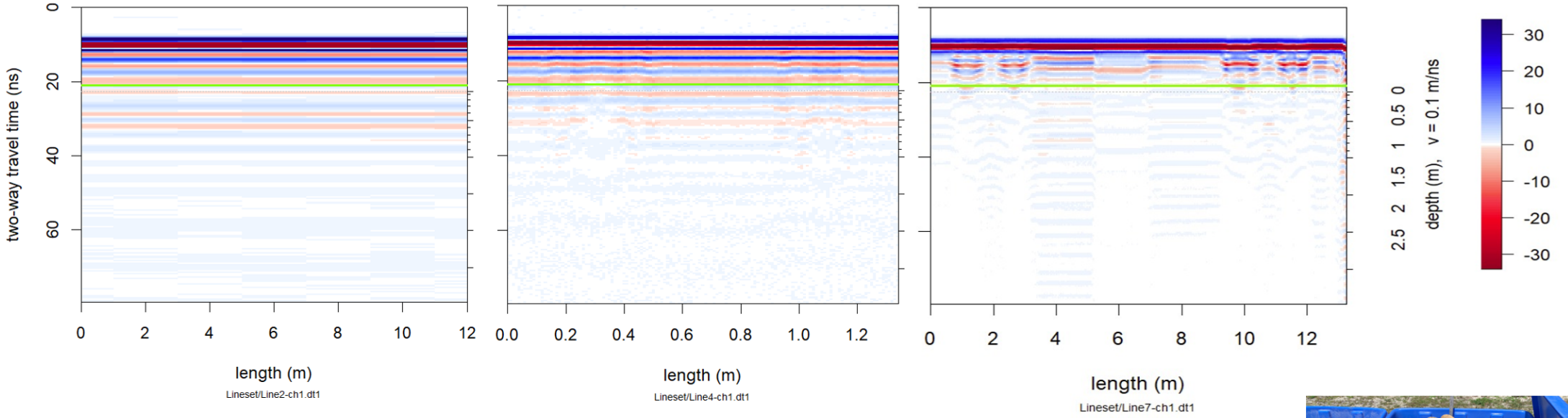


GPR Evaluation

Disposal Cell	Erosion Protection	Bedding	Frost Protection	Bio Intrusion Riprap Type A	Bedding	Radon Barrier
Durango	1'0"	6"	1'6"	1'6"	6"	2'0"
Rifle	1'0"	6"	7'6" - 18'	None	6"	1'6"
Mexican Hat	8" & 12"	6"	None	None	None	2'0"
Lakeview	1'0"	18"	None	None	None	18"
Sherwood	6"	12.6' - 20'	None	None	None	None

Testbed 3	Testbed 2	Testbed 1
1' Riprap (Layer of rocks)	0.656'Riprap (Layer of rocks)	1'Riprap (Layer of rocks)
½'Bedding (Layer of rock/soil mixture)	½'Bedding (Layer of rock/soil mixture)	½'Bedding (Layer of rock/soil mixture)
½' Frost protection (Layer of compacted soil)	½'Bentonite Clay (Radon barrier)	1'Frost protection (Layer of compacted soil)
½' Bentonite clay (Radon barrier)	N/A	N/A

GPR Evaluation



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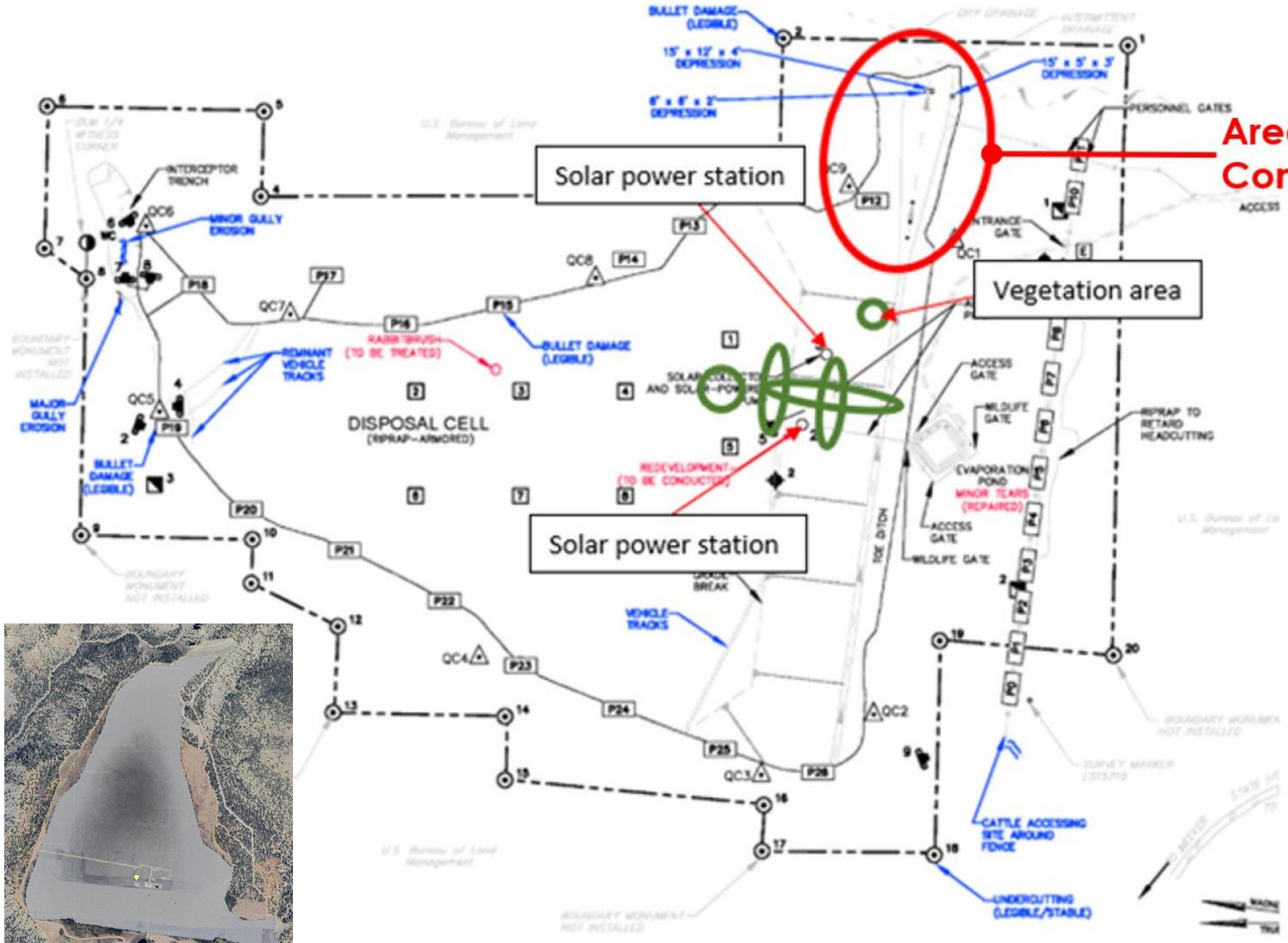
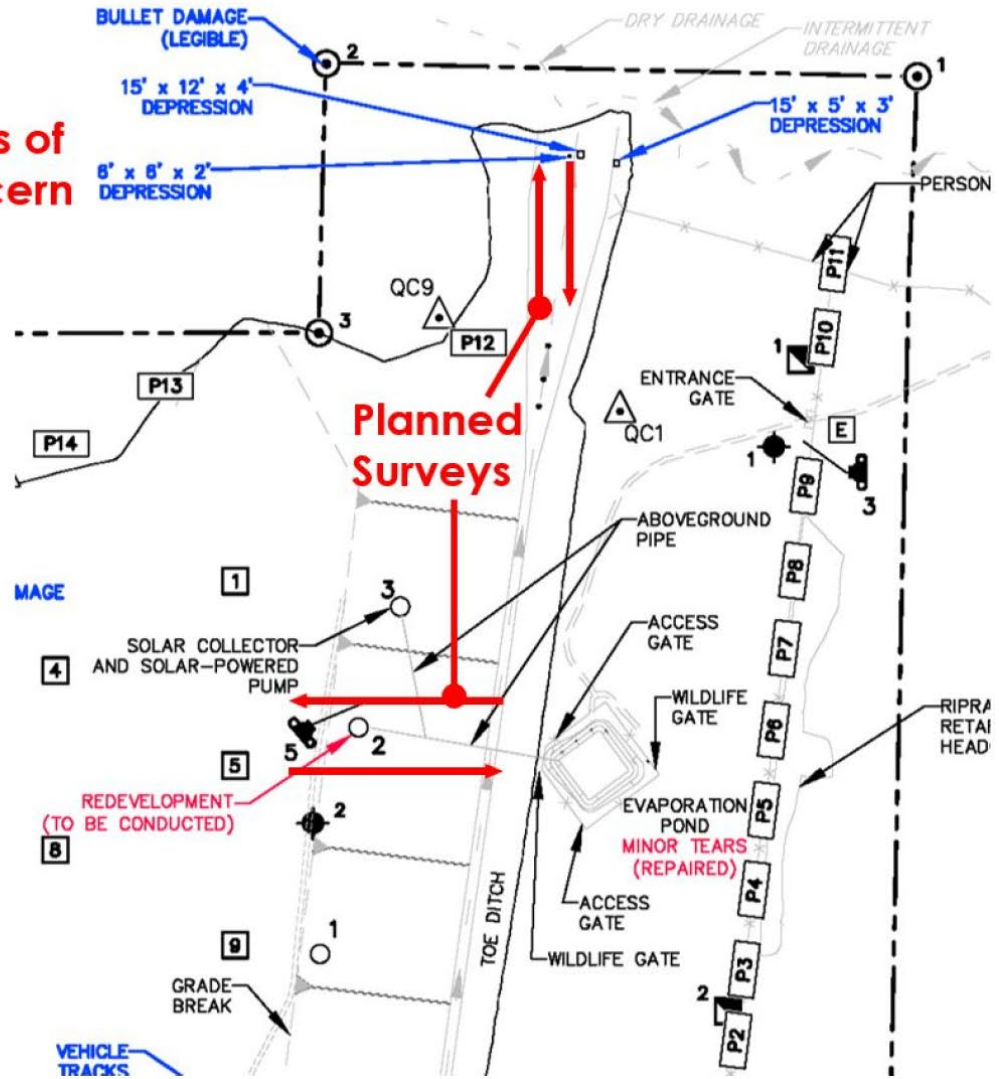
½' Bentonite clay (Radon barrier)	N/A	N/A

Prototype

2022 Rifle Deployment

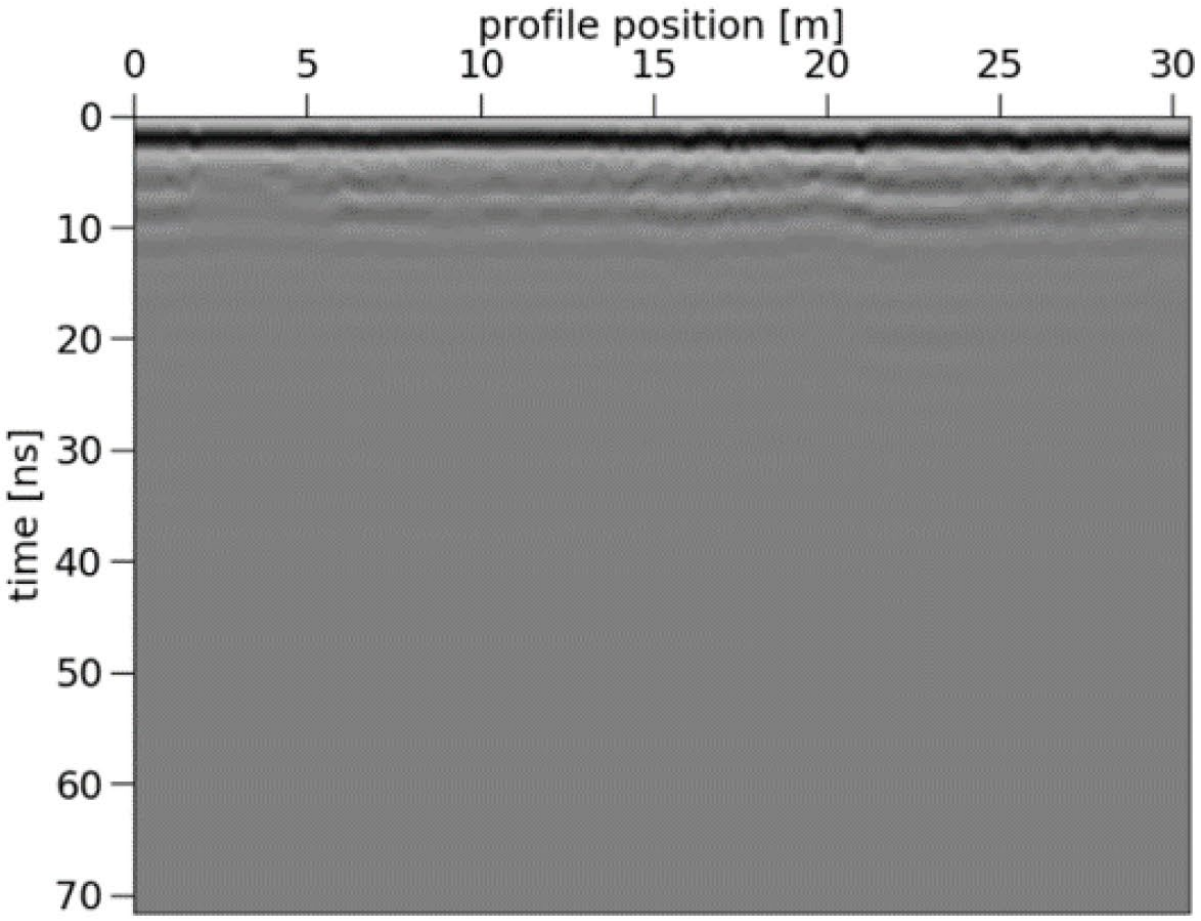
2022 Rifle Deployment

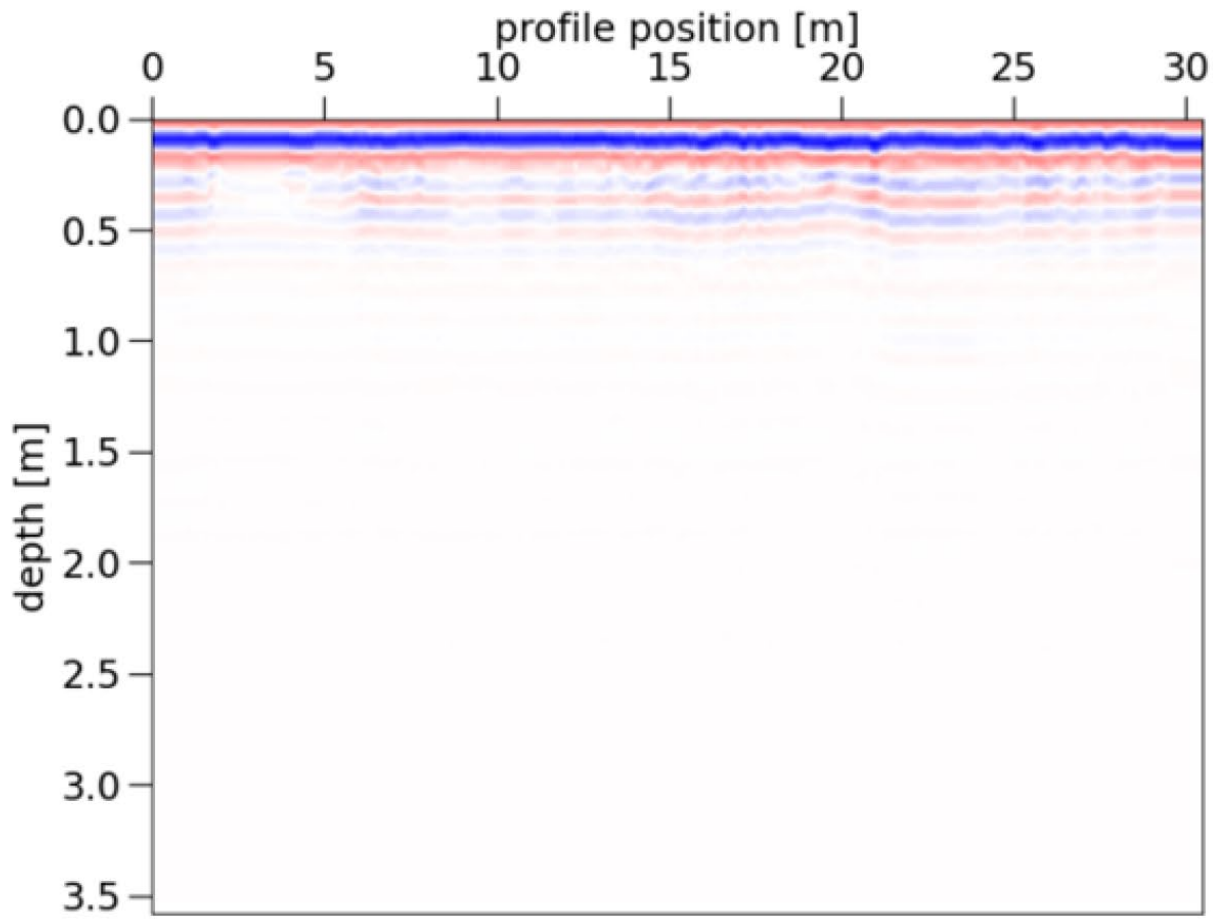




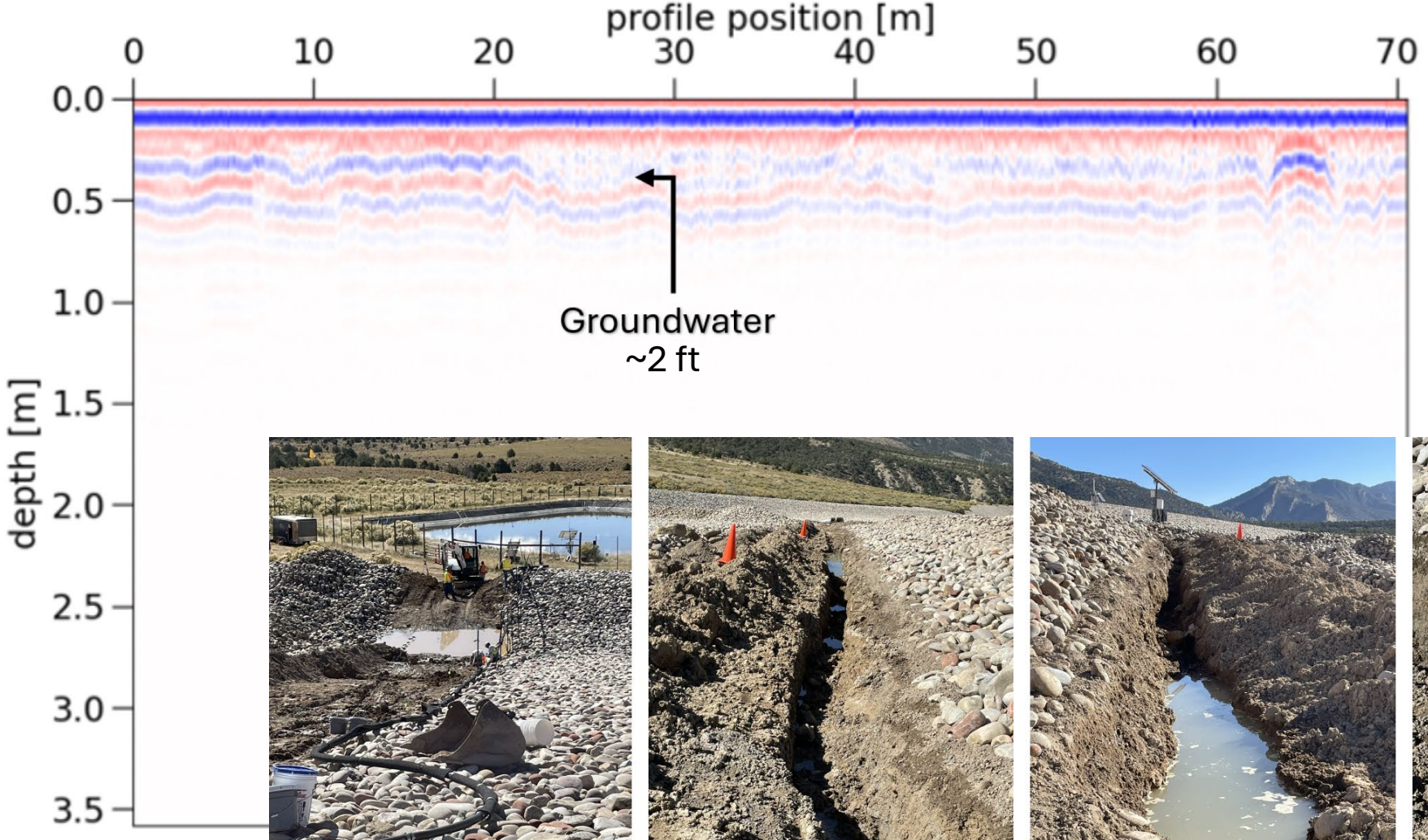
2022 Rifle Deployment

2022 Rifle Deployment

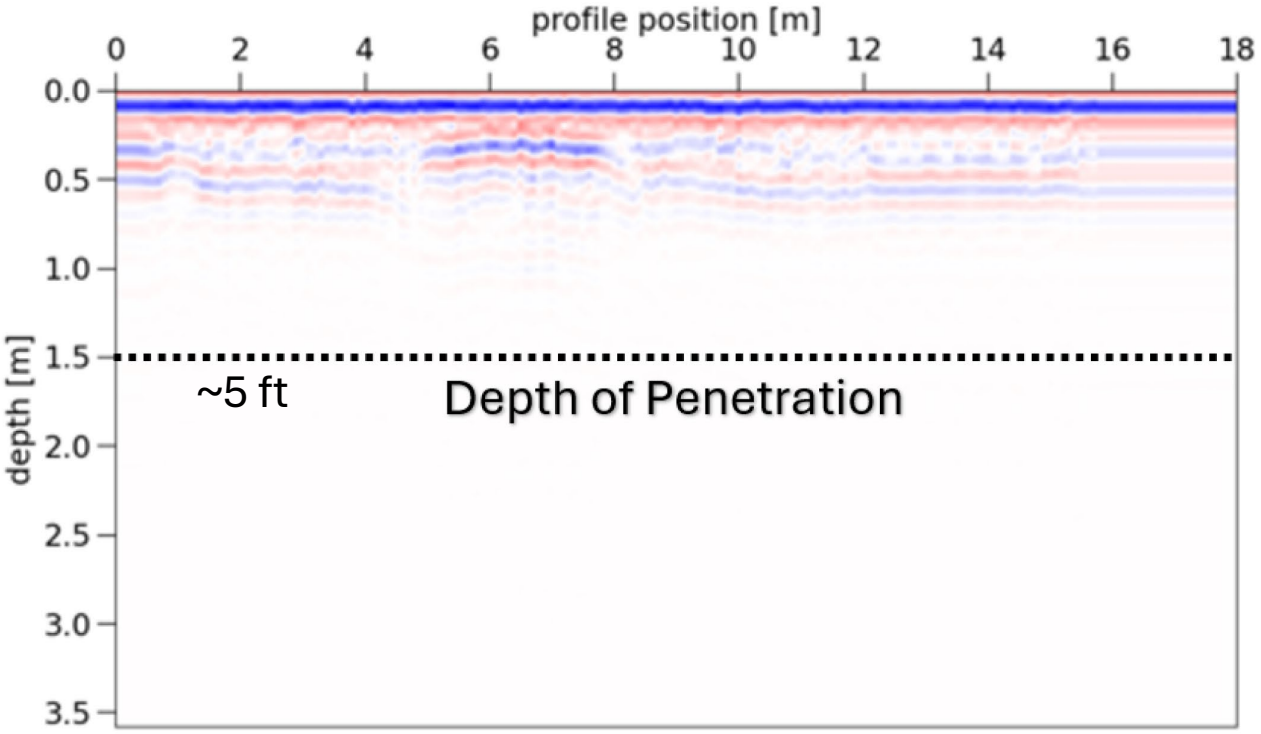


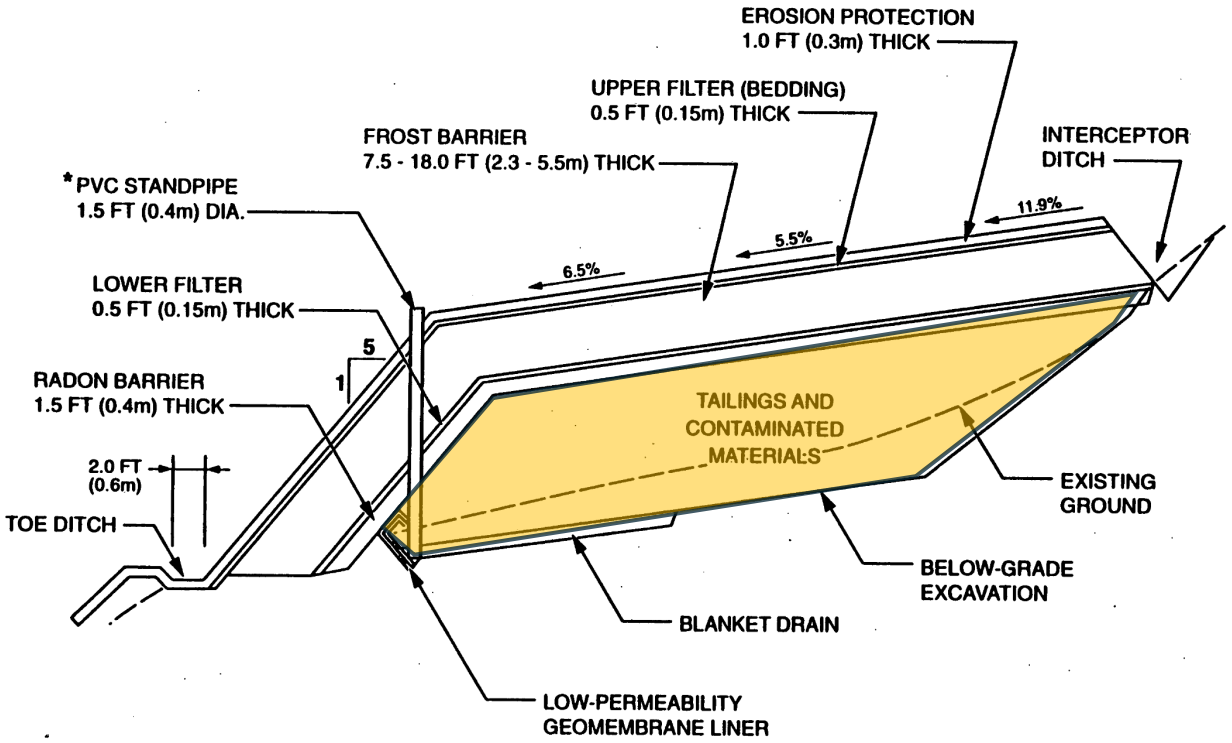


2022 Rifle Deployment

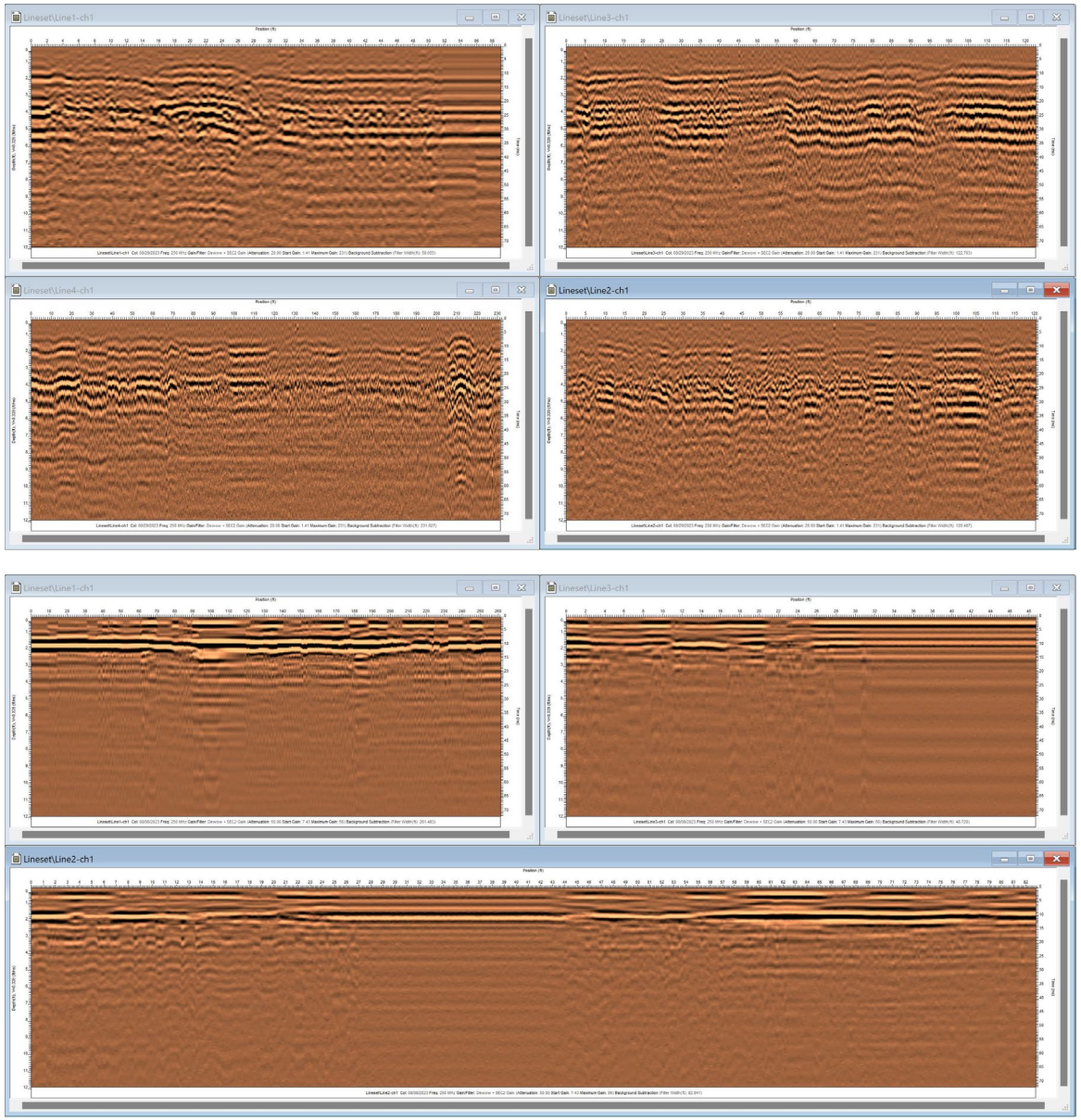


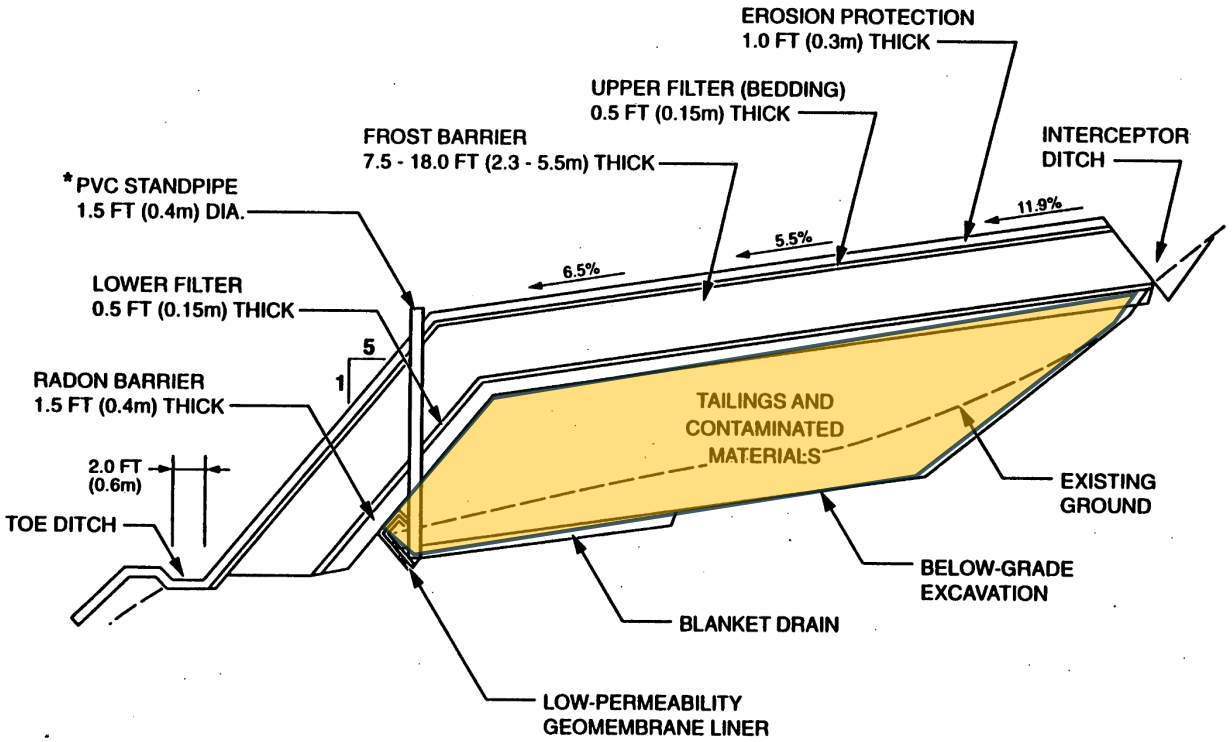
2022 Rifle Deployment





2022 Rifle Deployment





Methodology

2022

Phase I: Robot Development

- GPR robot design and prototype construction
- Remote-controlled testing in lab environments for core functionality
- The prototype is deployed in the disposal cell and other DOE sites
  - Evaluate the performance of the hardware
  - The accuracy of the GPR data
  - Provide preliminary subsurface conditions to the DOE for consideration of technology.

2024

Phase II: Automation

- Upgraded prototype with enhanced perception and navigation
- Autonomous navigation and sensor integration tests in field settings

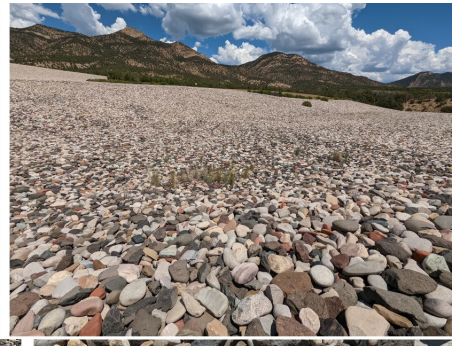
2025

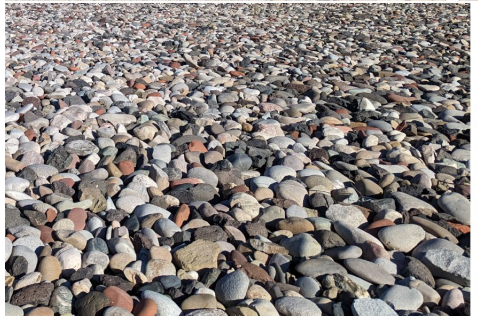
- Redeploy at DOE sites

Phase III: Full Autonomy

- Fully autonomous GPR surveys and data processing
- Goal: complete site coverage with minimal human intervention
  - Deploy a final system at DOE sites and demonstrate technology potential
  - Finally, transfer technology to DOE

2026





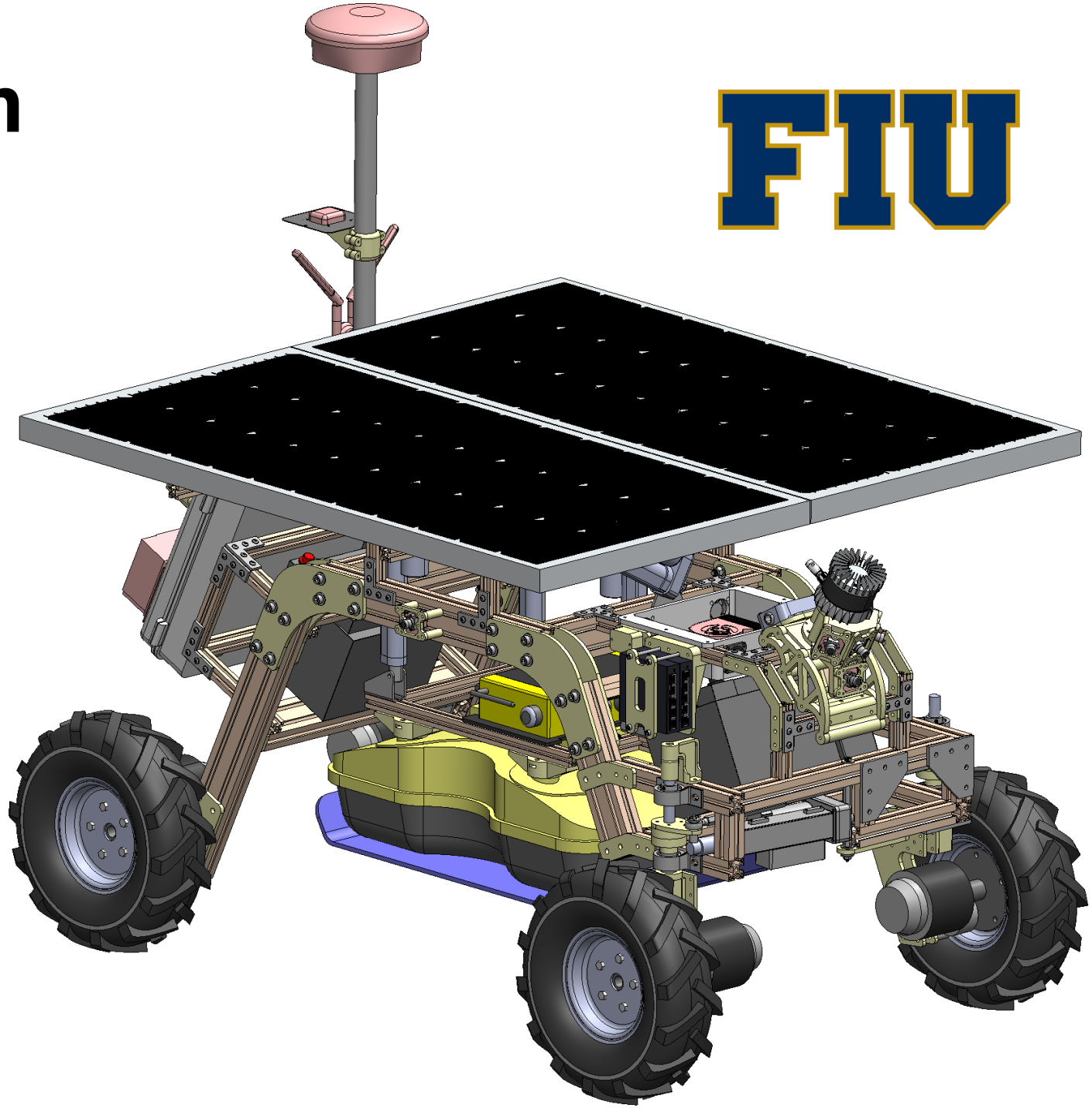
Phase II: Automation

Navigation Sensors

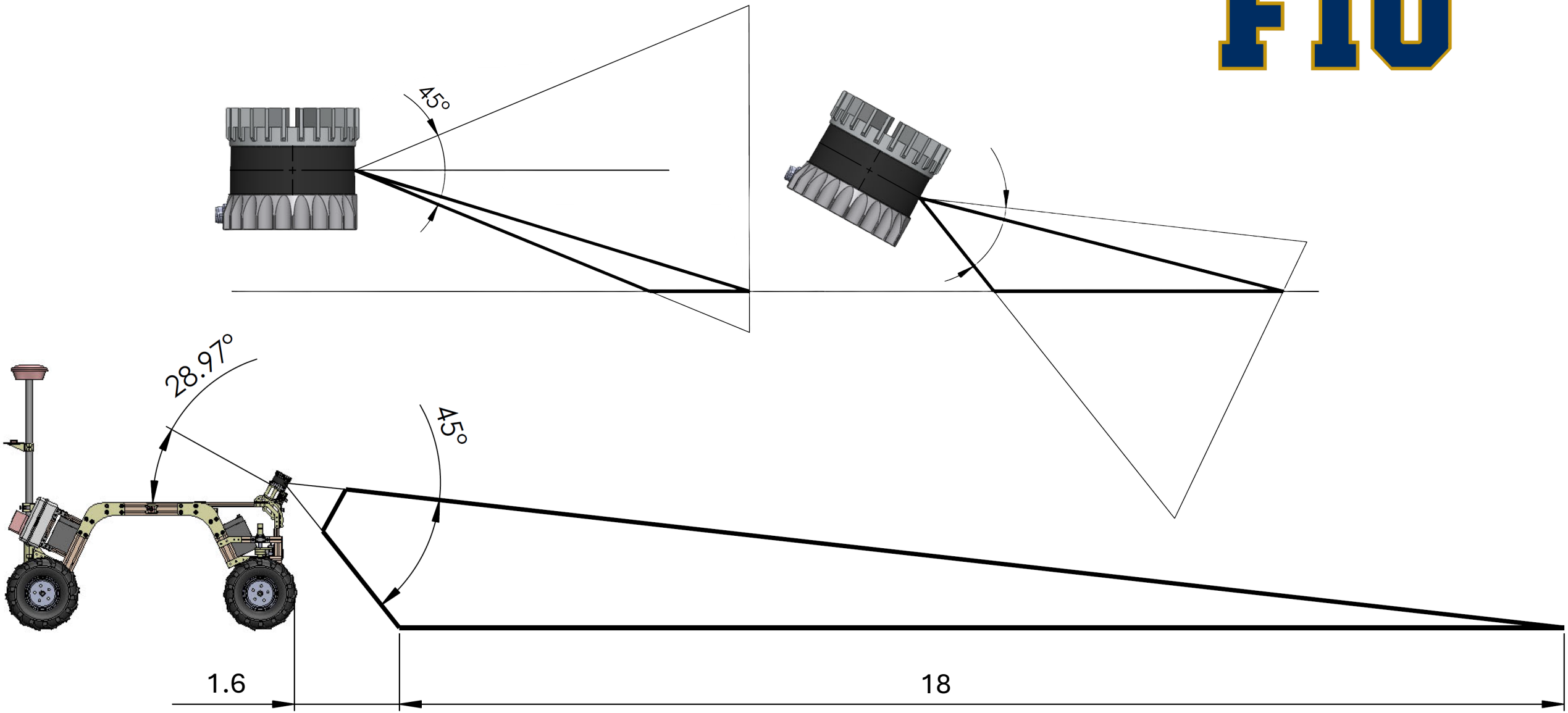
- RTK GPS
- 9-DOF IMU
- Wheel encoders
- Steering encoder

Mapping Sensors

- 32-channel LiDAR
- 3x high-resolution cameras
- Dual gamma spectrometers



Mapping Sensory



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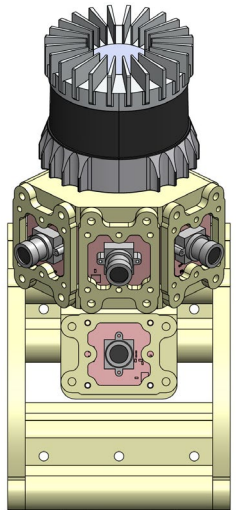
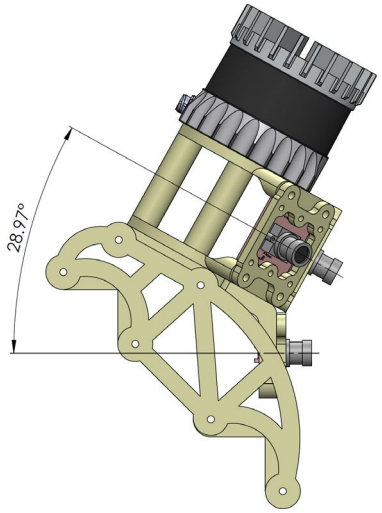
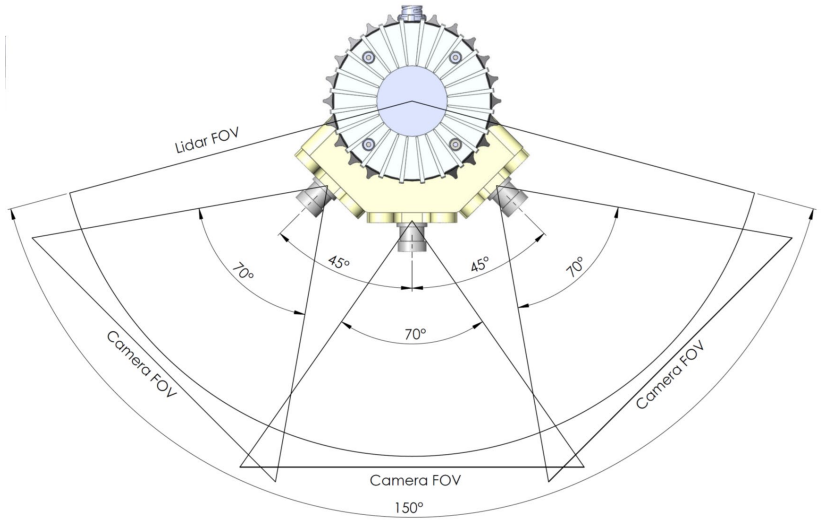
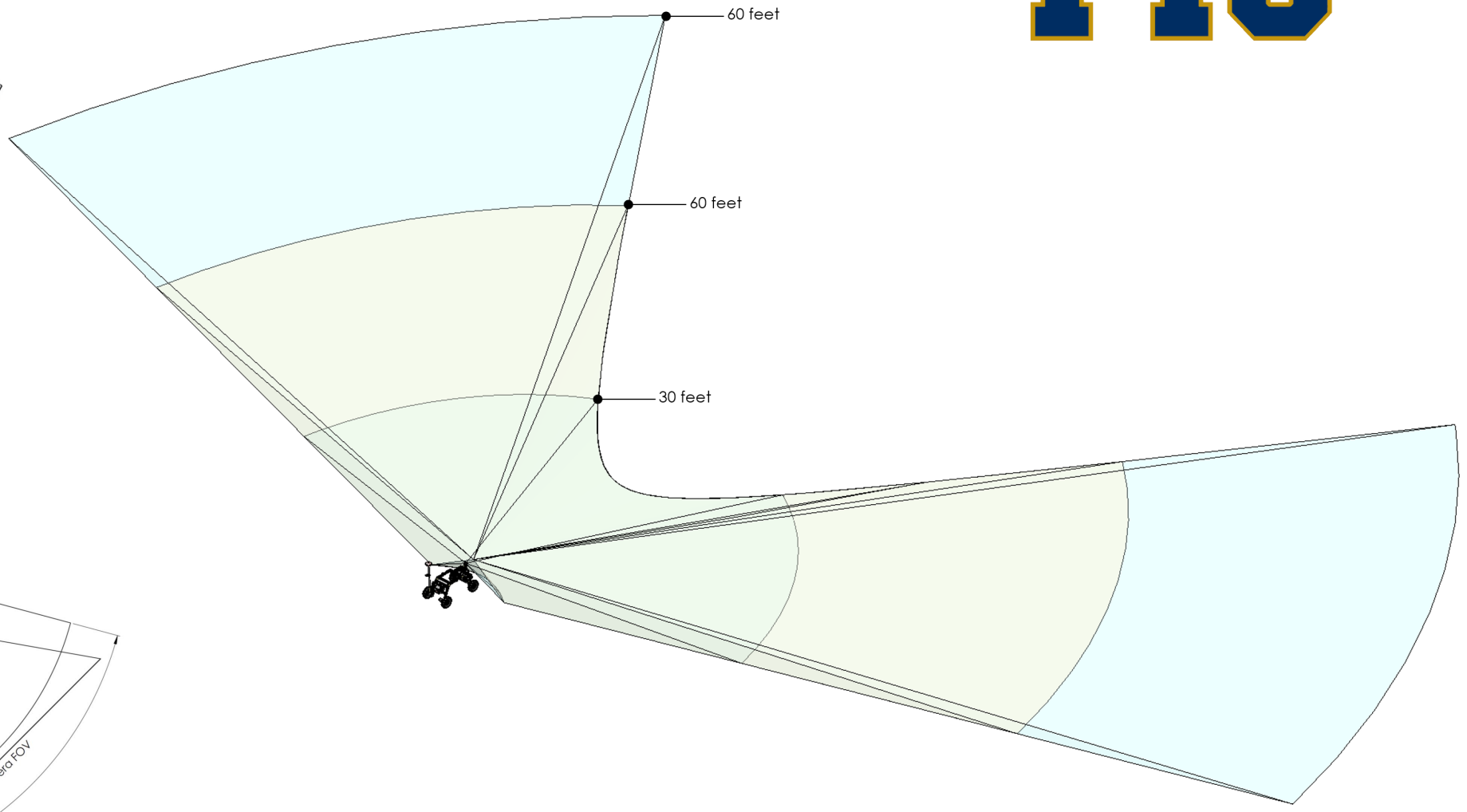
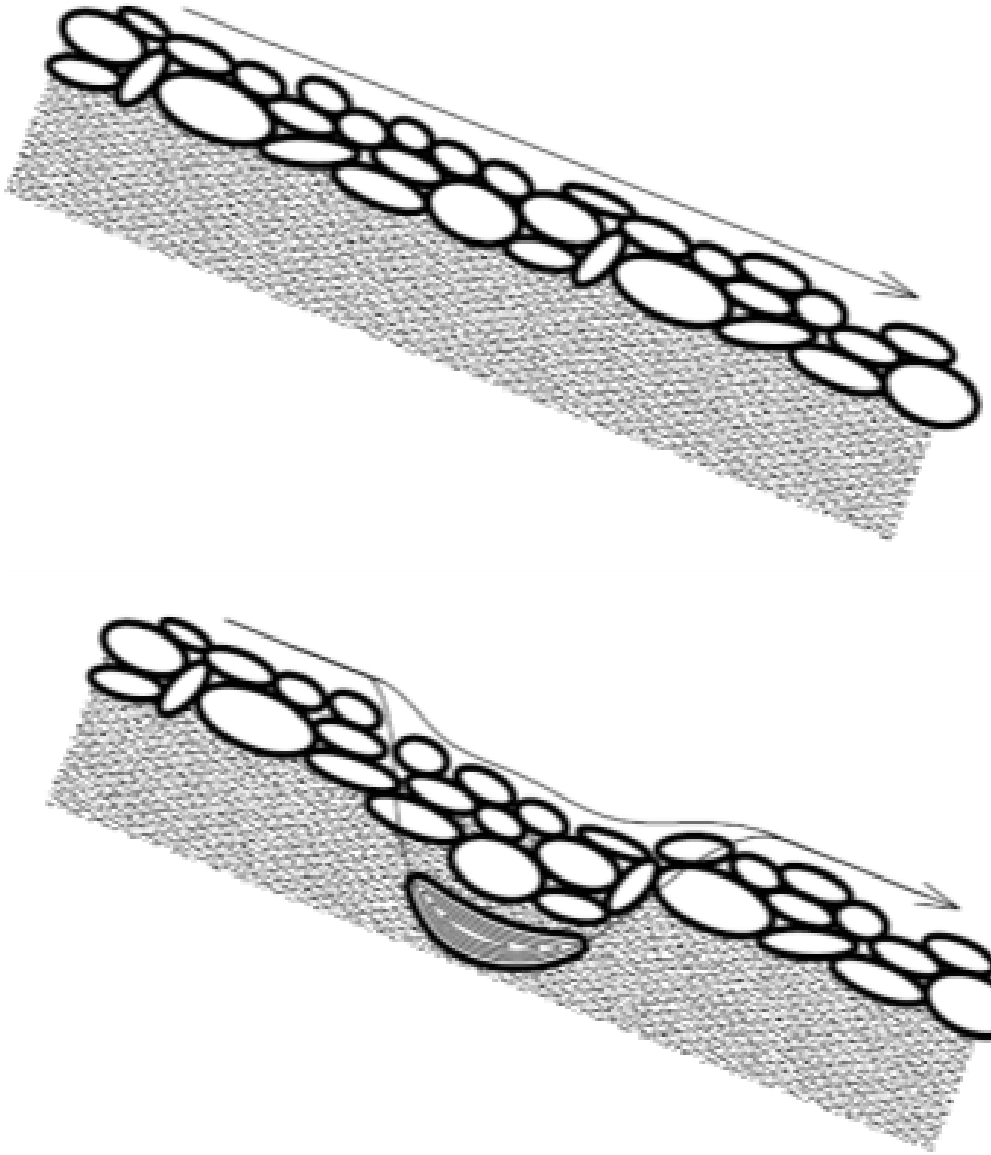


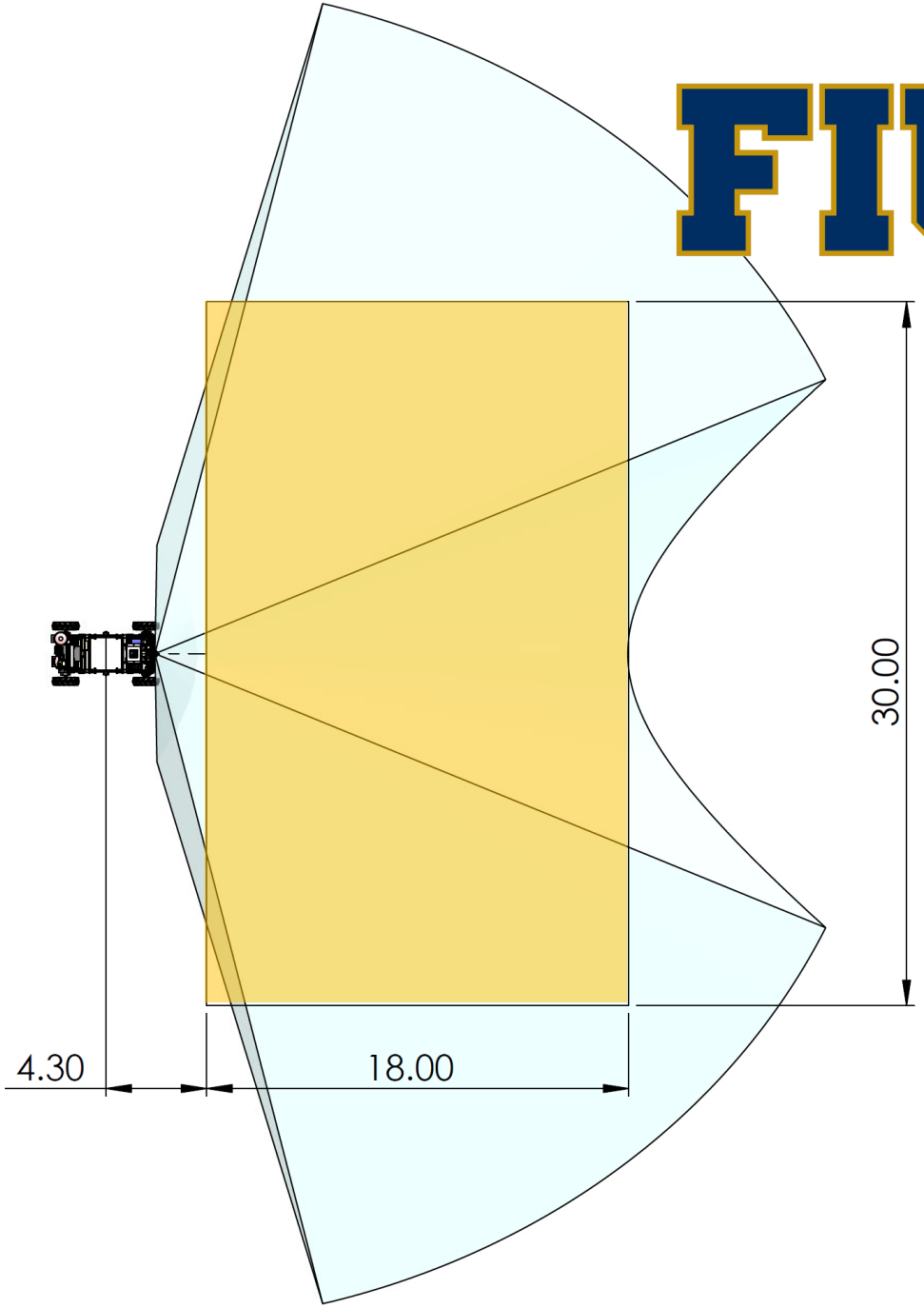




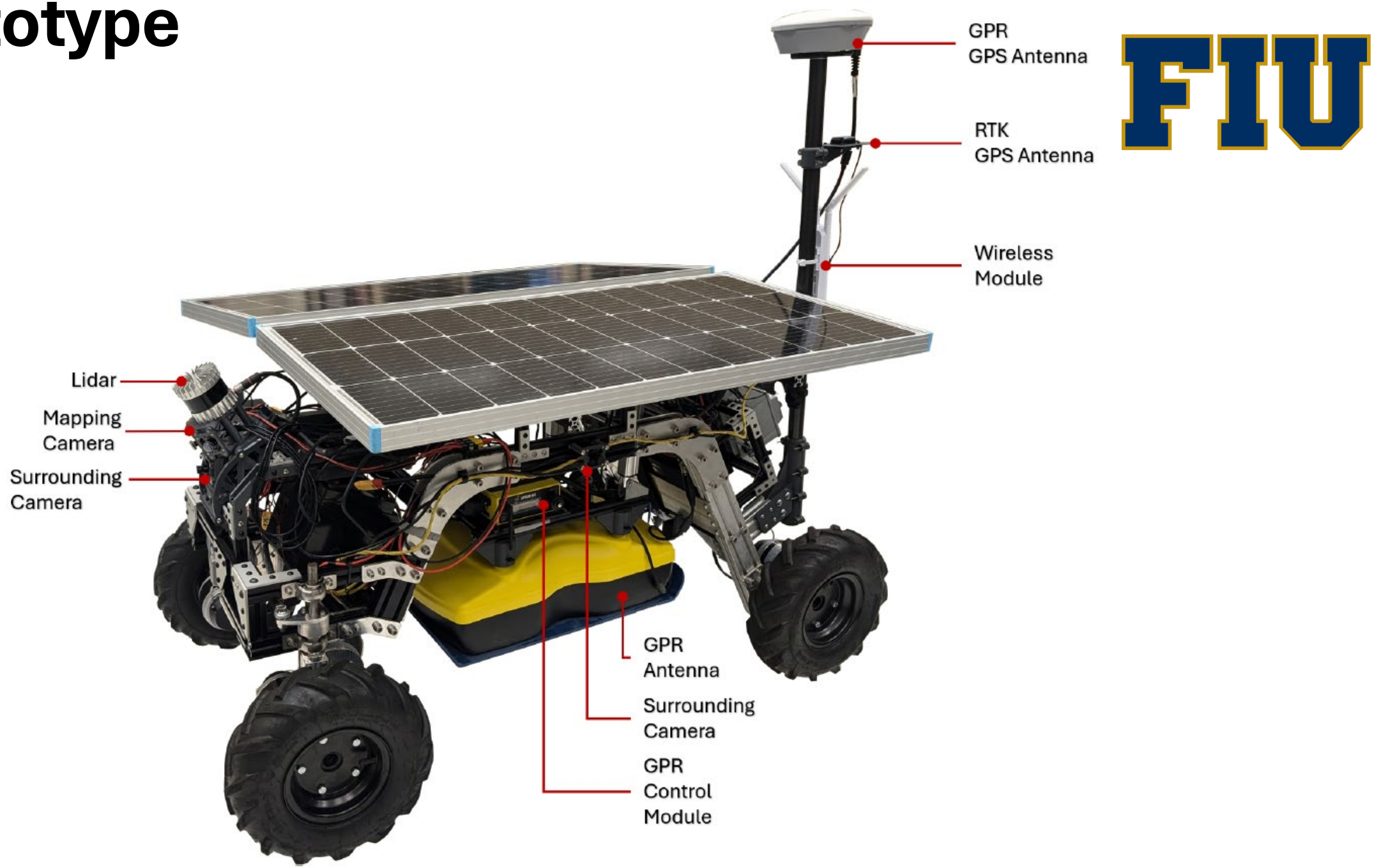


Mapping Sensory





Prototype

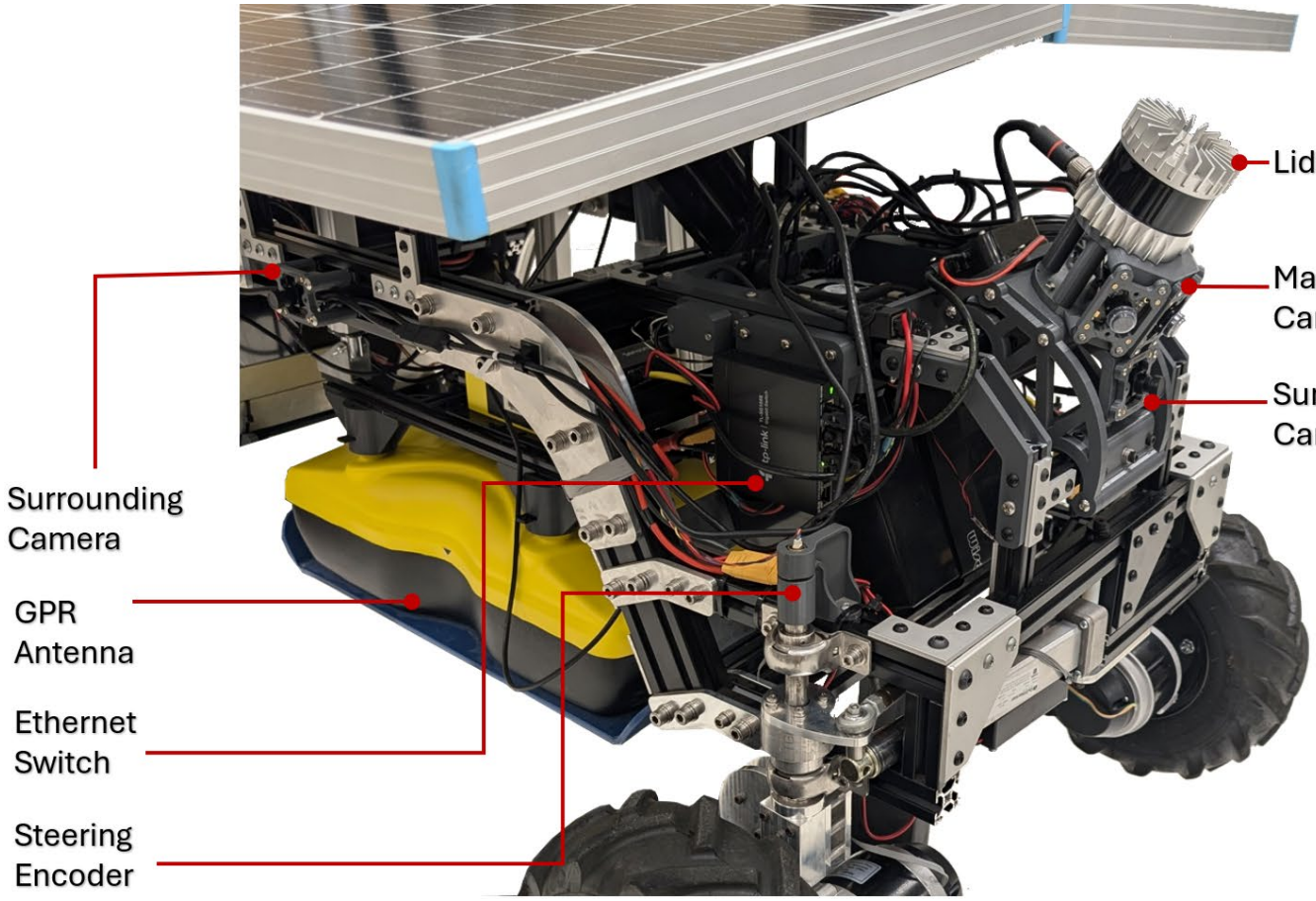

GPR
GPS Antenna
RTK
GPS Antenna
Wireless
Module
Lidar
Mapping
Camera
Surrounding
Camera
GPR
Antenna
Surrounding
Camera
GPR
Control
Module

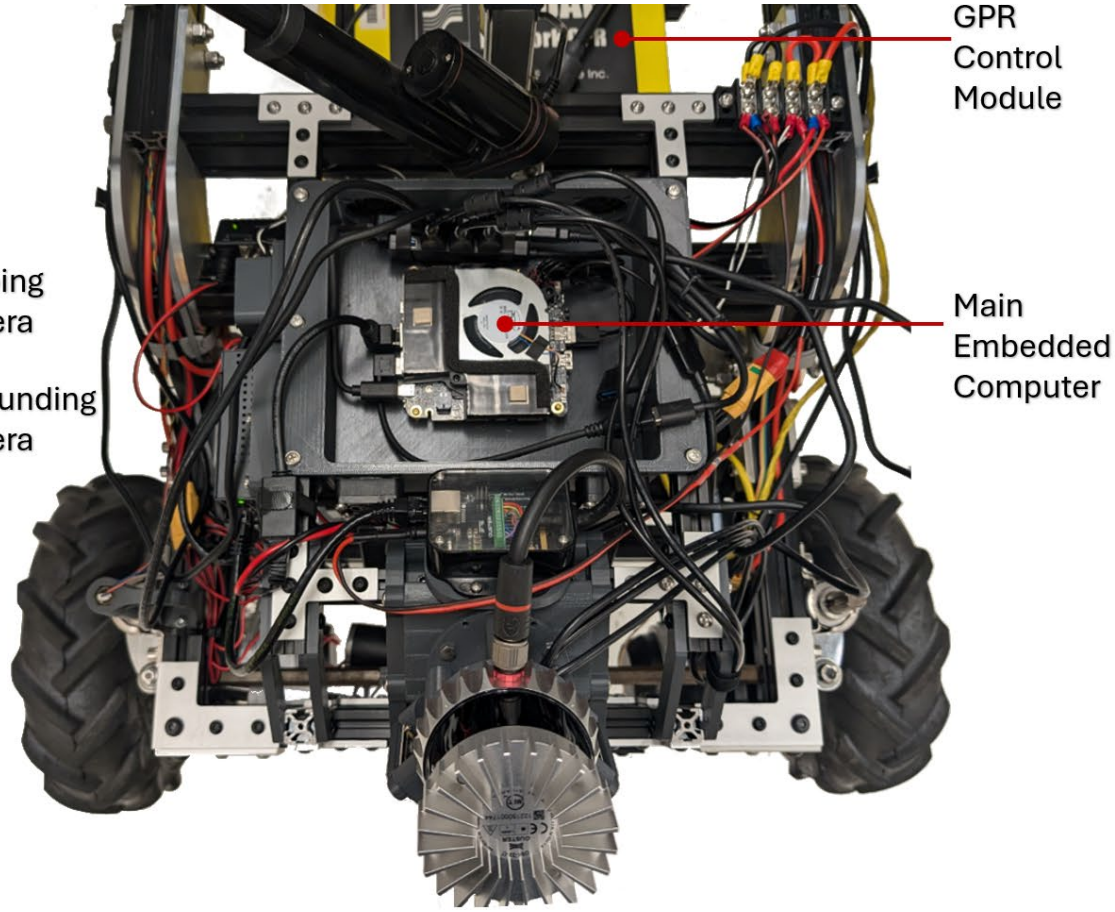
Prototype

Computer, lidar, cameras, fans, microcontroller, and ethernet
- **12 W** Idle
- **58 W 100% Load**

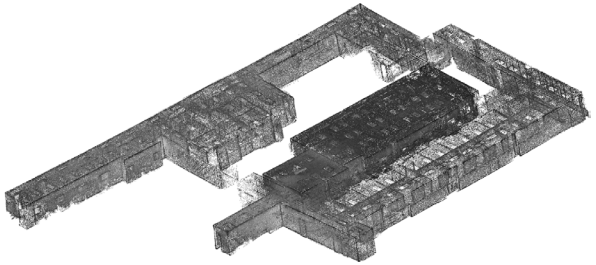
200 W Wheel Motors 100 % Load
- **40 W** Motor controllers

200 W Solar Panels

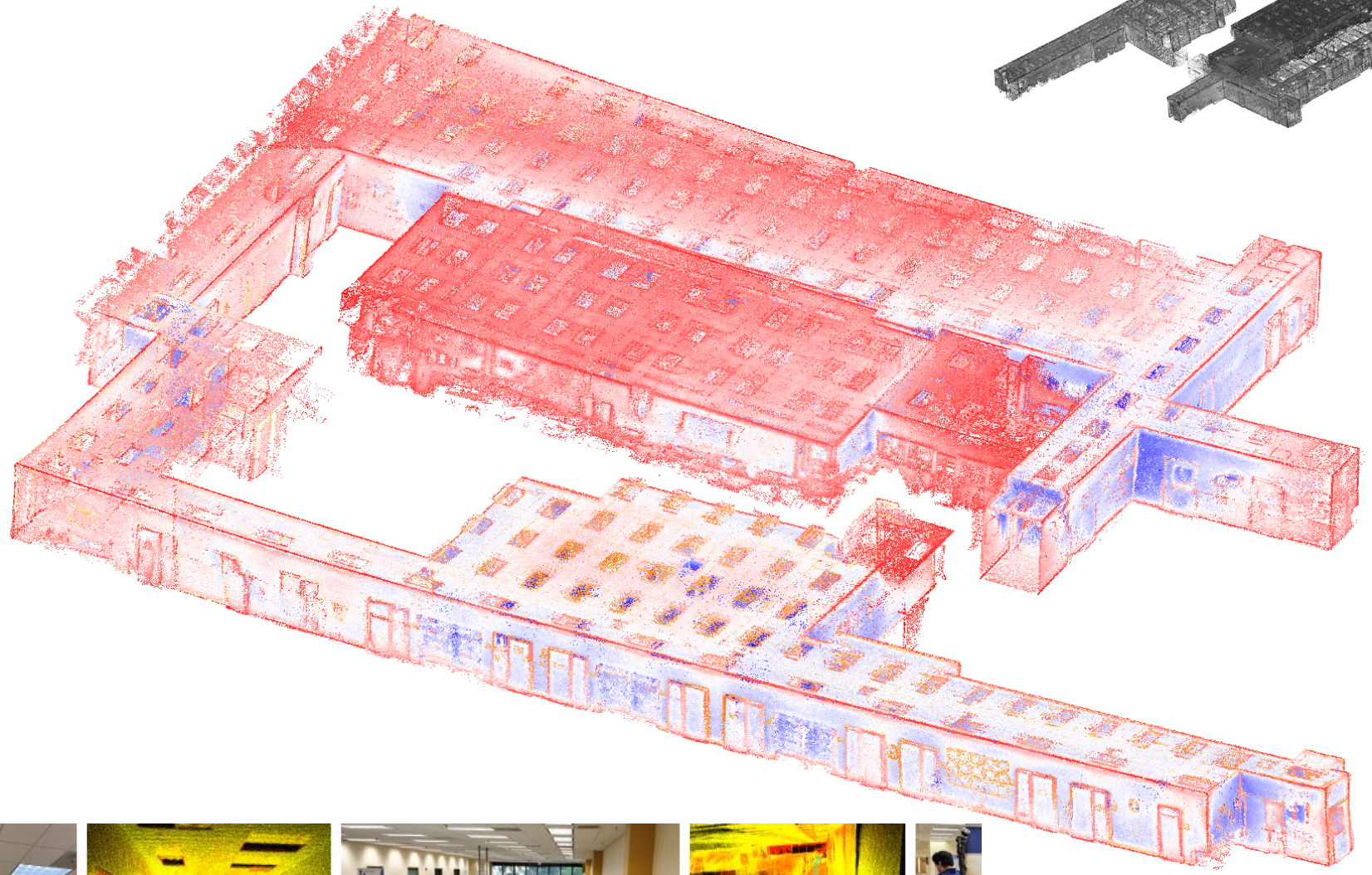


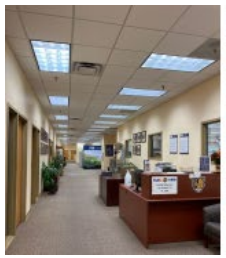


Indoor Lidar Data

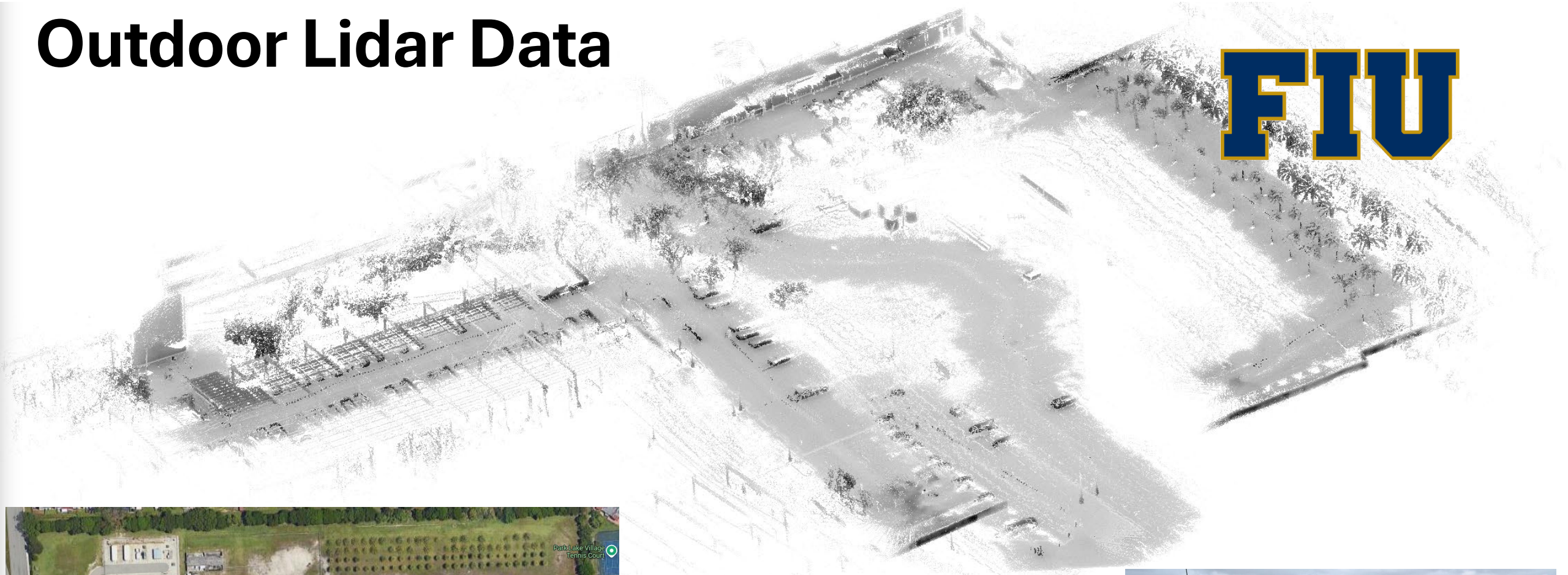


FIU

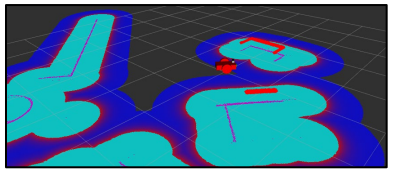


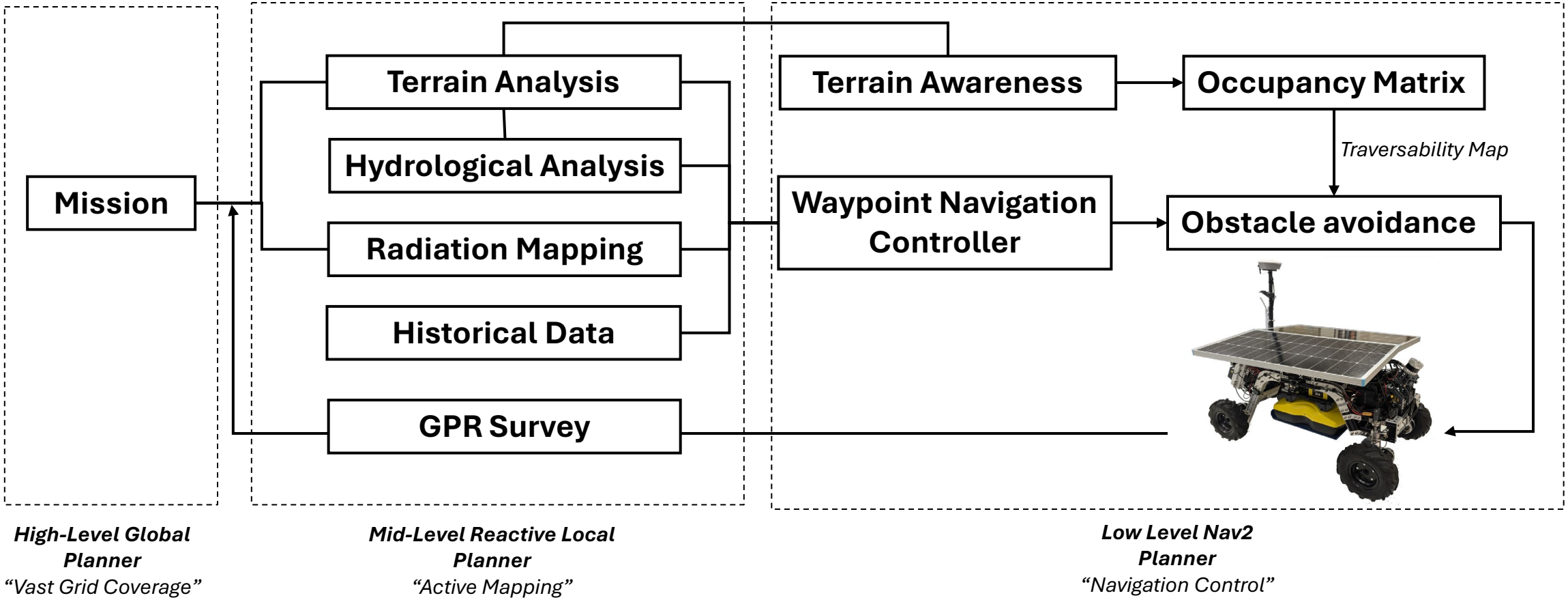


Outdoor Lidar Data



Robot's Control System



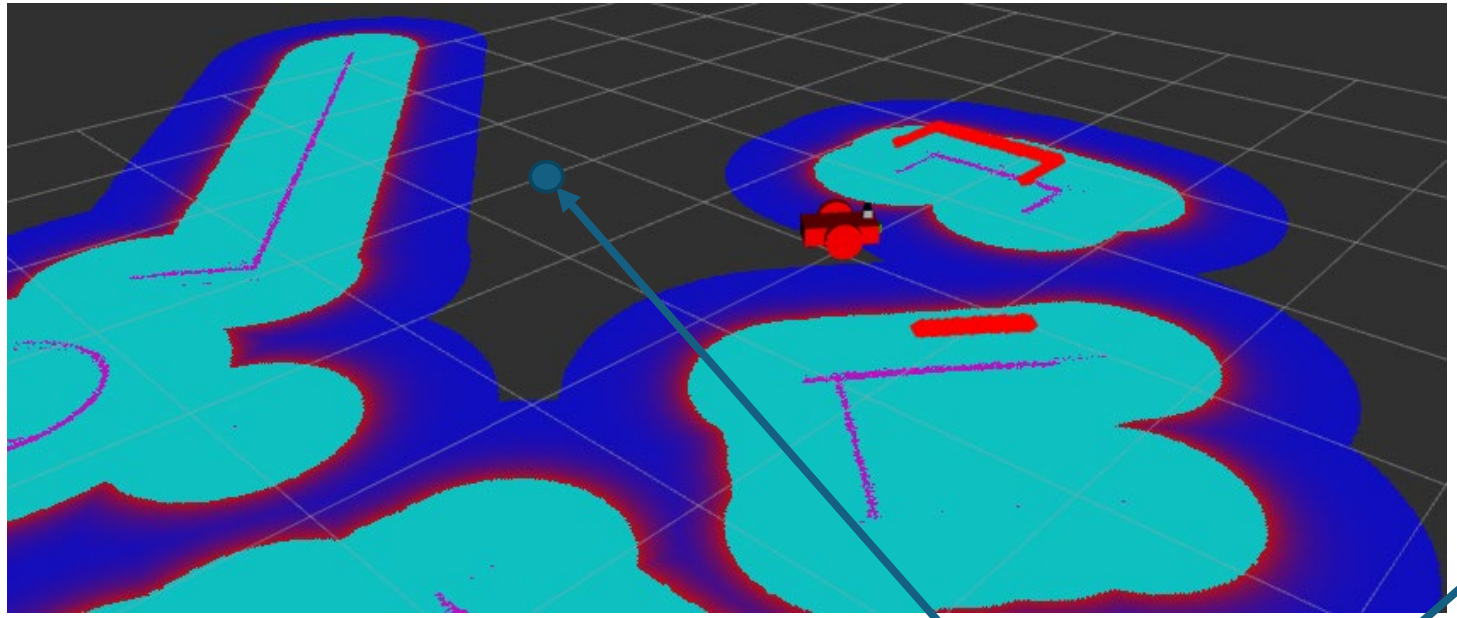


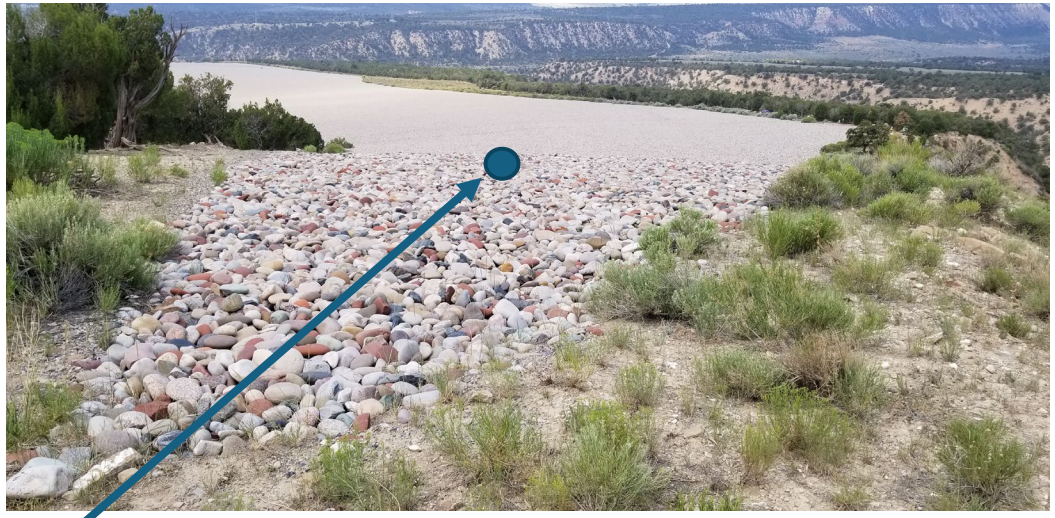
High-Level Global Planner
"Vast Grid Coverage"

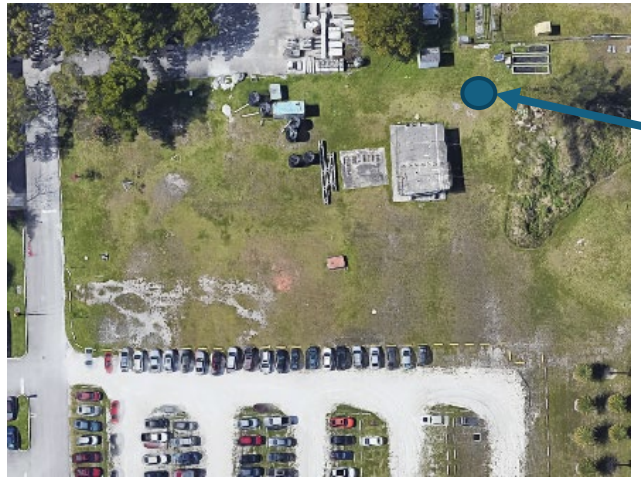
Mid-Level Reactive Local Planner
"Active Mapping"

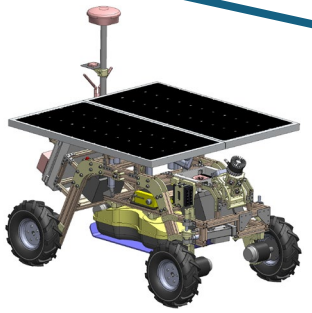
Low Level Nav2 Planner
"Navigation Control"

Terrain Awareness







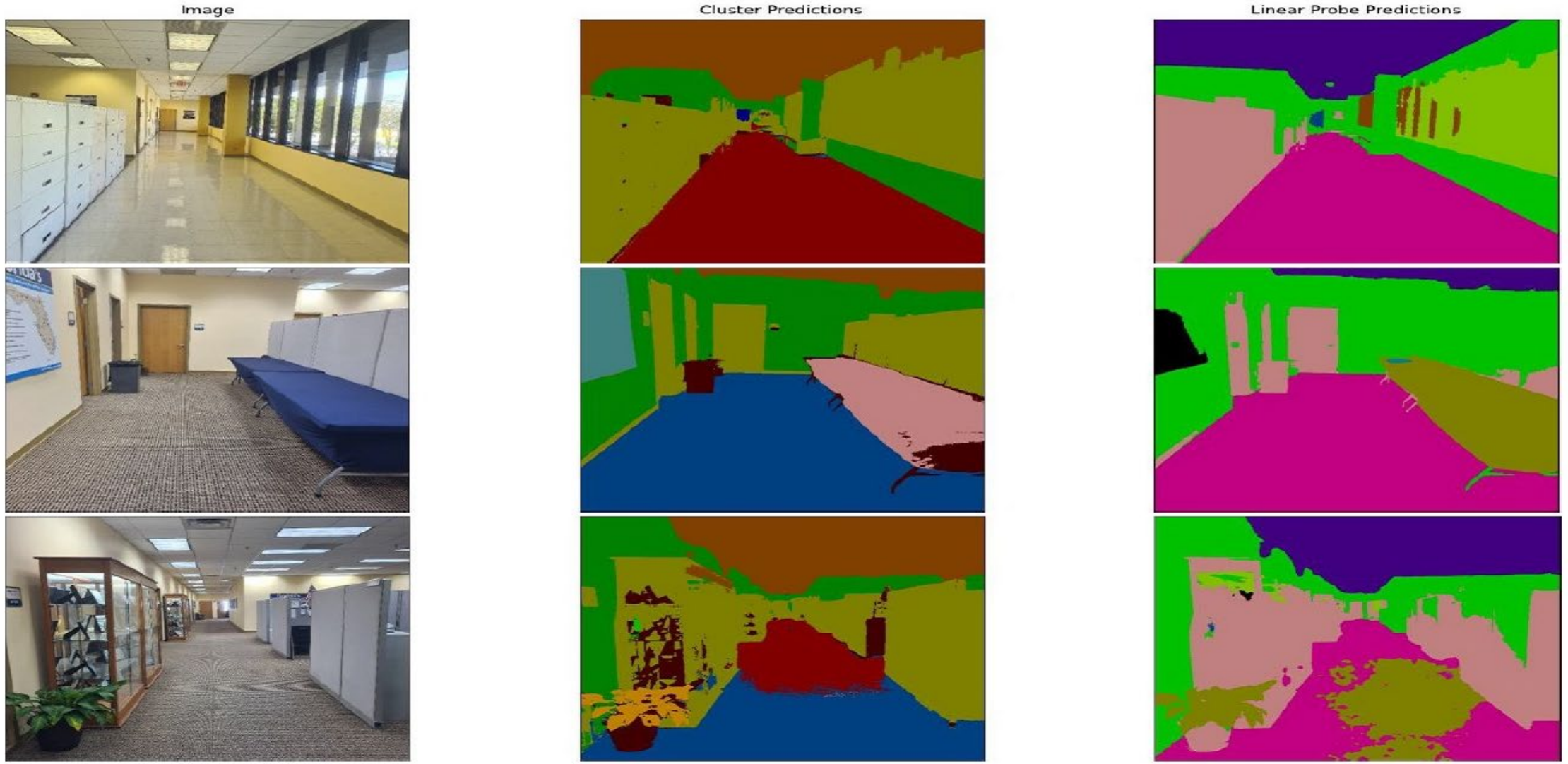


No obstacle!

Is the terrain safe?

Terrain Awareness

Using Unsupervised Texture Classification

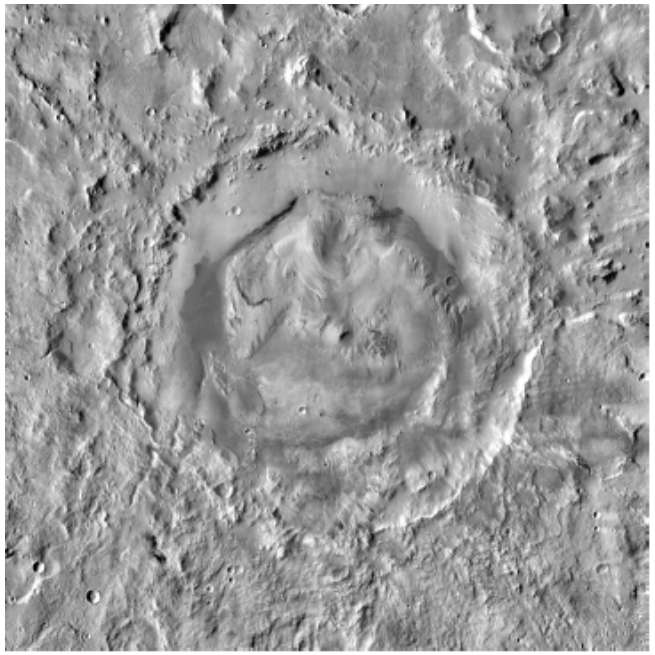


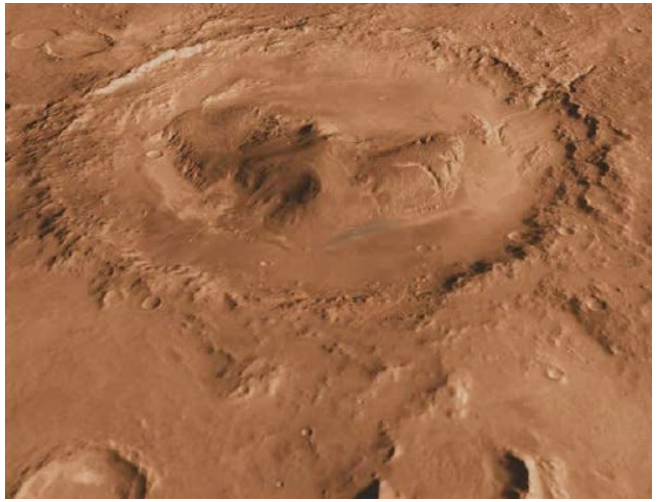
Terrain Awareness

Using Unsupervised Texture Classification

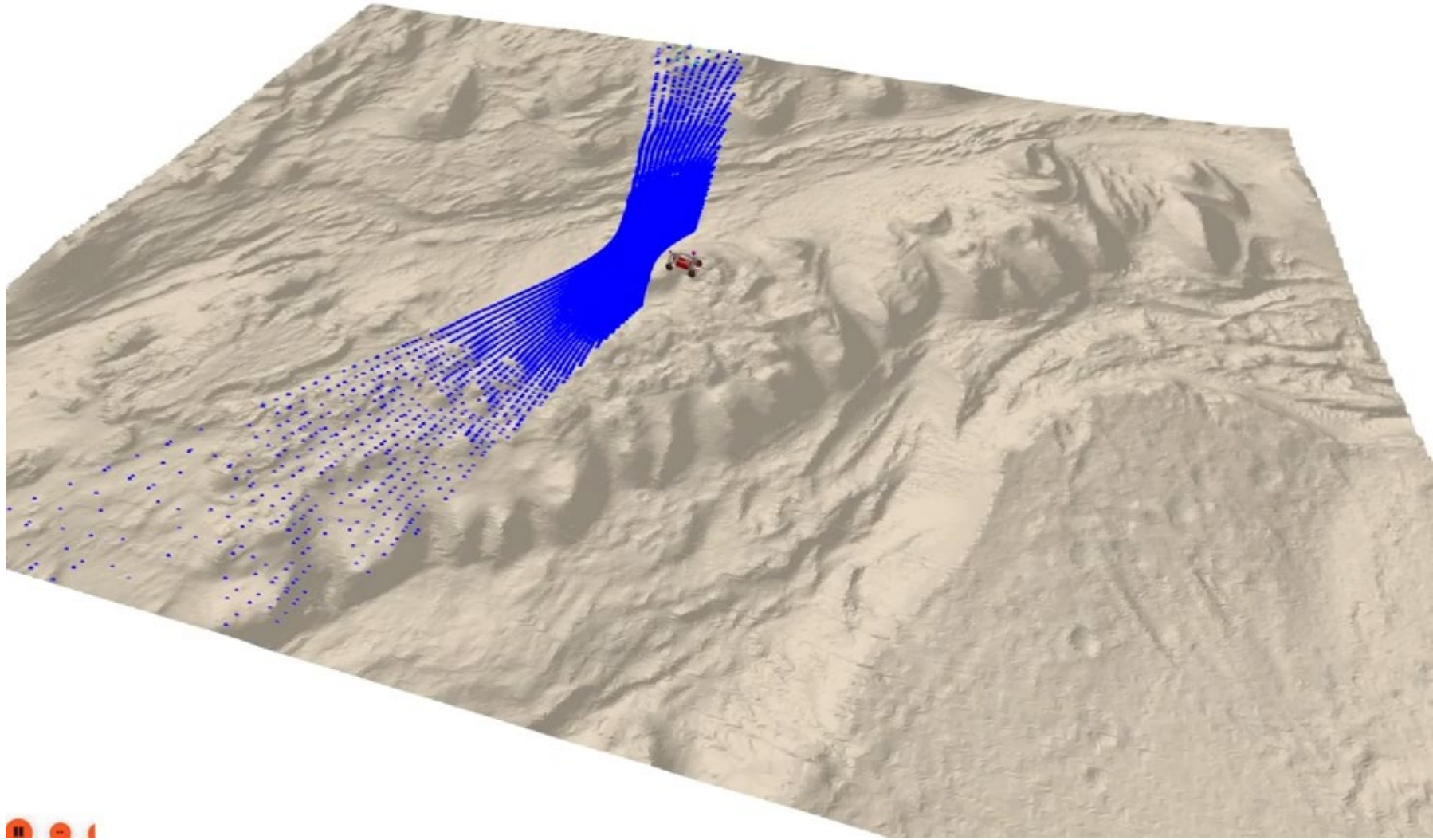
FIU

Virtual Deployments

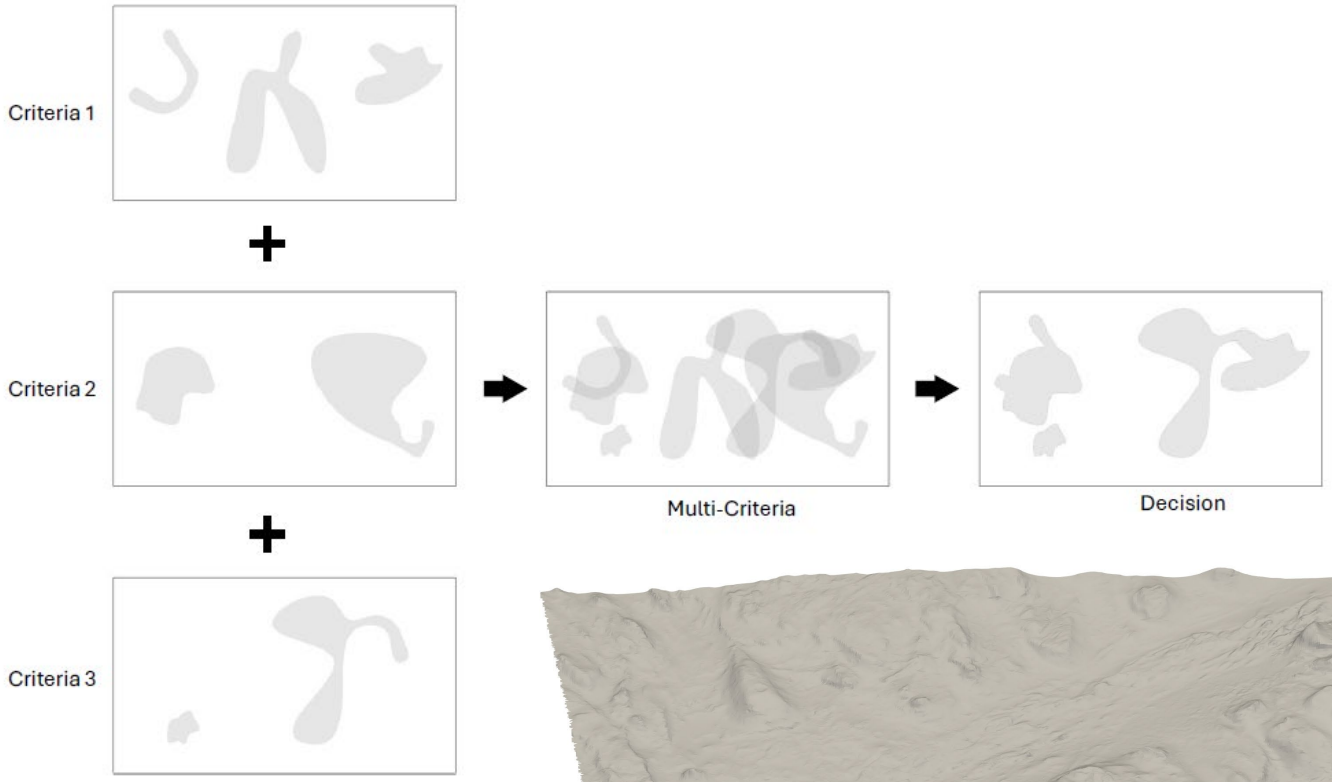


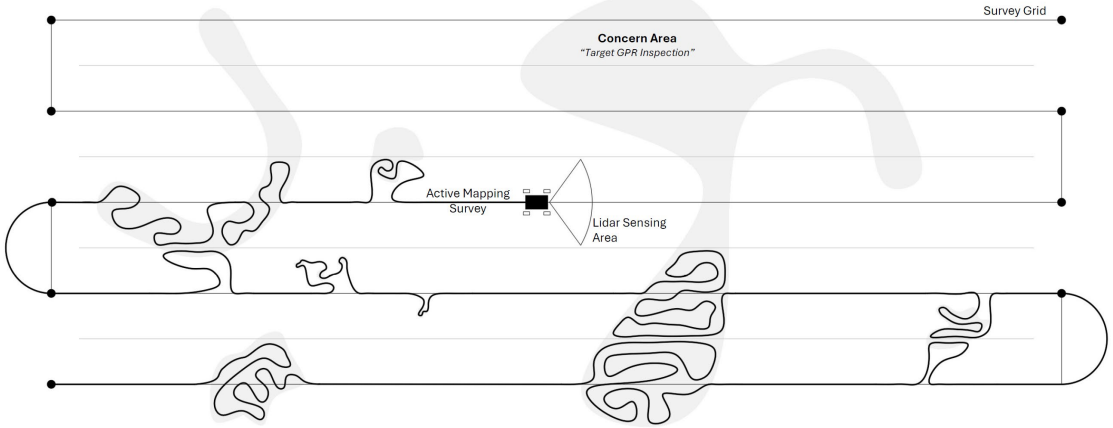


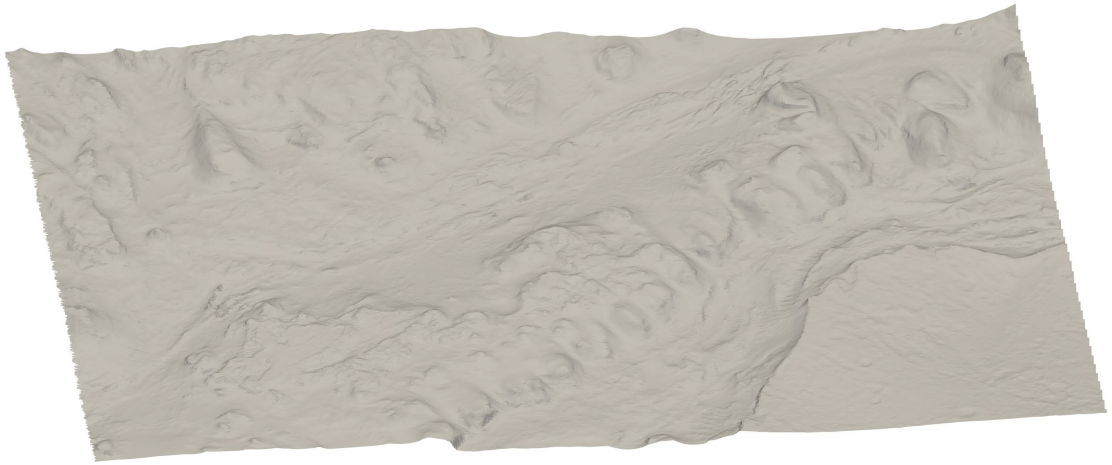
Mars's Gale Crater

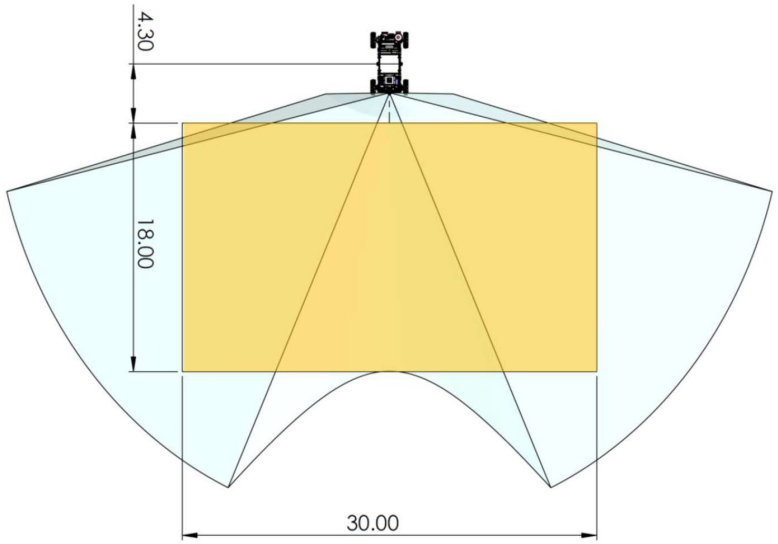


Multi-Criteria Decision-Making Based on DEMs

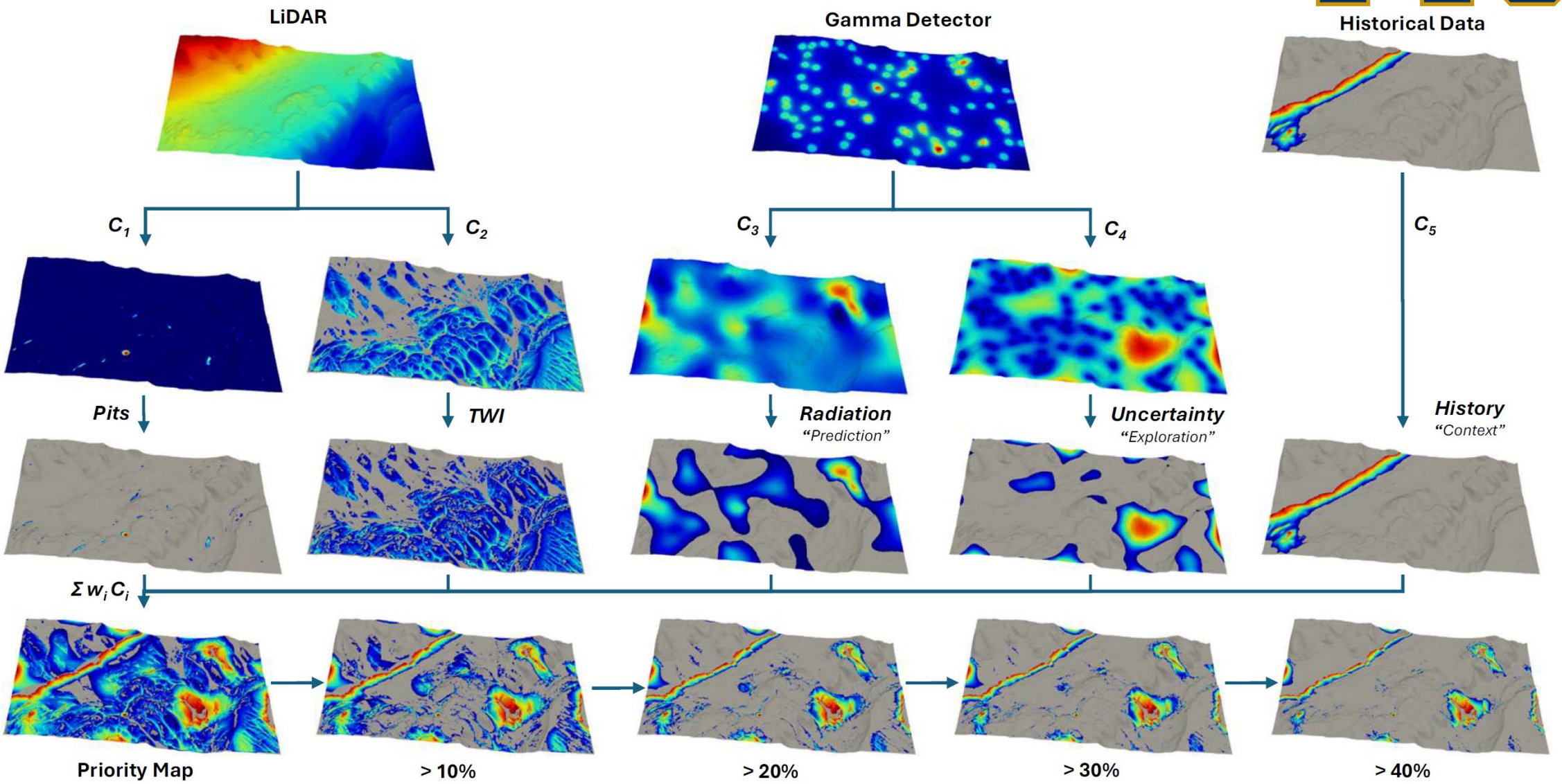




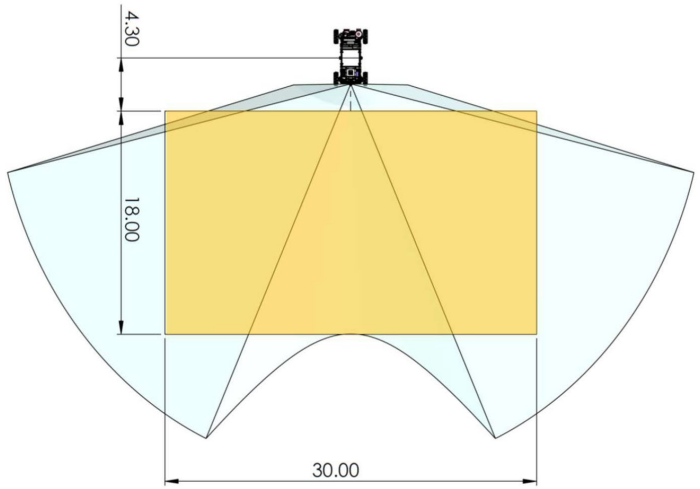




Multi-Criteria Decision-Making Based on Digital Elevation Models (DEMs)



Multi-Criteria Decision-Making Based on DEMs



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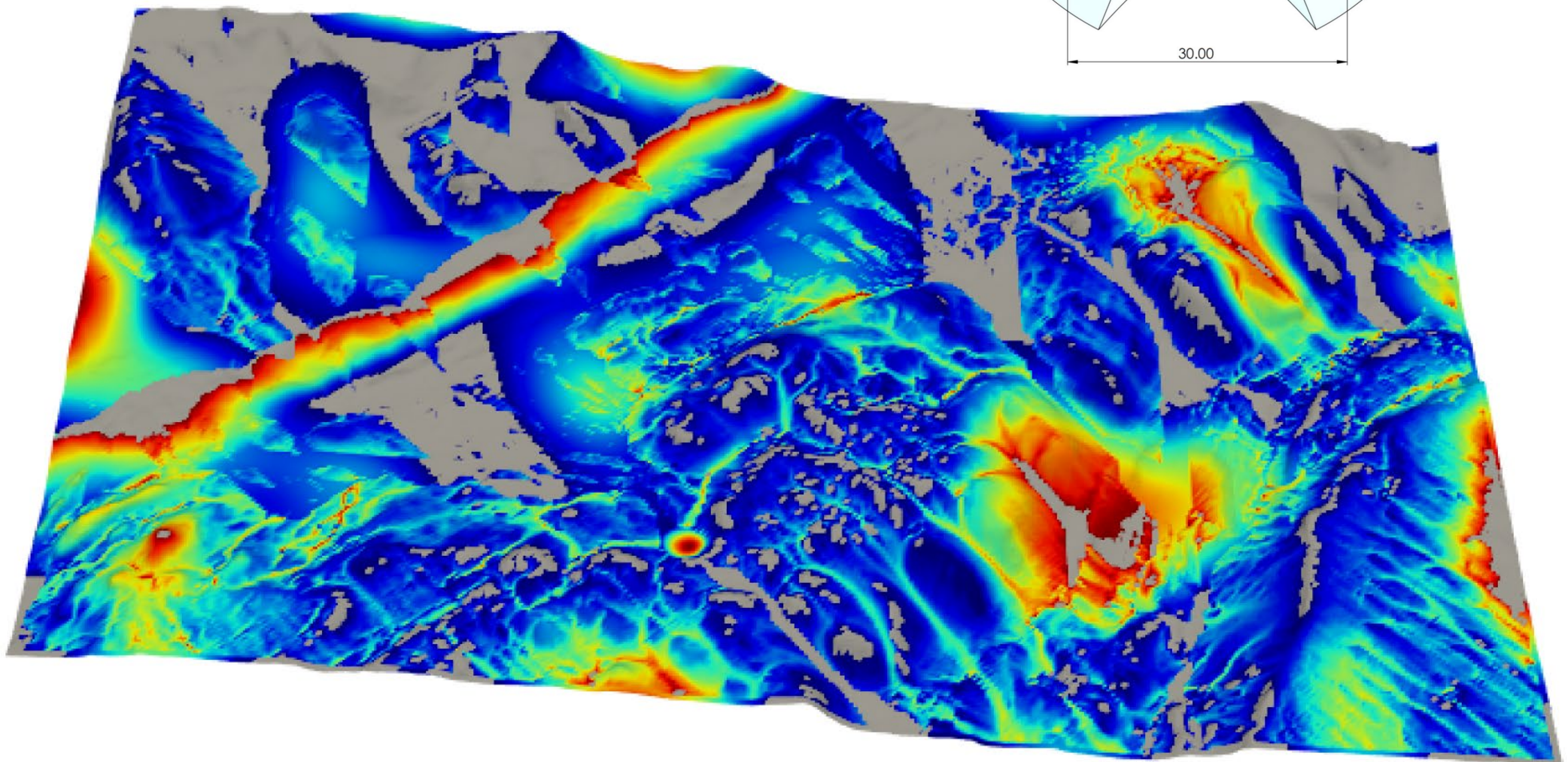
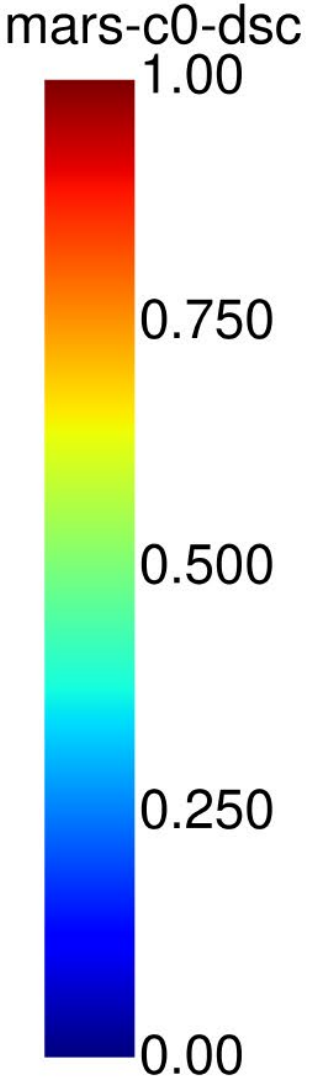
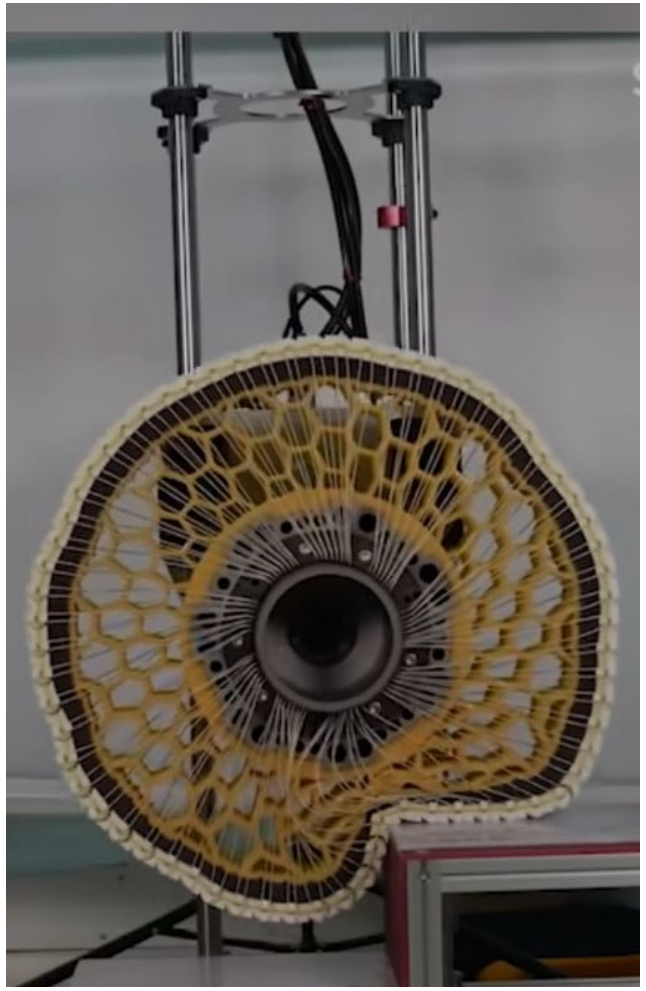


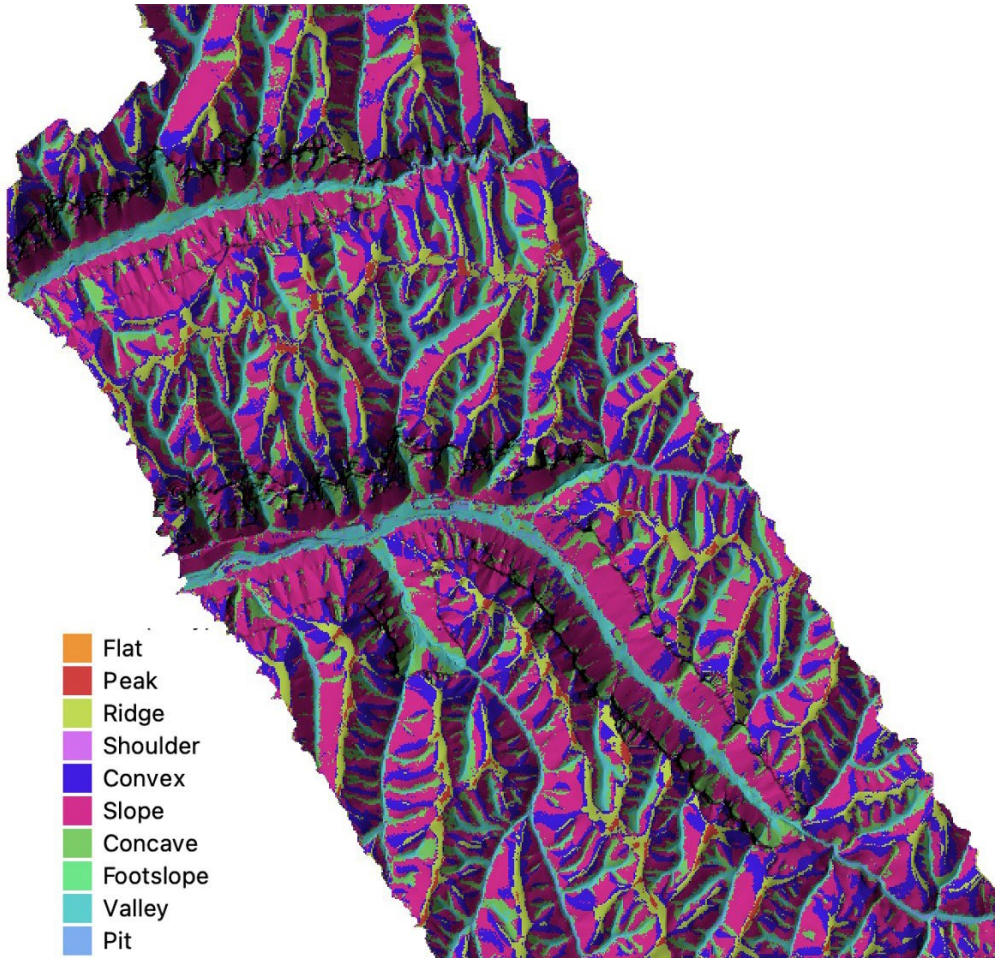


Path Forward



Enhance the system's autonomous capabilities

Heterogeneous Multi-Robot Systems



Incorporate Real-Time Terrain Classification Algorithms for Active Mapping

Conclusion

Automating inspections of DOE disposal cells poses significant challenges due to the vast areas and complex operational demands, making traditional grid surveys impractical.

A fully autonomous, multi-sensor robot capable of conducting comprehensive coverage surveys while employing energy-efficient navigation strategies represents a transformative solution.

Guided by active mapping, this system integrates terrain, radiation, and subsurface data with environmental sensors to detect and monitor critical trends, making it an invaluable tool for effective landfill management and long-term site monitoring.