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Utilizing Time Reversal Ultrasonics to Detect the Removal of Nuclear Materials from Geological Repositories

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Programmatic Overview

Detecting unauthorized nuclear material removal from storage environments, such as geological repositories, is a critical safeguards task essential to ensuring the integrity and non-diversion of nuclear materials. However, this process is fraught with significant technical challenges. Storage configurations often involve tightly packed nuclear material containers or obstructed environments, making detection of removal events exceedingly difficult. Optical surveillance cameras, which are commonly used for monitoring, suffer from substantial limitations, including restricted coverage, reliance on line-of-sight measurements, and vulnerability to environmental conditions in certain storage scenarios. As the global inventory of monitored nuclear materials increases and storage configurations become more complex—such as deep geological repositories, inaccessible storage vaults, and tightly packed containers—there is an urgent need for innovative detection technologies that can reliably identify unauthorized diversion events in these challenging environments.

The challenge of detecting nuclear material removal in complex storage environments is both significant and urgent. Preventing unauthorized access, diversion, or tampering with nuclear materials is a cornerstone of global nuclear safeguards and nonproliferation efforts. Current detection methods are increasingly inadequate as storage configurations become more intricate and inaccessible. The limitations of existing technologies—such as their inability to detect changes behind obstructions, reliance on costly and labor-intensive processes, and vulnerability to environmental conditions—pose risks to the effectiveness of safeguards systems. Addressing this challenge is critical to maintaining international trust in nuclear safeguards frameworks and ensuring compliance with nonproliferation agreements.

Our project builds on the proven concept of TRU technology that can address this unmet need. TRU has demonstrated exceptional spatial sensitivity and change detection capabilities in complex non-line-of-sight environments, making it uniquely suited for detecting unauthorized nuclear material removal in challenging storage configurations. Unlike optical methods, TRU is not limited by line-of-sight constraints or environmental conditions, enabling reliable detection of subtle alterations even behind obstructions. By leveraging TRU's ability to identify removal or tampering events, we aim to develop a robust detection system that enhances safeguards in geological repositories, storage vaults, and other complex environments.

Approach

Our goal is to monitor the removal or addition of nuclear storage containers by strategically positioning our equipment at the entrance of the room (Figure 1). This approach enables us to avoid physically entering the space, thereby reducing exposure to potential hazards typically encountered in a real-world repository environment. TRU will be deployed to monitor the integrity of storage containers and detect unauthorized removal or substitution events. To replicate complex storage environments, we will place stacked containers in configurations that mimic the challenges of real-world repositories, including tightly packed arrangements and obstructed line-of-sight scenarios. Using air-based ultrasonic transducers operating at approximately 40 kHz, we will probe the environment before and after containers are removed. Given the likelihood of additional changes in the repository, such as falling debris, we will

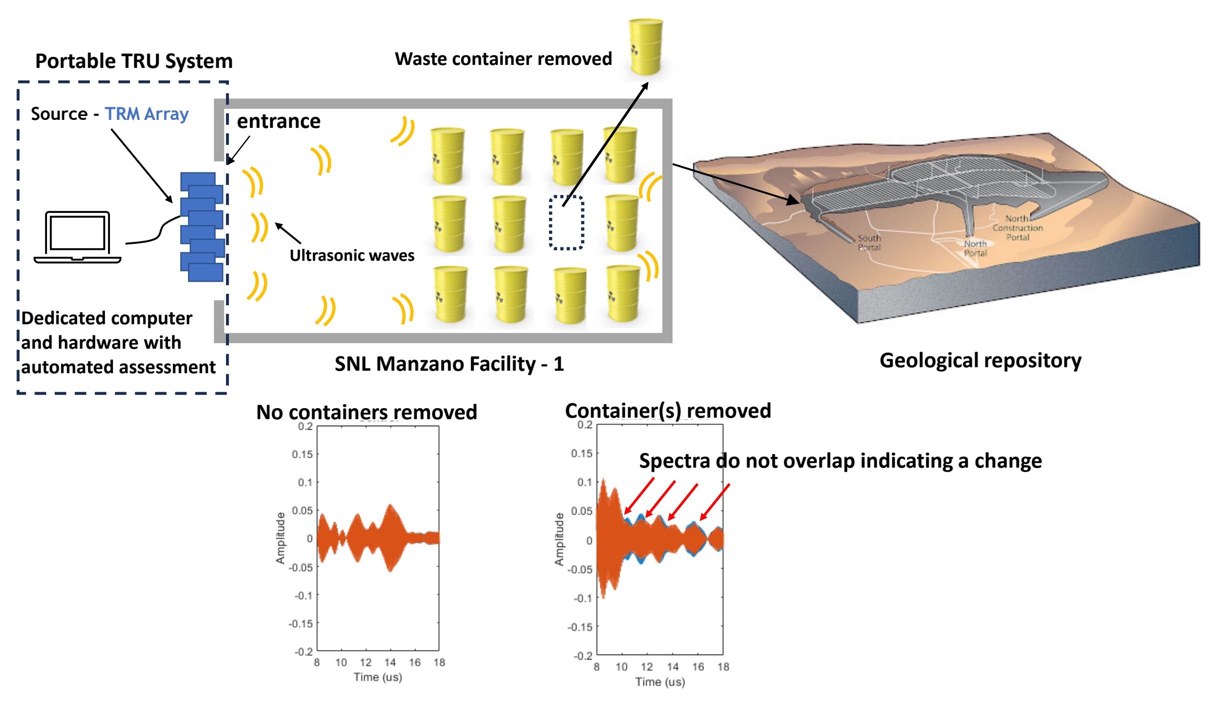

Figure 1. A geological repository testbed will be setup at the Manzano-Plant 1 facility at Kirtland AirForce Base to replicate inactive operations. The Portable TRU system will acquire signals at the entrance of the room which will be interpreted by a dedicated computer and will provide an automated assessment of container removal. Notably, ultrasonic waves can "probe" behind barriers and obstructions due to reflections from the containers and the environment. Measurement and analysis time will be approximately 10 seconds.

implement a thresholding method combined with statistical analysis to reliably differentiate between waste container removal events and other environmental alterations within the repository. Our approach enables comprehensive monitoring of the geological repository testbed, effectively covering areas obstructed by concrete pillars or densely packed storage configurations. By leveraging its ability to probe the entire environment simultaneously, TRU ensures reliable detection of changes, providing an effective solution for maintaining the integrity of nuclear materials

TRUGS Measurement System and Software Application

Over the last two and a half months, we focused on modernizing and preparing the system for larger underground room measurements under Task 2. We brought the software application up to date and improved the overall setup workflow, then updated and validated the measurement application in a controlled environment to assess signal quality and receiver performance with the existing hardware. Two notable software updates now enable the use of multiple acoustic sources rather than a single source. This enhancement improves signal-to-noise ratio and supports more complete interrogation and coverage of the full measurement volume.

In parallel, we began upgrading the hardware to support larger spaces by adding high-gain, low-noise preamplification; we selected the AD8429 low-noise 60 dB amplifier (scalable up to 80 dB gain with 100 kHz bandwidth and ~1 nV/√Hz input noise), updated the schematics to reflect this change, and initiated selection of a suitable power amplifier to drive the source transducer (Figure 2). To support underground deployment, we acquired a custom cart to house the digital processing hardware and drive electronics. We also identified limitations with the current 40 kHz transducers' narrow beam angles (i.e., 10°) for

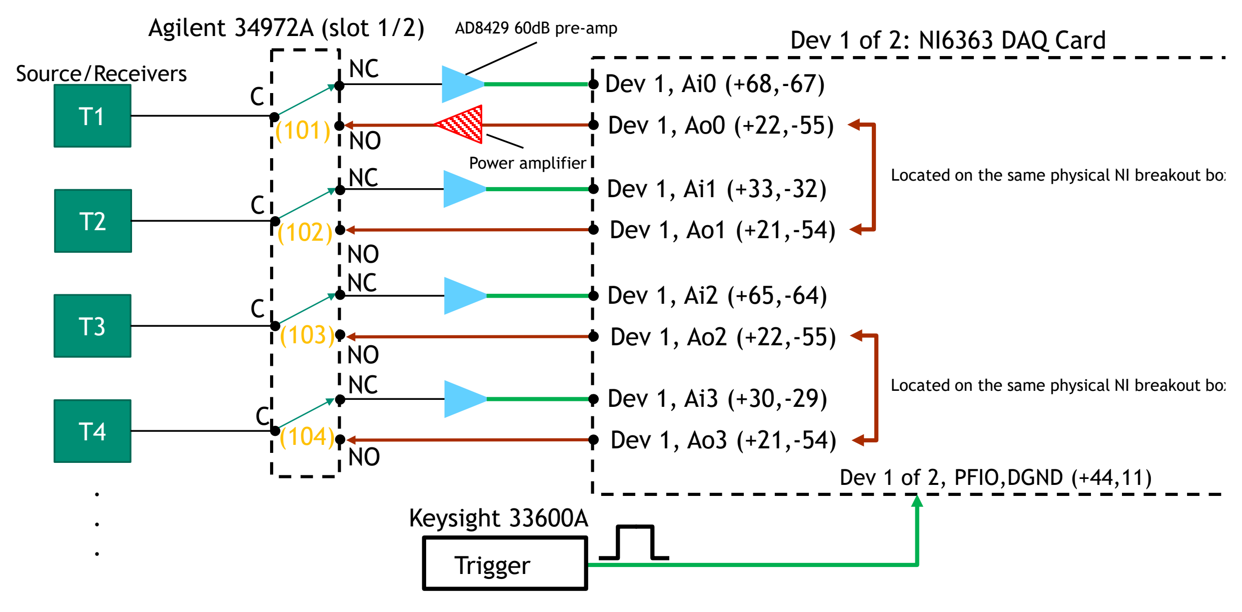

Figure 2. Updated electrical schematic for the TRUGS System which shows half of the setup. To improve signal acquisition from larger room environments, we have added 60 dB preamplifiers on the receivers. We are in the process of adding a power amplifier to the source transducer(s) to boost the signal output.

room-scale probing, and we are addressing this by procuring wide-beam (i.e., 60°-120°) acoustic transducers to better distribute acoustic energy across the target room volume (approximately 20 ft × 12 ft × 12 ft). Finally, we continued refining our change-detection approach using cross-correlation/time-reversal concepts, where TRM recordings are stored as a snapshot of the environment and replayed backward in time; incomplete reconstruction of the original pulse provides a robust indicator of change events. At this time, the current cross-correlation change detection algorithm appears very robust for detecting subtle changes in the environment.

After modernizing the software application, we conducted a series of controlled measurements in the lab using plastic tubes as representative test objects. These tests were designed to verify end-to-end system performance—confirming that the transmit waveform generation, receiver chain, timing/synchronization, data acquisition, and signal-processing workflows are all operating as expected and producing repeatable results with the current hardware configuration. Establishing this baseline in a controlled environment also allowed us to check signal quality and noise performance, identify any integration issues early, and document expected system behavior prior to transitioning the hardware onto a custom cart (Figure 3d) for the next phase of deployment and field-oriented testing. In Figure 3, we conducted a small-scale change-detection experiment to verify that the system could reliably identify a subtle change in a cluttered scene. Specifically, we arranged multiple plastic containers and then removed one container that was positioned behind the others (i.e., partially obscured and not in the direct line of sight of the transducers). We collected baseline measurements with the full set of containers in place, repeated the measurement after removal, and compared the two datasets using our change-detection processing. The results demonstrate that the system is sensitive enough to detect the removal event even

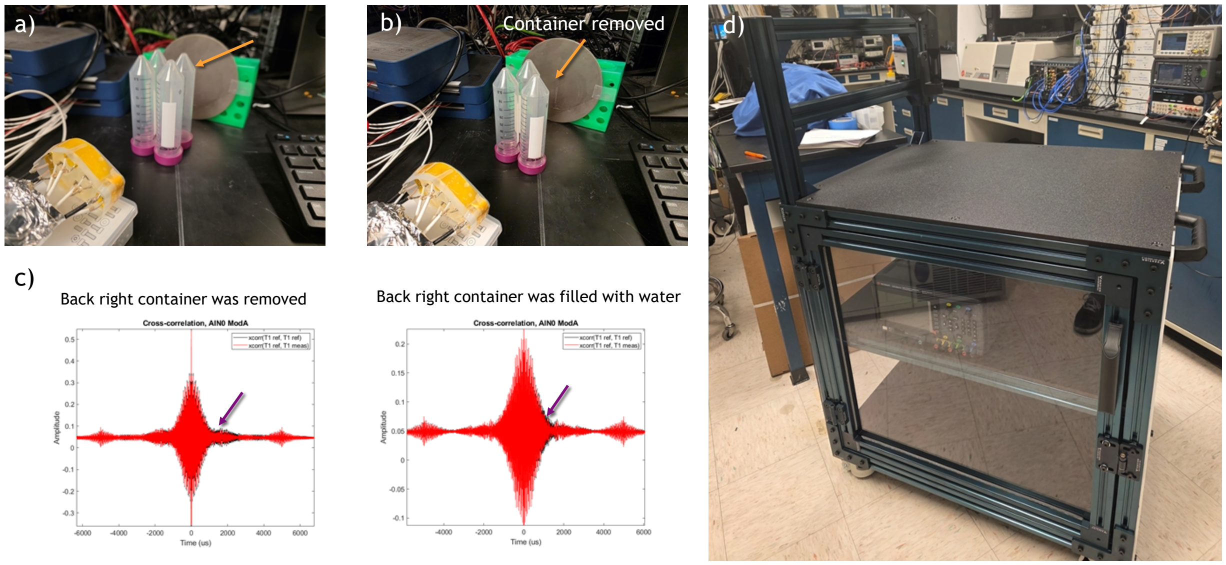

Figure 3. Confirmation measurements were performed using the updated software application and TRUGS hardware system. a) air-filled plastic tubes were placed in the acoustic beam path to act as liquid containers for the change detection measurements, b) the back right container was removed, c) when the back right container was removed or filled with water, the cross-correlation process was able to detect these changes, and d) we have built a portable cart and the measurement system will be transferred to the cart in the coming month.

when the changed object is located behind other items, providing confidence that the approach can detect non-obvious changes and is suitable for more complex room-scale environments.

Differential Measurements

As part of Task 1, we modified the software application to drive multiple transducers, improving signal return throughout the storage room. We are also conducting benchtop measurements to assess algorithm performance when the source is not placed in exactly the same position. Our approach reduces sensitivity to cart placement, ensuring that detected changes reflect object changes rather than shifts in equipment position at the entrance.

Underground Testing Facilities on Kirtland Airforce Base

The team conducted an on-site walkthrough of the DARTS underground testing facility located on Kirtland Air Force Base, which is owned and operated by the Defense Threat Reduction Agency (DTRA). The facility is situated approximately 30 ft below ground surface and offers several features that make it well-suited for upcoming change-detection demonstrations. These include available electrical connections for powering data acquisition and drive electronics, adequate fixed lighting for setup and troubleshooting, and ramp access that supports safe and efficient movement of carts and equipment to and from the underground level. The site also contains two separate rooms that can be configured for controlled measurement scenarios, including planned tests using 55-gallon storage barrels as representative objects for change detection. We are scheduled to tour the Manzano Mesa MP-1 next month. A photo of the facility is shown in Figure 4.

Figure 4. A hallway in the Manzano Mesa MP-1 underground complex.

Milestone Status

- We developed a simulation tool to guide the measurements.
- The team modernized the measurement application to enable single and multiple transducers studies. Differential measurements have also been implemented.
- We have performed several test cases of change events in a controlled laboratory environment for air and water filled containers.
- From our controlled measurements, we determined that 60 dB high-gain acoustic preamplifiers, a source power amplifier, and wide-beam-angle COT transducers are required for the 20 ft × 12 ft × 12 ft underground room.

Next Steps

Next steps focus on scaling the system from benchtop demonstrations to room-scale measurements in a 20 ft × 12 ft × 12 ft environment. We will upgrade the receive chain by adding high-gain, low-noise preamplifiers at the front end to improve sensitivity to weaker reflections and increase overall signal-to-noise ratio in larger spaces; the schematic has been updated to incorporate the selected AD8429 preamplifier. In parallel, we will select and integrate a suitable power amplifier to more effectively drive the source transducer and increase acoustic output for longer-range interrogation. To ensure full room coverage, we will also address the narrow beamwidth of the current transducers by transitioning to wider-beam acoustic transducers and implementing beam-spreading approaches to distribute acoustic energy more uniformly throughout the volume. Together, these upgrades are intended to extend operational range, reduce coverage gaps, and improve the robustness of change detection across the entire room.