IDEA

Innovations Deserving Exploratory Analysis Programs

Rail Safety IDEA Program

Railroad Tunnel Inspections for Maintenance and Replacement Prioritization Using Untethered Ground Penetrating Radar and LIDAR Capable Unmanned Aerial Vehicles (UAVs)

Final Report for
Rail Safety IDEA Project 42

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Executive Summary

The Adojam RS42 IDEA Project Team developed a safe, airborne railroad tunnel inspection technology called SATES[1], performed SATES field tests on example railroad tunnels, and met Stage 1 Project objectives. Conventional tunnel inspections are limited by rail bound, manned vehicle constraints at grade (qualitative and/or limited resolution). In contrast, SATES technology provides comprehensive, 3D, colorized tunnel liner measurements at high resolution to evaluate surface deterioration (via innovative SLAM LIDAR[2]) and subsurface moisture (via innovative Radar on a Chip technology), including difficult access tunnel ceiling evaluation. Novel SATES UAV[3] deployment and innovative sensors produced the following results in Stage 1:

- World's first surface + subsurface UAV measurements in a tunnel
- Detected and located subsurface water behind concrete tunnel liners
- Detected concrete tunnel deterioration features (spalls, cracks, etc.)
- Virtualized 3D tunnel geometry as a dense, colorized point cloud

The custom SATES UAV airframe and purpose-built sensor deployments were integrated specifically for railroad tunnel inspection applications. During Stage 1, the SATES UAV performed tunnel safety measurements untethered, contact-free, and reference-free, showcasing convenient scan capabilities at two field test sites. SATES sensing technologies accurately measured tunnel geometry within inspection tolerances, including difficult access features in tunnel ceilings (which are often dangerous and inconvenient to inspect via conventional means). SATES comprehensively documented tunnel deterioration features and provided information about excess water in concrete tunnel liners (linked to tunnel deterioration phenomena).

The Project Team performed a week of successful SATES field test flights and data collection in coordination with Norfolk Southern Corp. at Blair Tunnel in January 2020 (following a November 2019 field test where generation 1 SATES airframe performance required improvement) in addition to field tests at the Silver Run Tunnel and more.

Successful RS42 Project data collection during the January 2020 field test campaign was supported by an improved generation 2 (Gen2) SATES airframe and refinements to sensor systems. The Gen2 airframe and sensing systems are documented in the Stage 1 Project Performance Section of this report.

SATES nondestructive test results from the concrete tunnel liner subsurface (GPR[4]) and the surface (SLAM LIDAR) show the benefits the SATES system provides. SATES data agreed with independent observations of tunnel deterioration. The Adojam RS42 IDEA Project Team also built on these results in Stage 2.

[1] Safe Automated Tunnel Evaluation System

[2] Simultaneous Localization and Mapping Laser Imaging Detection and Ranging

[3] Unmanned Aerial Vehicle

[4] Ground Penetrating Radar

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IDEA Concept and Product

This project resulted in the development of an innovative prototype system implementation of untethered, contact-free, reference-free, railroad tunnel measurements (surface and subsurface) that improves railroad safety. The unique capability informs and optimizes railroad tunnel asset life cycle cost decisions. The product application provides GPR and LIDAR measurement capabilities via an efficient, specialized Unmanned Aerial Vehicle (UAV) deployment. It measures areas of moisture/water entrapment (behind the tunnel liner), tunnel wall liner thickness and reinforcement geometry, tunnel clearance dimensions, and tunnel material properties. Relevant metrics SATES evaluates are a function of moisture build up, geometry (tunnel clearance), and material properties impacting fire survivability and more. Our Team uniquely integrated, operationalized, applied, and field tested the subject Safe Automated Railroad Tunnel Evaluation System (SATES) technology. Specialized results address systemic railroad needs to improve overall railroad safety and maintenance related life cycle cost decisions.

Project Objectives

As specified by the subject contract, the project objectives are as follows:

The Subawardee shall furnish all necessary materials, facilities, equipment and qualified personnel to perform the services described below:

1. The work provided for hereunder is designated by the following title:
"Railroad Tunnel Inspections for Maintenance and Replacement Prioritization Using Untethered Ground Penetrating Radar and LIDAR Capable Unmanned Aerial Vehicles (UAVs)"

2. The research problem statement and objective(s) are as follows:
This project will provide Safe Automated Railroad Tunnel Evaluation System (SATES) technology to enhance safety and inform life cycle cost decisions by measuring and analyzing key railroad tunnel issues from an Unmanned Aerial Vehicle (UAV). The SATES system will be based on the proven Difficult Access Advanced Ground Penetrating Radar platform ADOJAM developed previously for select applications to civil infrastructure and defense applications to safely detect buried threats (where Global Positioning System (GPS) information is available). A specialized aspect of SATES will be GPS denied operation in railroad tunnels.

The project shall be performed in the following two (2) contingent stages. **Satisfactory performance of each stage must be approved by the IDEA program before the next stage of project activity can commence.**

Stage 1 Project Performance

During Stage 1, the project Team executed Tasks in eight key areas [A through H], consistent with Stage 1 Tasks [1 through 11] following a kickoff meeting [Figure A1]. Project progress in key areas is described as outlined immediately below as a narrative, while each Task accomplishment is featured in the *Task Summary Section* to account for more granular project progress point by point:

A. Prototype SATES design, build, and initial test
B. Field site reconnaissance [Oct 15-16, ‘19] in collaboration with NS Corp.
C. Field test 1 [Nov 11-15, ‘19] in collaboration with NS Corp.
D. Data analysis
E. Address SATES UAV flight issues (field test 1) and perform field test 2
F. Prototype Gen2 SATES airframe redesign, build, & test to support field test 2
G. Field test 2 [Jan 6-9, ‘20] in collaboration with NS Corp. and at Silver Run Tunnel [Jan 10, ‘20]
H. Field test 2 results and analysis (2021)

A. Prototype SATES design, build, and preliminary test

SATES prototype requirements addressed critical design challenges that were unprecedented for a UAV of its type, including flying and sensing in a tunnel environment. The Team focused early work on adapting and customizing ADOJAM’s Unmanned Aerial Vehicle [UAV] airframe to perform in a tunnel and worked in parallel on sensing aspects as the custom airframe matured.

A tunnel environment presents UAV design challenges, including denied access to Global Positioning System [GPS] signals that conventional Unmanned Aerial Vehicle [UAV] control systems rely on to maintain stability and navigate, plus instabilities caused by close proximity to the tunnel walls and ceiling. A counter-rotating prop design was specified and deployed to minimize flight instabilities in proximity to tunnel wall and ceiling features. Also, a custom pilot control system and instrument configuration was required to navigate and locate a UAV in real time in the tunnel to make relevant measurements. The SATES UAV airframe utilizes a control strategy where relative measurement results from two system control loops provide control data. Differences between the two control loop outputs (predictable via UAV kinematics) are substituted for GPS data to locally stabilize the UAV control system. The system ultimately provides a flight platform a UAV pilot can control like a conventional UAV (once tuned).

Figure 1 shows the SATES system configuration, where the control system is located at the near end of the rectangular electronics bay and the power system is at the far end of the same bay. As Figure 1 also shows schematically, a 3D Simultaneous Localization and Mapping [SLAM] LIDAR instrument (Appendix B) is mounted centrally on the UAV airframe to minimize control eccentricities introduced

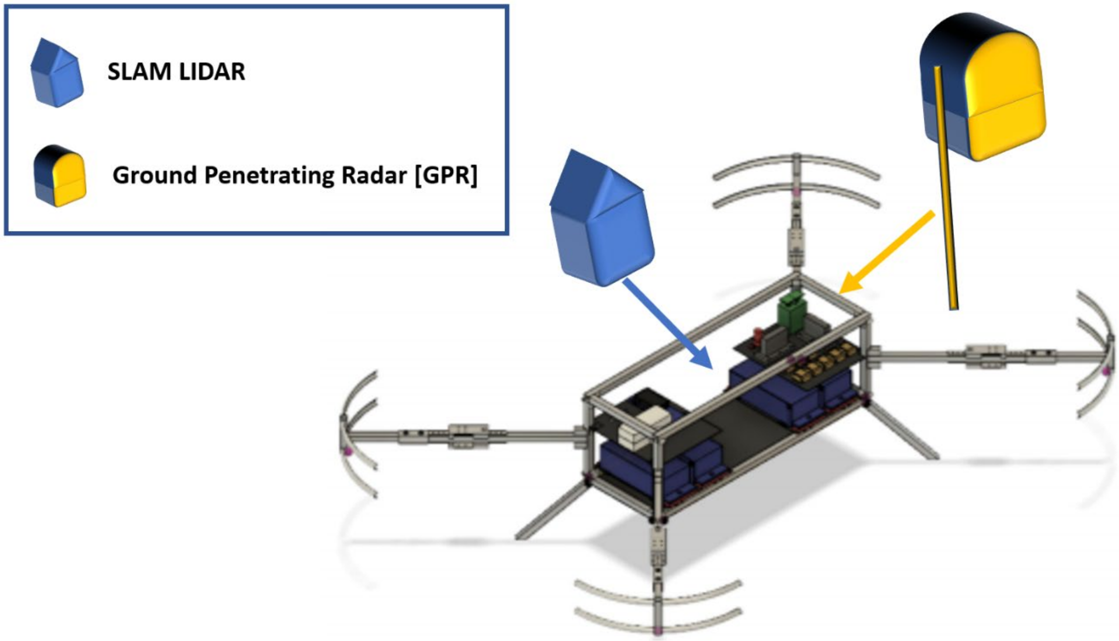


Figure 1. SATES prototype configuration including frame, electronics, SLAM LIDAR instrument mount location, and GPR mount location. No propellers are shown.

by the SLAM LIDAR mass. Finally, Figure 1 shows the Ground Penetrating Radar [GPR] sensor mounted on an extension rod, where GPR specifications are provided in Appendix C. The length of the rod affords access to the tunnel ceiling when the UAV is adequately airborne and provides GPR sensor standoff from the UAV itself. The extreme light weight of the GPR sensor allows it to be mounted at the end of the rod without inducing significant instability in the UAV.

Safe and effective SATES UAV airframe tunnel deployment required a series of progressive subsystem tests, control system tuning, flight experiments, and sensing work prior to going to the field. The system was built using modular aluminum components and bolted construction, including 3D printed parts at specific joints. Figures 2, 3, 4, A2 through A4, and 5 highlight SATES project design features and capabilities tested, as described in succession below.

Figure 2 illustrates a four-line tether configuration attached to the underside of the SATES UAV to perform safe tests of the newly designed control system (performed 1.5 months prior to the initial SATES field test). System flight parameters configured for a typical SATES pilot include gain curves, trim for the two-stick controller, and flight mode configurations (stabilize for minimal pilot assist and altitude hold for conventional pilot assist). Tuning and testing in the tethered flight mode enabled safe field deployment of the system.

Figure 2. Prototype configuration on a four-tether platform.

Figure 3 shows the SATES UAV in a spar prop guard configuration. This configuration enabled early flights off tether, where flight stability of the UAV was tested. Inherent stability of the counterrotating prop system provided significant advantages for initial tuning. Initial SATES UAV tuning off tether to operate without GPS above an altitude of 5 feet was facilitated by UAV prop spars.

Figure 3. SATES prototype UAV in four spar prop guard test configuration.

Figure 4. Successful test flight without payload.

Figure 4 shows the SATES UAV being test flown with standard prop guards and no sensor payload. Successful SATES UAV test flights with no payload showed exceptional stability while operating without GPS. System tuning (refined in tethered modes and with spar prop guards) produced even more stable results when standard prop guards were installed.

SATES UAV dummy sensor payloads (having the same mass and geometry as SATES sensors) were flown successfully for training purposes as shown in Figures A2, A3, and A4. Flights were performed during a 1 week training session with ADOJAM field test pilots prior to the tunnel field test. UAV control settings were fine tuned to ensure stable and consistent flight with the sensor payloads.

Figure 5 shows SATES deployed in a mock-up configuration with all sensors at a bridge in Ohio, including active propeller functions. The Ohio mock-up configuration is consistent with deployment for the tunnel project, except the metal GPR mount

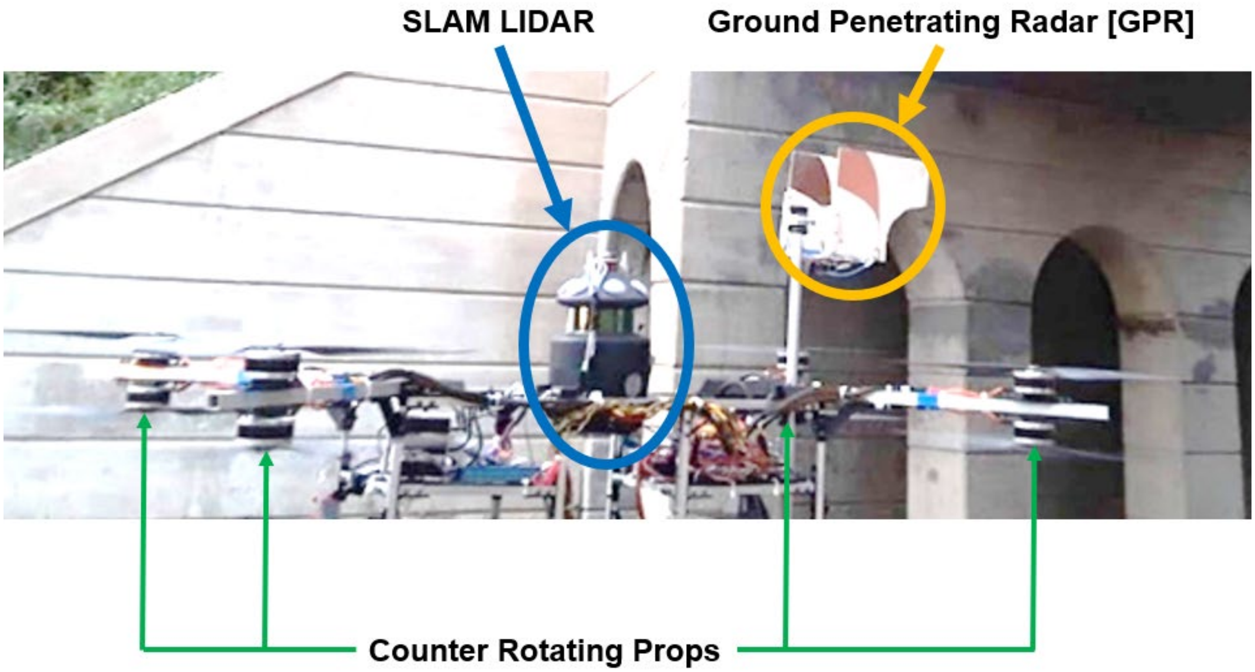


Figure 5. Initial SATES prototype configuration mocked up for testing at an Ohio bridge, including SLAM LIDAR instrument, GPR instrument, and counter -rotating propellers.

rod (made of wood in subsequent field tests) and protective packaging (including foam padding and a plastic cover in subsequent field tests).

B. Field site reconnaissance [Oct 15-16] in collaboration with NS Corp.

The project PI coordinated field test site reconnaissance with NS Corp. representatives at Blair Tunnel and Cregan Tunnel relevant to planned field testing. In addition to the PI, an Adojam UAS pilot and field technician, Mr. William Padukiewicz, supported field reconnaissance work on site. The PI performed a series of initial, terrestrial GPR sensor tests (Figure 6 on the following page) plus SLAM LIDAR sensor tests on site to verify sensor performance in the field. Initial SLAM LIDAR results indicated that supplemental lighting was needed in many field test scenarios at Blair Tunnel to produce high quality results and preliminary GPR tests of tunnel walls showed that sensor proximity to concrete surfaces was deceptive to discern by eye when sensors were positioned close to the ceiling and viewed from below. Both Blair Tunnel and Cregan Tunnel were traversed completely on foot by the PI and Mr. Padukiewicz during the reconnaissance trip.

C. Field test [Nov 11-15] in collaboration with NS Corp.

During the week of November 11 through 15, field test plans were executed by the PI, SATES UAV pilots, SATES UAV airframe support, and the Co-PI at Blair Tunnel

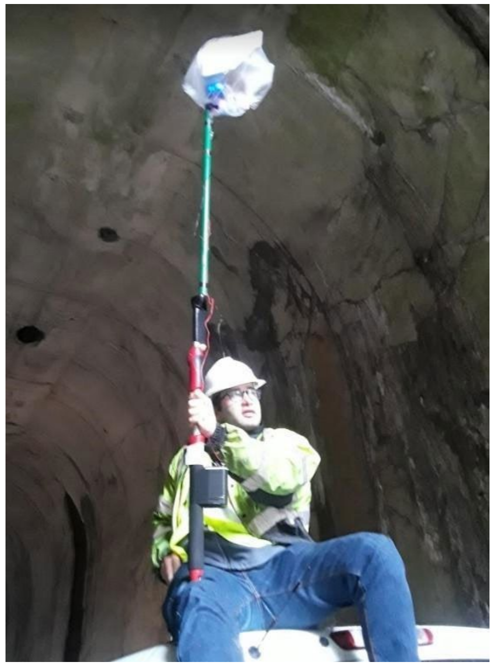


Figure 6. GPR on extension rod.

in coordination with NS Corp support staff who provided track time. The SATES airframe deployed in initial test flights (Figures 7) was flown at the mouth of Blair Tunnel on Monday, November 11, followed by a successful mid-day flight (Figure 8) into the tunnel that ended with a hard landing on a prepositioned wooden platform (spanning the railroad track). Following the hard landing, which deformed the UAV landing gear and airframe, significant issues involving the SATES UAV were immediately identified. The PI therefore directed UAV airframe support and a subset of UAV pilots to focus on repairing the UAV airframe while the PI and his Technician/UAV Pilot performed terrestrial sensor data collection work at the tunnel for the remainder of Monday, November 11.

On November 12 through 15, two important thrusts were pursued by the PI and the project Team consistent with field test challenges. One thrust was to use every available means to address the UAV airframe issue and move forward with the original test plan. The second thrust used available means to collect terrestrial SLAM LIDAR and terrestrial GPR field data, even if the SATES UAV airframe was not air worthy (pending a UAV redesign). Manual data collection became critical during the November field test pending UAV improvements (for a follow up field test). Manual SLAM LIDAR data was collected from the track bed and from a hi rail vehicle. GPR data was collected by mounting the GPR on an elevated pole, held above a hi rail vehicle. Example results are shown in Figures 10 and A7 through A10.

The November field test was a critical opportunity to advance project goals and produce the best attainable project results under challenging circumstances. The project Team worked to attain these results via manual data collection, which

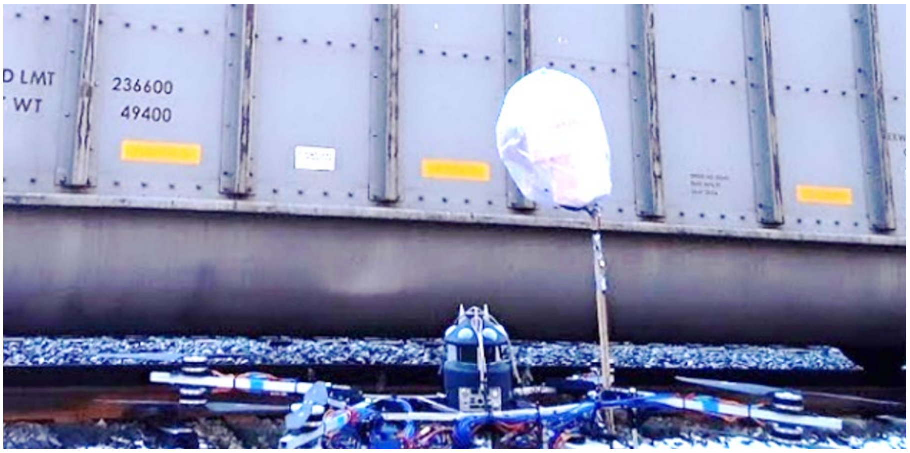


Figure 7. Instruments mounted on SATES platform in the field.

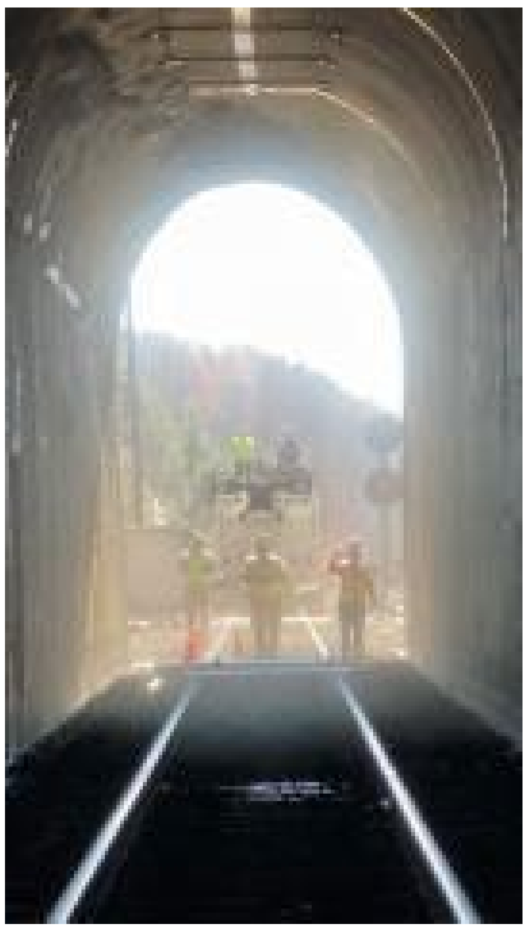


Figure 8. Successful initial flight in Blair Tunnel.

provided one avenue to attain a subset of project goals. On review of the field test week and its challenges, a SATES UAV airframe redesign and a second test week was planned to assure all key project goals are ultimately achieved.

D. Data analysis

Two SATES data types provide a powerful combination to assess tunnel deterioration, where:

- Figures 9, A5 and A6 show example SLAM LIDAR data, and
- Figures 10 and A7 through A10 show example GPR data

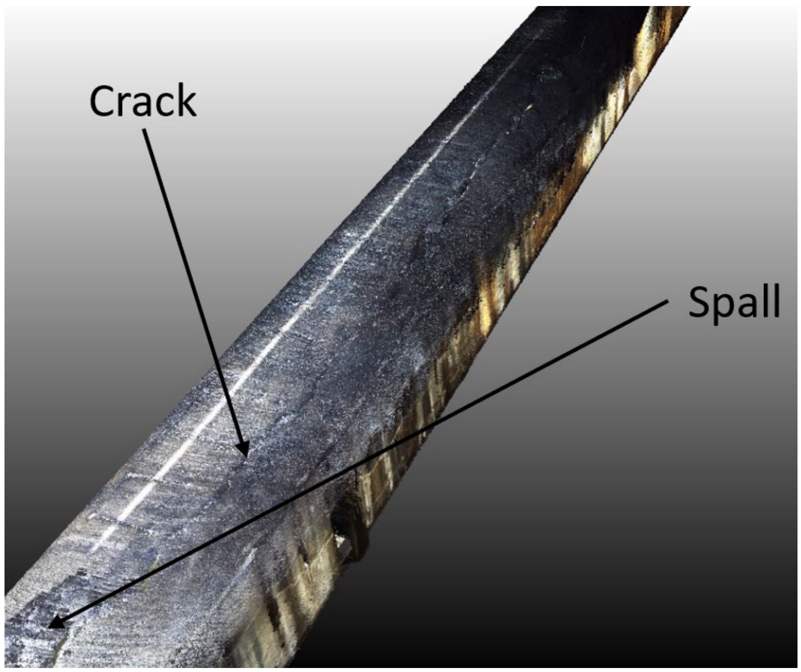


Figure 9. SLAM LIDAR tunnel data (top oblique view) including high fidelity crack & spall features.

Specifically, Figure 9 SLAM LIDAR data represents an exterior view of the 3D tunnel geometry, accurately representing detailed crack and spall features in the concrete tunnel ceiling, indicating severe deterioration, plus full scale railroad tunnel geometry within accurate tolerances (measurable to a 3D uncorrected tolerance of a few inches or less). Figures A5 and A6 also show accurate large tunnel geometry that provides results deeper inside the tunnel. However, it is notable that deeper tunnel images have lighting issues illustrated in Figures A5 and A6, where contrast was low. These contrast issues reduce the ability to discern and assess features such as cracks.

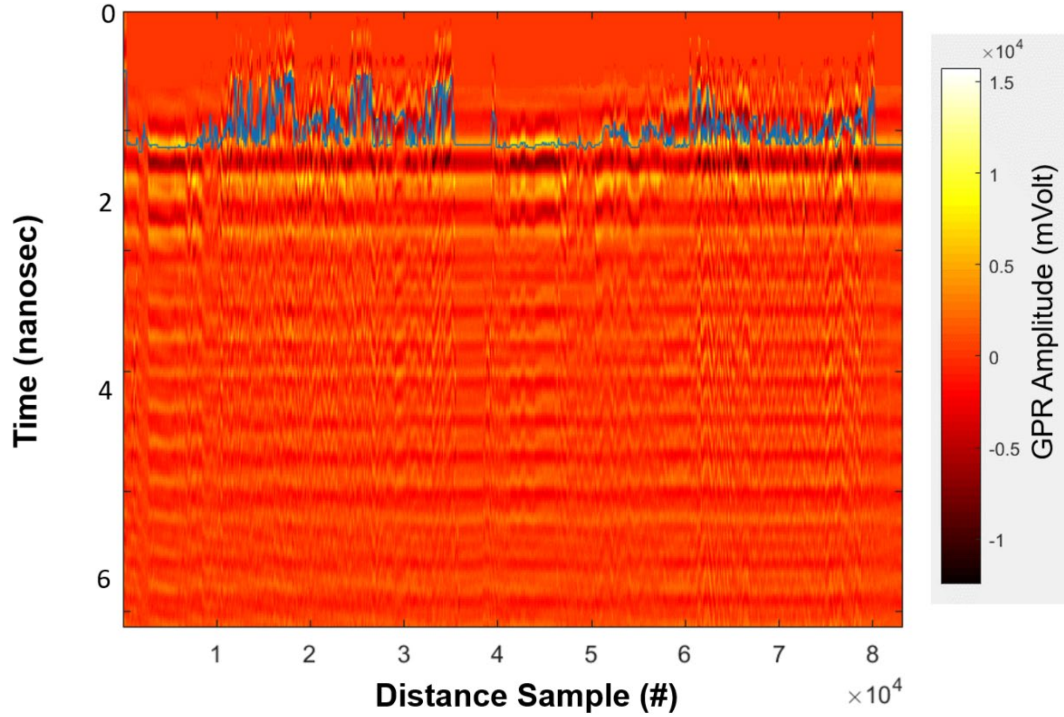


Figure 10. Equalized Ground Penetrating [GPR] data with concrete surface reflection labeled/identified (blue line), near surface response (above blue line), subsurface response (below blue line), and time scale.

Figure 10 illustrates example Ground Penetrating Radar [GPR] results including a surface response (labeled with a blue line), near surface features immediately above the blue line, and subsurface features below the blue line. The output shown in Figure 10 was produced by the following process:

- Collect raw GPR data shown in Figure A7
    - Move the GPR sensor linearly along the long tunnel axis @ ≤ 1 ft/s while collecting GPR responses at regular intervals
        - Position the GPR sensor within ≤ 3 ft. of the tunnel ceiling
        - Direct the GPR antenna upward (in its mounted configuration), normal to the surface of the tunnel ceiling (crown)
        - Start a GPR data acquisition sequence via a toggle switch
        - Laterally position the GPR antenna on the tunnel crown while collecting data along the tunnel length dimension and maintain this lateral position (via terrestrial or airborne platform)
    - Transmit and receive UWB GPR impulses at regular intervals along the long tunnel axis [where frequency content is 700 MHz to 3 GHz]
    - Blue line variations show GPR antenna proximity to the surface of the concrete tunnel ceiling, where larger travel times represent greater distances between the antenna and the surface.
- Figure A7 raw GPR data is equalized [including a common DC offset] to produce Figure A8. Floating DC offsets observed in raw sensor results are

corrected to equalize results (where vertical banding in Figure A7 indicates variations of DC offsets).
    - Raw GPR data contains dark and light vertical bands (Figure A7)
    - The mean DC GPR response is determined for collected data
    - All GPR responses are equalized to match the mean DC offset
- Background subtract Figure A8 end reflection and detect surface Figure A9
    - Extract a background response (end reflection) that represents the GPR antenna propagating into empty space
    - Subtract the end reflection from the GPR response to minimize signal ringing effects.
- Reinsert GPR near surface features as shown in Figure A10
    - Above the GPR surface response (blue line in Figure A9) open bins and reinsert near surface features (within a nearby neighborhood)
    - Near surface features will now appear, including responses to metal retention brackets

Additional Stage 1 data processing and interpretation is provided in Key Area Section H.

E. Address SATES UAV flight issues (field test 1) and perform field test 2

SATES field testing at Blair tunnel produced limited initial results, but it also identified UAV airframe performance issues in the tunnel environment (involving aerodynamics, ruggedness, and more). Limitations imposed by early damage to the SATES UAV airframe on Monday, Nov 11 prevented many planned data acquisition activities from being completed (requiring a follow up field test).

Airframe resilience issues due to a crash or hard landing were among the most significant for the UAV to improve. Stiffness of the airframe (from a vibration and flexure point of view) was also problematic based on observed field test performance under field conditions. Therefore, a rapid plan was developed to improve UAV airframe strength and resilience by stiffening the airframe substantially in the longitudinal dimension. The PI worked with UAV airframe support and the research Team to develop and plan an updated UAV in time to perform a second field test during the week of January 6 through 10.

F. Prototype SATES UAV airframe redesign, build, & test to support field test 2

Background for a SATES UAV Gen1 [Figure 11a] airframe redesign follows:

(a) SATES UAV Airframe Gen1

(b) SATES UAV Airframe Gen2 [with LIDAR mounted]

(c) SATES UAV Airframe Gen2 [with LIDAR and GPR mounted]

Figure 11. SATES airframe (a) generation 1 [Gen1] and (b,c) generation 2 [Gen 2].

Early SATES UAV Gen1 airframe field test flights outside Blair Tunnel exhibited manageable, predictable flight characteristics when flown unburdened or with sensor payloads, but a subsequent Gen1 SATES UAV airframe flight became less predictable as it crossed the tunnel threshold and entered its interior. Increased vibration feedback and aerodynamic instabilities within the tunnel boundaries stressed the Gen1 airframe, making it more difficult to pilot smoothly and effectively. As the Gen1 system became less manageable inside the tunnel, the UAV pilot landed the airframe abruptly and stressed the airframe beyond its elastic limits. Following many repair and field test efforts from November 12-15, the Gen1 airframe geometry was ultimately determined to be irreparably damaged by the Gen1 airframe's initial hard landing.

Therefore, a Gen2 SATES UAV airframe with improved stiffness and resilience (to reduce vibration during flight) was needed to support a second field test. Figures 11b and 11c show the prototype Gen2 SATES UAV airframe, redesigned to support RS-42 field test 2. Key differences between the Gen1 and Gen 2 airframe include:

- *The Gen2 airframe geometry was redesigned to be symmetric with square cross sections to enhance stiffness and minimize vibrations [Figures 11b and 11c]*
    - The Gen1 airframe was asymmetric, incorporating long rectangular sections [Figure 11a], making it susceptible to vibration issues. This Gen1 airframe feature made room for the SLAM LIDAR sensor within the internal structure of the UAS

- *The Gen2 airframe controller was centrally located within the UAV, minimizing perturbation effects a GPS denied UAV is susceptible to [Figures 11b and 11c]*
    - o The Gen1 airframe controller was located at an extreme end of the UAV and it therefore amplified dynamic perturbation effects a GPS denied UAV controller is susceptible to in this position [Figure 11a]
- *Gen2 airframe prop guards included integrated struts [Figures 11b and 11c]*
    - o The Gen1 airframe prop guards utilized two curved guard elements for each prop [Figure 11a], thus increasing weight
- *Gen2 airframe power systems were relocated centrally within the frame reducing system mass eccentricities*
    - o Gen1 airframe power systems were located at one extreme end of the UAV
- *Gen2 sensor mount points were completely exterior to the UAV frame, separating internal UAV component mount points from external sensor mount components.* Improved modularity of the Gen2 design made it more practical for field test applications
    - o The Gen1 airframe required the SLAM LIDAR to be mounted partially inside the UAV airframe. The wide, asymmetric Gen1 design made this compromised configuration more stable

The Gen2 SATES UAV airframe was rapidly proven flight worthy, and it was next tested at a presently abandoned industrial site. Enclosed and partially enclosed spaces at the abandoned industrial site supported similar test scenarios to the enclosed tunnel space. With the benefit of on-site tuning at the abandoned industrial site and airframe improvements, the Gen2 SATES UAV was optimized to perform in the enclosed tunnel space [Figure 11b and Figure 11c].

G. Field test 2 [Jan 6-9] in collaboration with NS Corp. and at Silver Run Tunnel Jan 10

The Gen2 SATES UAV and airframe mounted SATES sensors were deployed to perform field test 2 at Blair Tunnel from January 6 through 9 and at the Silver Run Tunnel on January 10. Figure 9 shows key Blair tunnel features near the southeast portal entrance (including cracks and ceiling spalls), while Figure 12 shows a broader area of interest from 37+687 (the southeast portal entrance) to 38+687 (1000 ft inside Blair tunnel) where key Gen2 SATES UAV field test 2 work was focused. Figure 13 summarizes field test 2 results from Blair Tunnel, where visually observed water locations (on the concrete surface) predominantly agreed with subsurface water locations detected via GPR. Figure 13 results will be discussed in detail in Subsection H immediately below, among other related data analysis details. This Subsection focuses on the field test 2 data collection process and the role the Gen2 SATES UAV (and its airframe mounted SATES sensors) played in the process.

Figure 14 shows the Gen2 SATES airframe and sensor system at the field test 2 project site in Blair tunnel. Redesigned SATES mounting configurations for SLAM

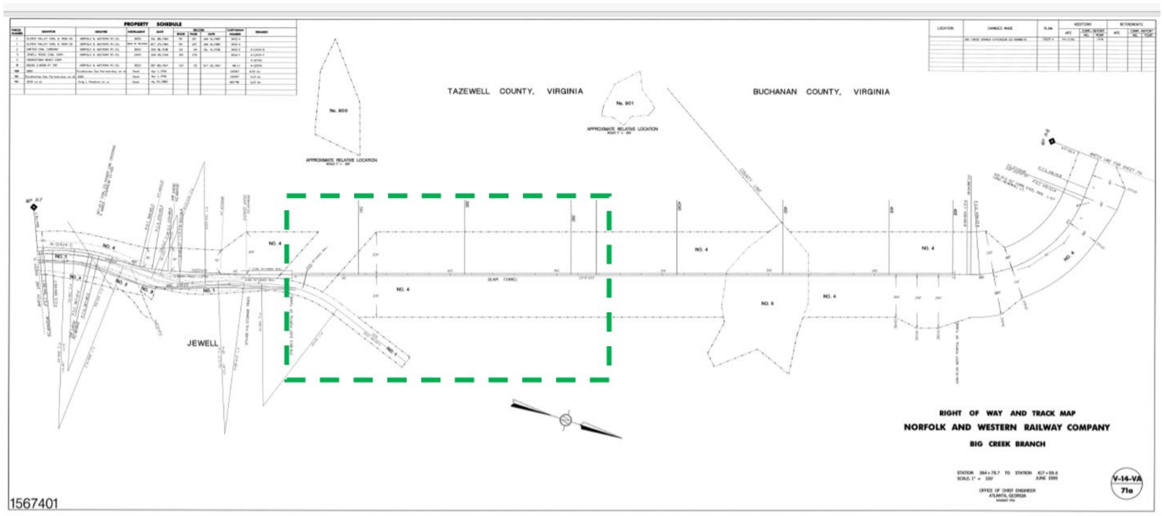


Figure 12. Blair Tunnel schematic site drawing including an area of interest (green dashed line).

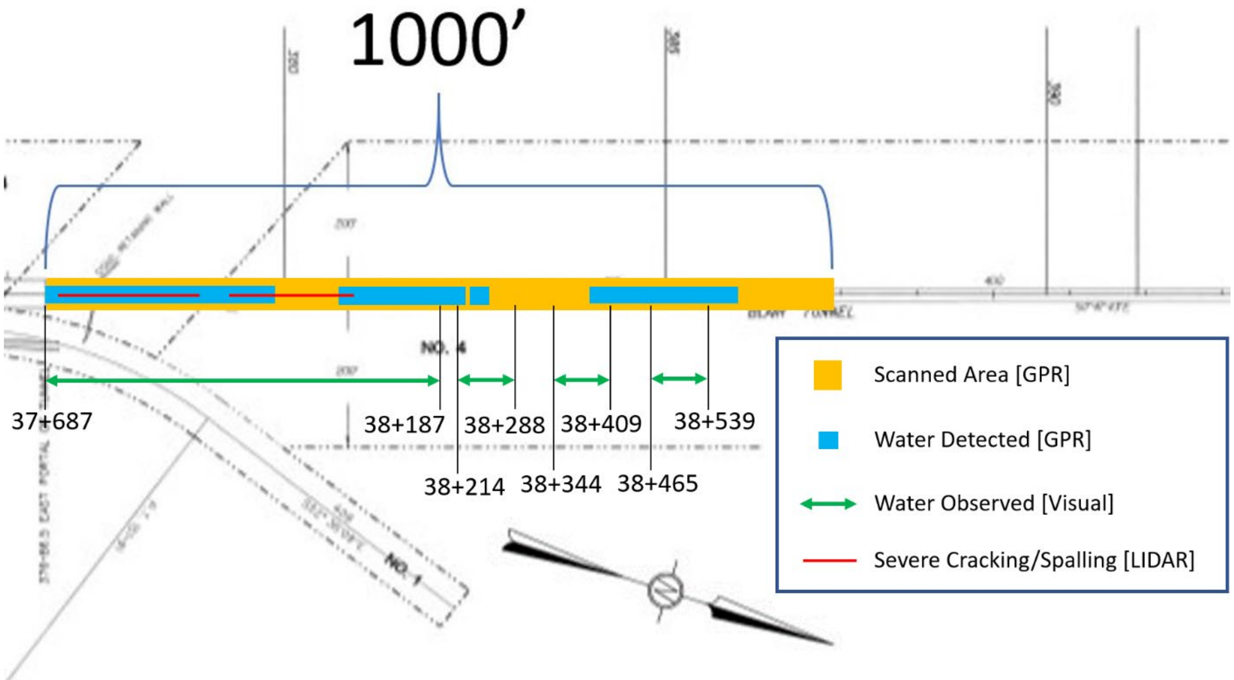


Figure 13. Blair tunnel results showing SATES sensor results [GPR + LIDAR] versus conventional results [Visual]. Severe cracking and spalling coincided directly with Visual and LIDAR results observed in Figure 20 and 21 through 25.

Figure 14. PI with fully updated, configured system (GPR and SLAM LIDAR mounted) at the field test site. Revisions included a symmetric frame and rotor arm struts.

LIDAR (on top of the Gen2 airframe) and GPR (rod mounted near the Gen2 airframe center of mass) sensors are clearly shown. The Gen2 SATES UAV (with key redesigned features described in Subsection F) are also noted.

Figures 15 through 19 illustrate airborne data collection capabilities the Gen2 SATES UAV sensing system supported at Blair tunnel. In Figure 15, the fully deployed system is shown taking off inside the tunnel and subsequently collects data using both SLAM LIDAR and GPR sensing modalities. In Figure 16, a test flight is shown where only SLAM LIDAR data is collected near the southeast Blair tunnel entrance. In Figures 17 and 18, a SLAM LIDAR data collection sequence deeper inside Blair tunnel is shown, where an LED light panel (mounted on and powered by the Gen2 SATES UAV) enables SLAM LIDAR imaging functions. These imaging functions colorize LIDAR point cloud range measurements, enhancing interpretation and analysis. LED lighting intensity and distribution factors were each evaluated manually and via SATES to initially achieve system function and ultimately, best results. Finally, Figure 19 shows a live view of a tablet computer screen displaying raw streamed LIDAR data via a wireless connection to the LIDAR sensor (supported via the SATES platform). As this Figure 15 through 19 sequence indicates, the Gen2 SATES airframe performed well at the tunnel site and typically provided a stable flight platform to support most desired data collection functions. Improved performance of the Gen2 SATES UAV airframe (versus issues with the Gen1 SATES UAV airframe inside the tunnel) was notable.

Figure 15. SATES GPR and SLAM LIDAR data collection take off at field test site.

Gen2 field data collection at Blair tunnel focused on tunnel measurements where the tunnel environment supported consistently available track time. Flights with higher risk (closer to the tunnel ceiling) were only performed after careful build up, consistent with safe practices in an unprecedented flight environment. Based on this safety conscious approach, a significant amount of LIDAR data was collected during field test 2, supported by diverse standoff measurements from tunnel walls, while a much smaller amount of GPR data was collected during field test 2 (which required flights much closer to the tunnel walls and ceiling.

Figures A12 through A14 show Gen2 SATES UAV data collection at the Silver Run Tunnel. On January 9, NS Corp informed the PI that Blair Tunnel or Cregan Tunnel track time were not supportable on January 10 due to unforeseen circumstances. Therefore, the project team traveled to the Silver Run Tunnel in Cairo, WV on January 10 and acquired additional field test data, characterizing system performance in this second tunnel environment.

Field test 2 data was successfully acquired during the week of January 6 through 10, which provided baseline RS-42 results presented at the TRB IDEA poster session on January 14. SATES performed well, as it provided unprecedented data acquisition functions in a GPS denied tunnel and met demanding difficult access requirements to enable new sensing and asset management information opportunities.

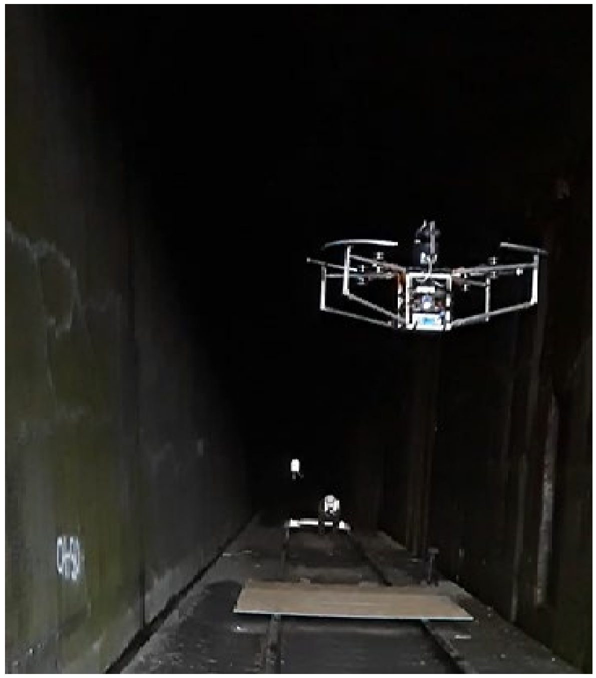


Figure 16. SLAM LIDAR data collection.

Figure 17. SATES platform: SLAM LIDAR and on board LED panel light source active.

Figure 18. SATES data collection.

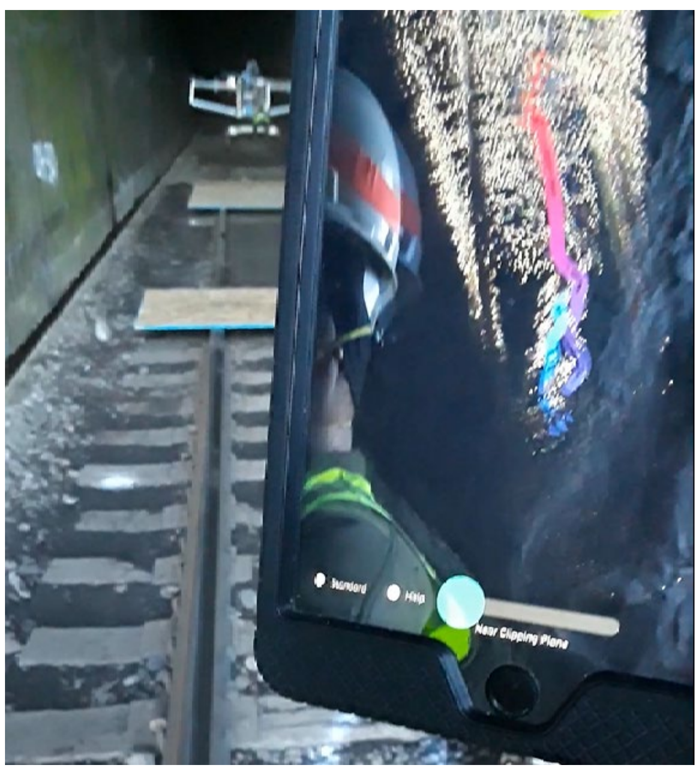


Figure 19. SATES data collection at Blair Tunnel.

H. Field test results and analysis

Field test 2 demonstrated unprecedented Gen2 SATES sensing and analysis capabilities. For the first time ever, Gen2 SATES provided difficult access tunnel asset management information via a SLAM LIDAR and GPR enabled UAV. Figure A24 shows SATES results while supporting analysis is summarized in Figures A34 through A39.

(a) (b)

Figure 20. Blair tunnel SATES LIDAR results corresponding to a 430 ft data Section. Severe cracking and spalling are evident.

At a high level, Figure 13 shows where water ingress compromised the Blair tunnel structure within the first 1000 of the tunnel bore (measured from the southeast portal entrance). Weakened concrete materials, corrosion induced cracking, concrete delamination, and concrete spalling phenomena are all contributing factors. In addition to SATES detection of water intrusion that causes deterioration, areas where severe cracking and spalling phenomena were detected via SATES are highlighted in red on Figure 13. Comprehensive results provided by SATES and their analytical support are a powerful emerging tool.

Regarding analytical support for Figure 13 results, Figures 20 through 25 provide supporting details. First, Figure 20 shows SLAM LIDAR results from field test 2. The airborne sensing perspective [Figure 20] provides greater detail throughout the tunnel aperture plus analysis benefits that complement the GPR data. With airborne SLAM LIDAR, more accurate representations of cracks, spalls and other surface details throughout the tunnel cross section are supported, as the LIDAR samples at higher resolution when it is in closer proximity to scanned features.

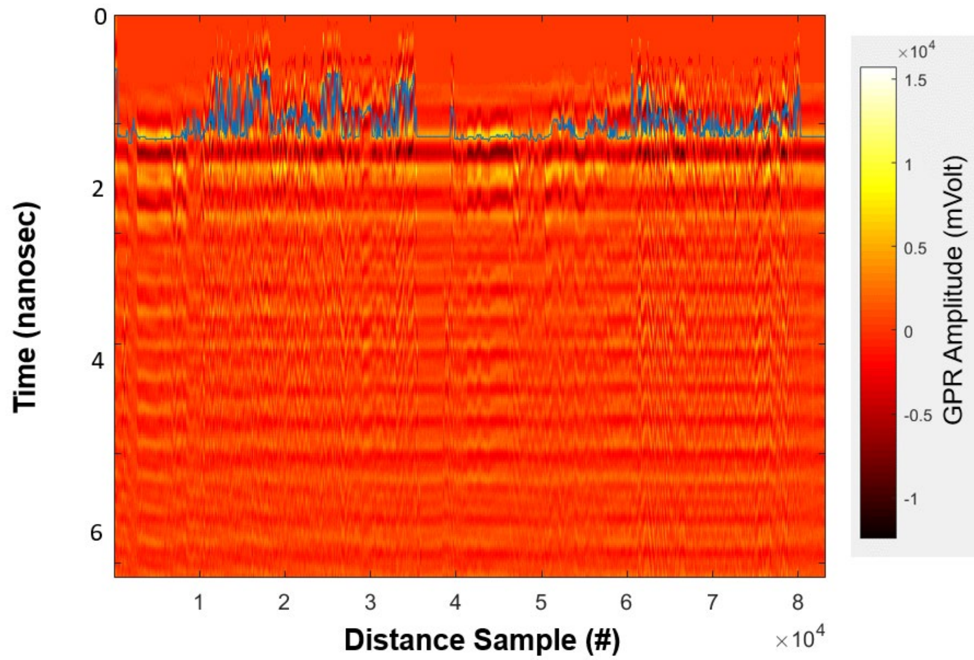


Figure 21. SATES GPR results following analysis to detect surface (blue line) and near surface features.

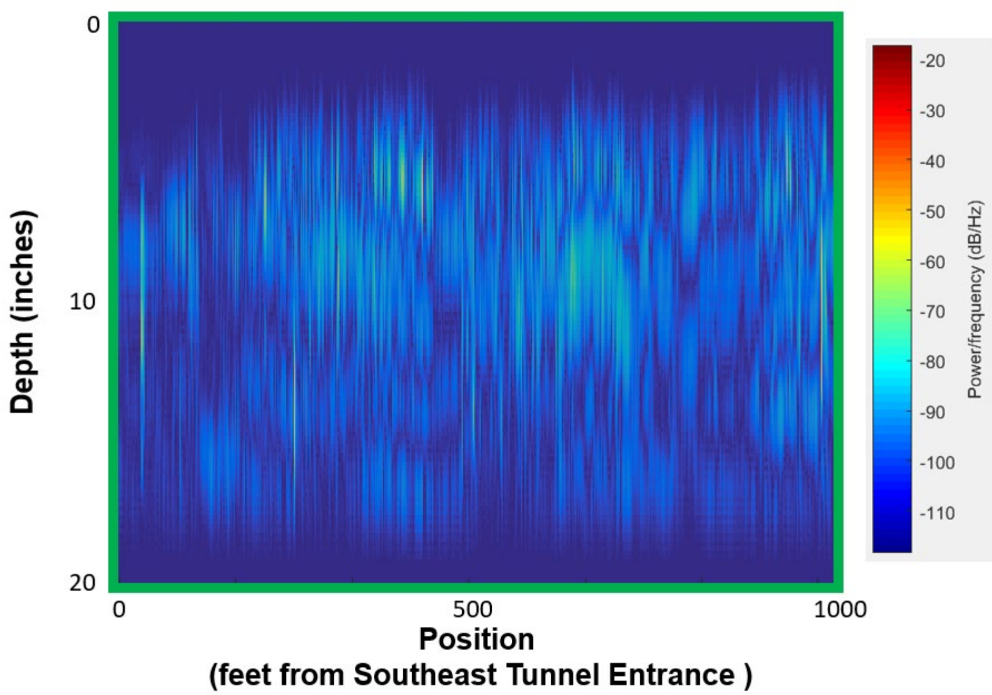


Figure 22. Zoom view of power/frequency characterization of GPR response features in Figure 22 data.

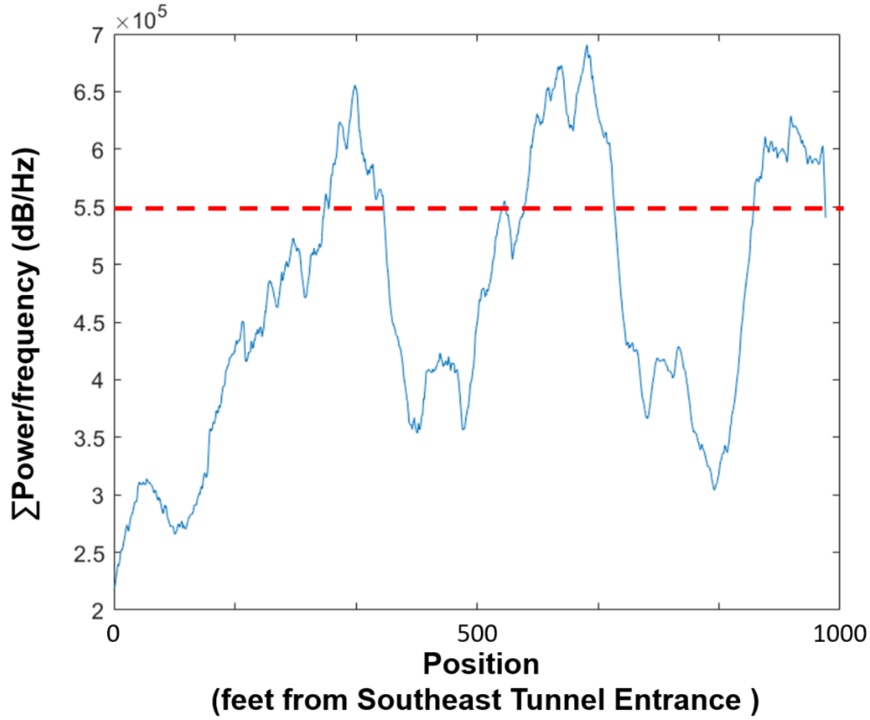


Figure 23. Sum of power/frequency characterization of GPR response features in Figure 23 data with water detection threshold.

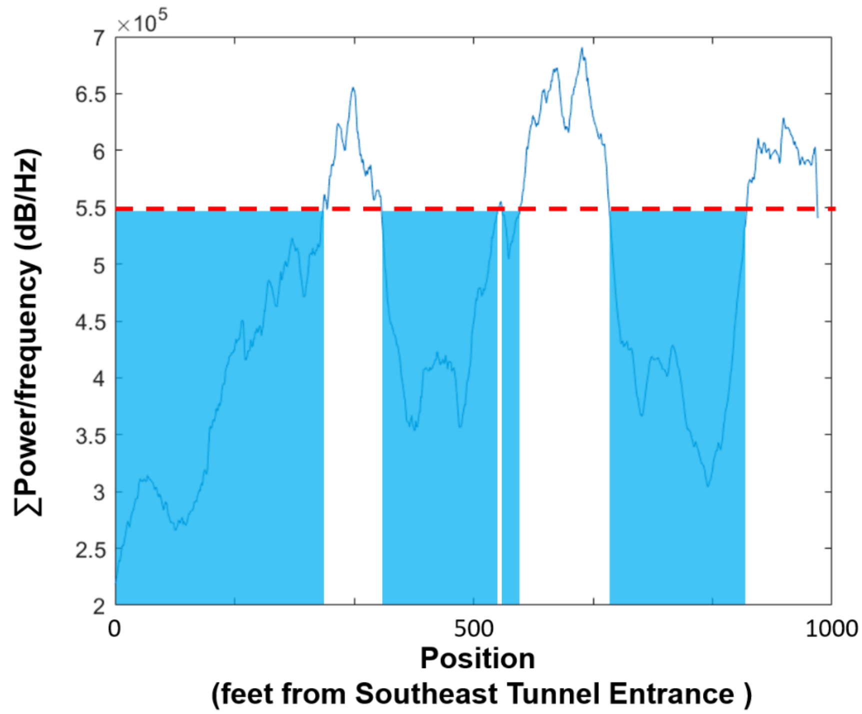


Figure 24. Sum of power/frequency characterization of GPR response features in Figure A23 data with detected water locations shown in solid blue. The detection threshold is consistent with laboratory data and phenomena Adojam addresses.

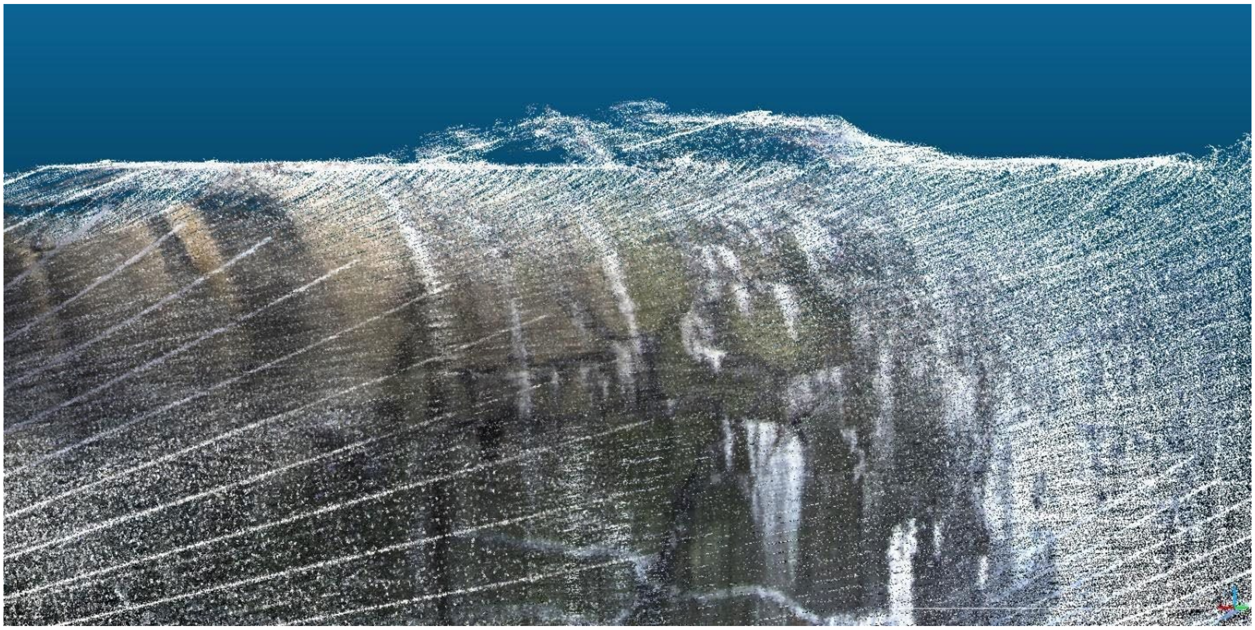
Figures 21 through 24 show GPR analysis to complement SLAM LIDAR results shown in Figure 20.

In Figure 22, The first 1000 feet of Figure 21 GPR data is analyzed to detect free water within the Blair Tunnel concrete liner using a Short Time Fourier Transform [STFT] technique (which highlights GPR dispersion and energy absorption phenomena water produces in this context). Figure 23 presents the sum of frequency dependent phenomena at each sample location, where below a specific threshold water is detected. Finally, Figure 24 shows how frequency dependent features below the water threshold indicate the presence of water (shown in blue). The Figure 12 map was subsequently used to overlay GPR detected water features onto data, as shown in Figure 13.

Also, SLAM LIDAR results complement GPR results and are improved by airborne data collection. A comparison of terrestrial LIDAR data and airborne SATES data is shown in Figure 25. The comparison shows benefits of airborne SATES data collection including clearer, crisper LIDAR results than terrestrial data collection.

In sum, field test 2 showed that SATES results match up with corroborating data, while obtaining information faster, more comprehensively, and with less labor than conventional techniques. In Stage II a more refined analysis will be developed to make results even more effective and comprehensive.

(a)



(b)

Figure 25. SLAM LIDAR results produced via (a) terrestrial data collection, and (b) airborne SATES data collection. This exterior view shows that the tunnel ceiling results are clearer from the airborne perspective due to closer proximity of the SLAM LIDAR (which enhances resolution). Cracking, discoloration, and a large spall on top of the tunnel are clearly represented in (b) whereas they are fuzzy in (a).

Task Summary

As specified by the subject contract, project Tasks are summarized below (including status information corresponding to this QPR #1 reporting period). Completed Tasks have a check mark indicator adjacent to them and a completion date, while remaining Tasks have an open circle next to them.

Stage 1: Configuration, testing, data collection and analysis

- ✔ ***Task 1 [Task Completed on 9/19/19] Kick-off meeting with expert review panel and communication with stakeholders:*** A project kick-off meeting will be held with the expert review panel arid Rail Safety IDEA Program Manager.

- ✔ ***Task 2: [Task Completed on 10/22/19]*** **Finalize and build SATES GPR Configuration (1 Month):** ADOJAM will specify and build prototype details and improvements to support ADOJAM SATES Ground Penetrating Radar (GPR) applications including an appropriately configured UAV (including adjustable GPR mount orientation and closed space operating components).

- ✔ ***Task 3: [Task Completed on 10/22/19]*** **Integrate SATES LIDAR (1 Month):** ADOJAM will specify and build SATES SLAM LIDAR mount points, power wiring, data synchronization, and provide for sensor ventilation.

- ✔ ***Task 4 [Task Completed on 11/6/19]*** **Test SATES UAS [UAV] configuration in controlled test scenarios (1 Month):** At an ADOJAM controlled test site, a series of controlled tests will be performed to prove system capabilities in scenarios that simulate railroad tunnel data collection requirements. Preliminary testing at initial field sites may also be performed to evaluate initial functions.

- ✔ ***Task 5 [Task Completed on 8/25/20]*** **Analyze SATES GPR Data to detect moisture in a controlled scenario (1 Month):** *Forcing Function will devise and implement fundamental data filtering and analysis of GPR signals to detect moisture response signals within concrete tunnel wall liners.*

- ✔ ***Task 6 [Task Completed on 10/16/19]*** **Reconnaissance trip to Cregan Tunnel and Blair Tunnel (2 Days):** A reconnaissance trip with sensors and no UA V will be taken to the tunnel by Team Lead Mike Scott and an ADOJAM technician.

- ✔ ***Task 7 [Task Completed on 1/10/20]*** **Initial Data Analysis (2 Months):** *ADOJAM will plot initial, limited GPR results onto a representative LIDAR data geometry from at least one of the two NS Corp. example tunnels to visualize example detected moisture locations.*

- ✔ ***Task 8 [Task Completed on 11/8/19]*** **Field test mobilization:** Mobilize SATES by completing the system build and performing basic system tests prior to field tests.

- ✔ ***Task 9 [Task Completed on 1/10/20]*** **Field Test:** Field tests will be performed on two Norfolk Southern Railroad tunnels: Blair Tunnel and Cregan Tunnel. Data will be collected in a series of tunnel segments to ensure representative data capture. Manual data collection and rudimentary radar cart data collection will be performed and analyzed for comparison with airborne SA TES data. SA TES testing will be divided into 3 days at Blair Tunnel and 2 days at Cregan Tunnel.

  Blair Tunnel Testing was performed:
  November 11 through 15 and
  January 6 through 9
  As of January 9, Cregan Tunnel access was not available on January 10. Therefore the Silver Run Tunnel was tested in Cairo, WV as it is a similar brick lined tunnel to Cregan Tunnel.

- ✔ ***Task 10 [Task Completed on 8/25/20]*** Initial field test data analysis: SATES analysis will provide results with convenience and accuracy for the following tunnel parameters:

- 3D tunnel geometry
- Tunnel deterioration map
- Tunnel trapped water GPR analysis
- Trapped water map (behind tunnel liner walls/ceiling)
- Examples of recommended locations to drill relief holes will be provided

ADOJAM is responsible for all fundamental aspects of the project and Forcing Function will provide key analytics for trapped ·water GPR analysis/detection and trapped water mapping.

✔ ***Task 11 [Completed on 9/3/2020] Stage I Report:*** A Stage I draft report will be prepared and submitted by the investigator to the expert review panel for review and comment. Following this review, a revised Stage I final report will be submitted to the Rail Safety IDEA Program, along with expert review panel comments and point-by-point investigator responses. The Stage I report will detail the results and findings of this stage and identify strategies to address any project issues in Stage II.

Stage 2 [Completed 9/30/2021] SATES refinement, including system hardware and analysis

✔ ***Task 12 [Completed 2/15/2021]*** **Optimize the Performance and Robustness of the System:** ADOJAM will optimize SATES based on STAGE I performance and needs to improve it identified in Stage I. Forcing Function will support by optimizing GPR signal trapped water detection analysis capabilities. ADOJAM will investigate performance in controlled test scenarios for the Stage II configuration.

✔ ***Task 13 [Completed 7/15/2021]*** **Final Testing, Analysis, and Refinements:** ADOJAM will perform final tests at an ADOJAM test site or in coordination with NS at their field test site to demonstrate the system's improvements. Tests of Forcing Function optimized trapped water detection analysis will also be supported. Note: As agreed with the ERP, Task 13 requirements to test in the field are satisfied at an ADOJAM test site. In addition, Forcing Function trapped water detection analysis was supported via modeling of relevant phenomena, as agreed with the ERP.

✔ ***Task 14. [Completed 12/31/2021]*** **Draft Final Report and Final Report***:* The project investigators will prepare and submit a draft final report documenting the results of this project. The draft final report will include the results of all stages of this project, a statistical analysis and potential recommendations. The draft final report will also include information for the industrial partner and other industries, including the railroads, can consider using the system developed in this project for enhancing tunnel safety. The project investigators will distribute the draft final report to the expert review panel for review and comment. The investigator will address the review comments in a revised draft report and submit the report, along with the point-by-point written responses to review comments, to the Rail Safety IDEA Program Manager no later than 60 days before the completion of the contract. The Rail Safety IDEA Program Manager will distribute the final report to the Rail Safety IDEA Program Oversight Panel for review and comment. The project investigators will provide pointby-point written response to the review comments and submit a revised Final Report to the Rail Safety IDEA Program Manager.

Project Budget

The subject project budget has been expended as shown in Table 1. The project budget was maintained, consistent with project requirements.

Budget Category/Item	QPR1	QPR2	3/20 to 9/20	9/20 to 9/21	9/21 to 12/21	Total
Personnel						
M. Scott (PI)	8,832.00	6,624.00	$ 3,091.00	$ 6,000.00	7,381.50	31,928.50
Consult. & Subs						
G. Subramaniam (Co-PI)	$ 2,950.00	$ 1,050.00	$ 945.00	$ 7,665.00	$ 10,340.00	$ 20,000.00
W. Padukiewicz (UAS Pilot)	$ 750.00					$ -
T. Hoff (UAS Pilot)	$ 625.00					$ -
P. Smith (UAS Pilot)	$ 625.00					$ -
SATES UAS Hardware						
UAS Hardware Components	$ 9,650.00					$ -
Travel	$ 2,000.00					$ -
Overhead Base Amount	$ 8,832.00	$ 6,624.00	$ 3,091.00	$ 6,000.00	$ 7,381.50	$ 23,096.50
Overhead (69.2%)	$ 6,111.74	$ 4,583.81	$ 2,138.97	$ 4,152.00	$ 5,108.00	$ 15,982.78
Subtotal	$ 31,543.74	$ 12,257.81	$ 6,174.97	$ 17,817.00	$ 22,829.50	$ 59,079.28
G&A (10%)	$ 3,154.37	$ 1,225.78	$ 617.50	$ 1,781.70	$ 2,282.95	$ 5,907.93
GRAND TOTAL	**$ 34,698.12**	**$ 13,483.59**	**$ 6,792.47**	**$ 19,598.70**	**$ 25,112.45**	**$ 99,685.33**

Table 1. Budgeted expended.

Project Schedule

The project schedule experienced delays versus original project plans and it is being recovered with a No Cost Extension (NCE) of time as outlined below. Unforeseen challenges arose that were beyond the Adojam Team’s control and ultimately required the NCE. Item (a) was recoverable but item (b) subsequently required an NCE:

(a) A hard landing damaged the UAV airframe during field test 1 in November. Novel aerodynamic effects in the field test tunnel created UAV vibrations and control issues that caused the hard landing. Subsequent system airframe improvements produced a successful field test 2 in January.

(b) Covid 19 challenges caused significant delays to the project schedule.

The planned project schedule was adhered to early on, and technical work proceeded as planned through the week of November 11 as anticipated, (as documented in Tasks 1 through 8, Table 2, and in Figures A1 through A10). Figures A11 through A20 document aspects of field test work during the week of Nov 11-15.

Although many aspects of the field test were productive and successful, including significant data collection via LIDAR and Ground Penetrating Radar [GPR], the test week was challenged by damage to the primary SATES data collection Unmanned Aerial System [UAV] platform on Monday November 11. Although significant efforts were made to recover the UAV to make it flight worthy (and a spare airframe was also configured for flight) productive data collection flights were not possible. Therefore, a revised UAS configuration and design was implemented for a second field test during the week of January 6 through 10.

The initial success of the undamaged UAS flight in the tunnel, coupled with the unsuccessful landing (and UAS issues that followed) during the Nov 11-15 field test week informed basic changes that were made to the SATES UAS platform to make it ready for a second field test week. In addition, field data was collected terrestrially to confirm the type of lighting conditions needed to optimize SLAM LIDAR performance in the tunnel. Finally, example GPR data was collected to confirm basic system performance characteristics.

In addition, the project Team supported a RS 42 IDEA poster and video presentation on January 14, 2020. The PI, Co-PI, and a project UAS Pilot presented the poster.

The remaining project schedule was recovered as follows:

Draft final delivery to Program Manager = Original date: 12/15/20, Revised date: 9/30/21
Includes Tasks 12, 13, and 14 completion on dates noted in Table 2.
Final report completed = Original date: 2/15/21, Revised date: 12/15/21

Table 2. Project Schedule Summary

RS 42 Project Schedule
Stage 2

Key: Completed

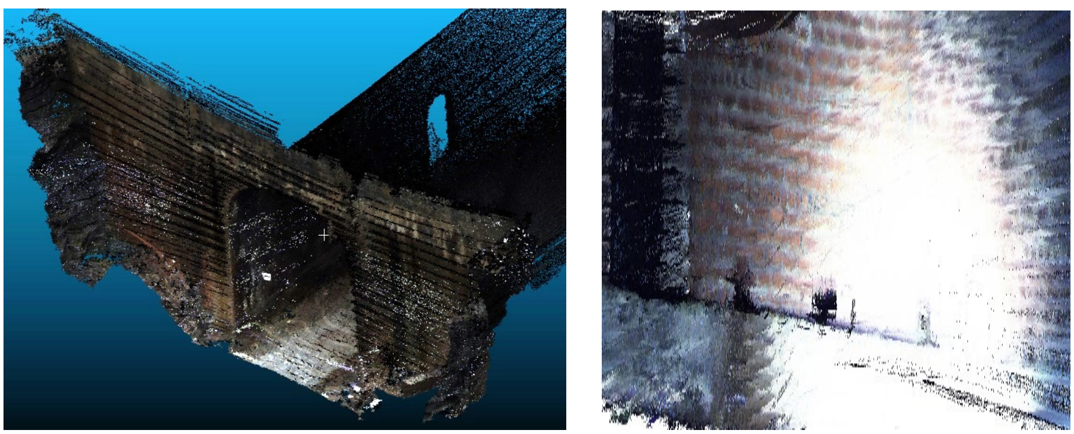
	2019				2020											
Task or Stage	**Sept**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Stage 1																
Task 1	9/19/2019															
Task 2		10/22/2019														
Task 3		10/22/2019														
Task 4			11/6/2019													
Task 5					1/10/2020											
Task 6		10/16/2019														
Task 7					1/10/2020											
Task 8			11/8/2019													
Task 9					1/10/2020											
Task 10												8/25/2020				
Task 11													9/3/2020			
Qarterly Report (Sept -Dec)												8/27/2020				
Qarterly Report (Dec- Mar)												8/28/2020				
Stage 1 Report													9/3/2020			
Annual Report												7/31/2020				

	2021											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
Stage 2												
Task 12		2/15/2021										
Task 13				4/20/2021								
Task 14							7/15/2021					
Final Report [Draft]									9/30/2021			
Final Report												12/31/2021

Table 2. Project schedule.

Stage 2 Project Performance

The ADOJAM project Team completed Tasks 12, 13, and 14. We successfully tested improved measurement capabilities at a local ADOJAM field site and analytically modeled key project phenomena. In addition, important Stage I features and observations at the brick lined Silver Run (Figure 26) tunnel are discussed for Stage 2. Key system refinements and improvements pertinent to Task 12 included trajectory sensing with live data display, a live dual camera (infrared + visible light) system for enhanced drone/UAV pilot awareness, and more. Example field testing in a relevant, GPS denied environment (under a bridge deck) showed how pilots gained greater situational awareness using improved instrumentation. In addition, Finite Difference Time Domain [FDTD] GPR modeling results (created in the GPRMax software tool www.gprmax.com and developed by the ADOJAM Team in Stage II) substantiate field test results and effectiveness.



(a) (b)

Figure 26. Silver Run Tunnel (a) geometry and (b) brick features imaged by SATES LIDAR.

Task 12 and 13 work enhanced reliable flight characteristics to perform SATES functions with greater confidence (via pilot aids) and sensing analysis simulations that improved interpretation. The improvements included:

i) a live, laser-based drone/UAV height clearance sensor (which measures the offset between the top of the drone and the ceiling above), and
ii) a pair of live video cameras (infrared and visible light, respectively).

Figures 27 and 28 show views of drone flight trajectories recorded by the SATES LIDAR during Stage 2 field test sessions with enhanced instrumentation. Although these flights were at lower altitudes than prior tunnel data collection (due to higher winds in the open) the the ceiling clearance sensor and first person view cameras on the drone/UAV informed pilots and enhanced their control of UAV/drone flights. In addition, the infrared camera provided enhanced information in the low light environment tested, as illustrated by drone/UAV footage under a bridge (Figures 29 and 30). Figures 29 and 30 also show the drone ceiling clearance measurement ADOJAM Team pilots saw on their display during testing (circled in green). Additional SATES safety functions are also shown under Figure 29 and 30 images, including an emergency power “kill” button that shuts the drone down from an app (which any drone/UAV team member with permission can control for added safety). Improved pilot aids and field tests showed SATES performs best when system drone/UAV pilots have enhanced information and control.

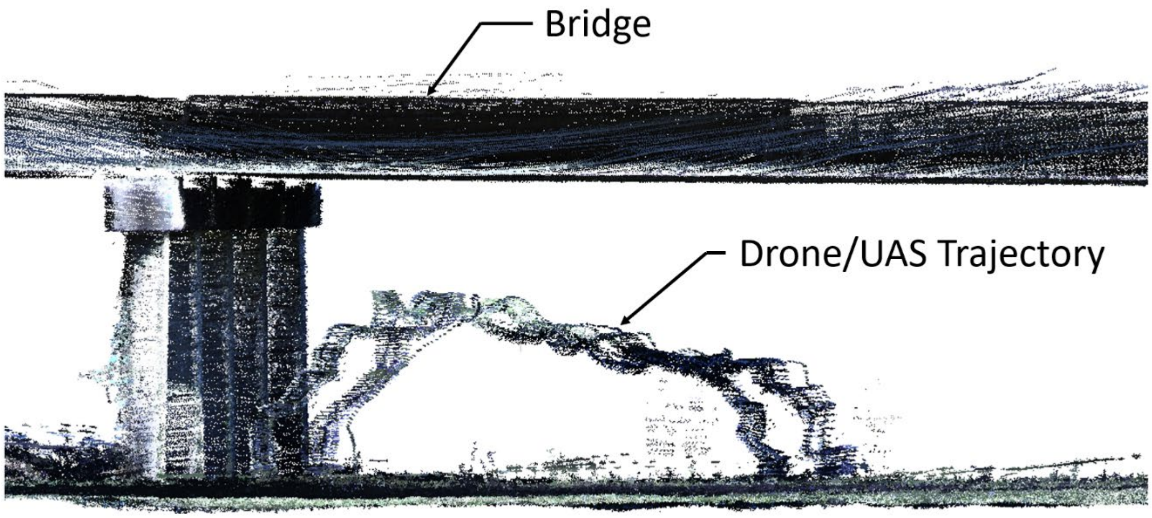


Figure 27. Refined SATES UAS field trajectory on ADOJAM test site (underneath a bridge, operating without GPS denied).

Figure 28. Refined SATES UAS field trajectory on ADOJAM test site (underneath a bridge, operating without GPS).

Task 12 and 13 work also included analysis improvements summarized in Figures 31 through 35. The analysis focused on determining GPR responses to varying amount of water in a concentrated area. Figure 31 specifically shows a series of responses to water filled voids behind a concrete wall (with diameters from 1 cm to 6 cm, plus a control with no water). An example A-scan GPR response to a large void is shown in Figure 32, (a zoom view of the largest void response presented at left in Figure 31).

Emergency Shut Off	1	KILL PWR PWR ON
Spot Lights	0	TURN ON TURN OFF
Position Lights	0	TURN ON TURN OFF
AUX	0	TURN ON TURN OFF

Figure 29. Pilot laser rangefinder and camera to measure clearance (circled in green, measured in feet), including dual infrared (left) and visible light camera (right) results.

Emergency Shut Off	1	KILL PWR PWR ON
Spot Lights	0	TURN ON TURN OFF
Position Lights	0	TURN ON TURN OFF
AUX	0	TURN ON TURN OFF

Figure 30. Pilot laser rangefinder and camera to measure drone/UAS ceiling clearance (circled in green, measured in feet), including dual infrared (left) and visible light camera (right) results. The ceiling clearance from Figure 30 to Figure 31 was correctly measured as 5.3 ft.

Figure 33 shows a complete, simulated B-scan GPR response to high moisture content (indicated by a 6 cm diameter water filled void). The hyperbola shaped water response feature is centered in Figure 33. The frequency transform of the Figure 33 response enables quantitative interpretation of water content. Figures 34 and 35 show the

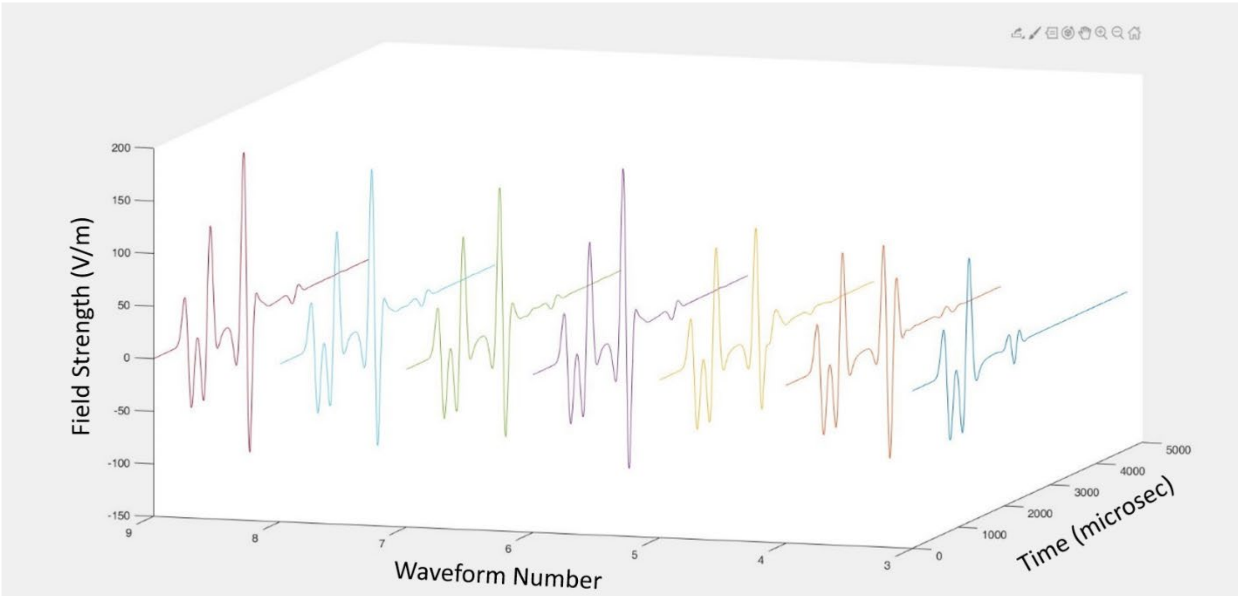


Figure 31. Finite Difference Time Domain [FDTD] SATES Ground Penetrating Radar [GPR] waveform simulation response to varying sizes of water filled voids from left (largest = 6 cm diameter) to right (smallest = 1 cm diameter) and a control response (no water) at far right.

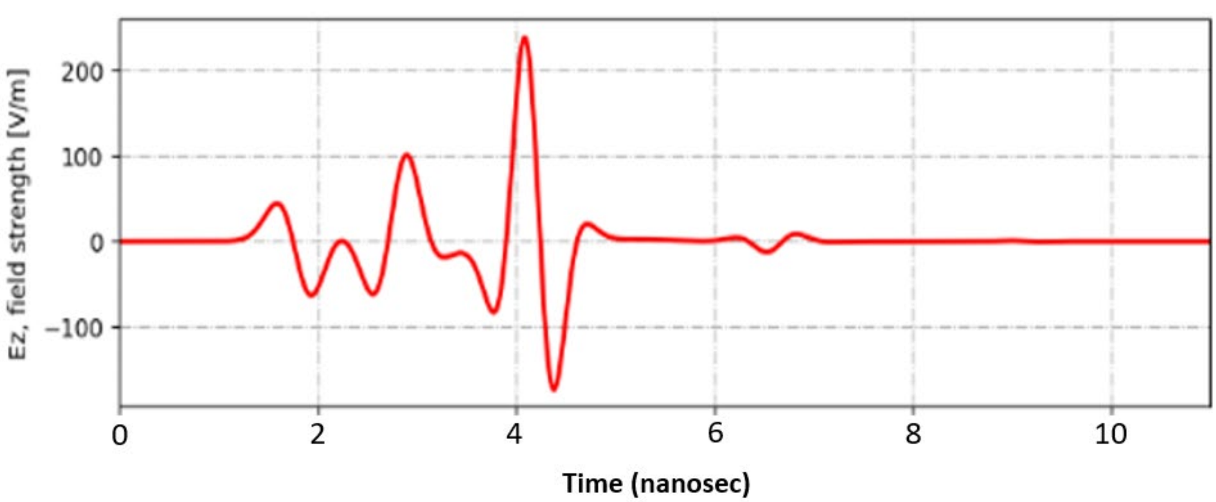


Figure 32. FDTD simulation of a SATES GPR response to the largest water void feature in Figure 31 (diameter = 6 cm).

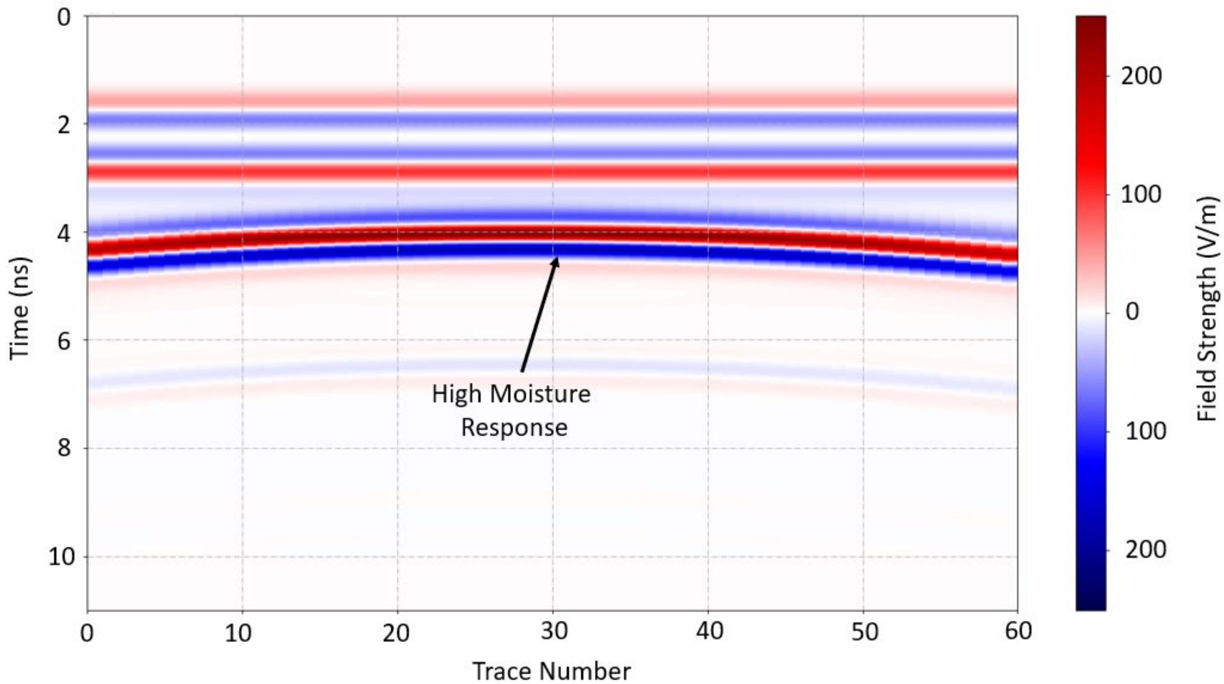


Figure 33. FDTD SATES GPR simulation of a 6 cm diameter response feature corresponding to a high moisture content tunnel liner location.

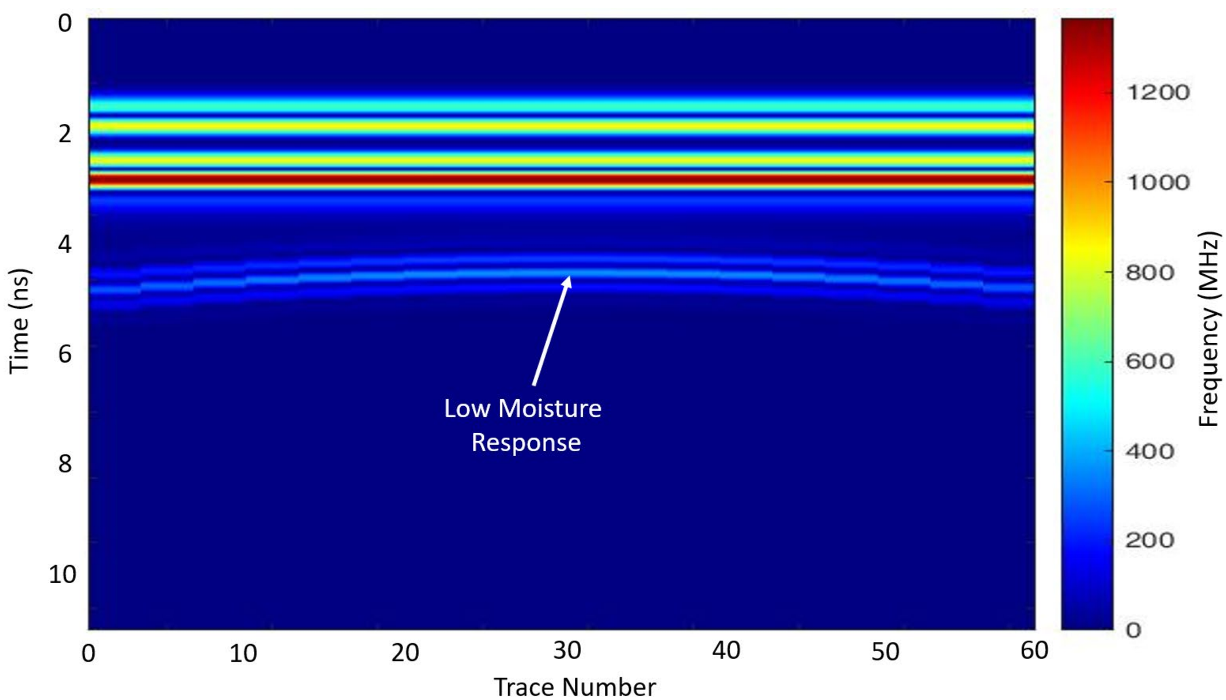


Figure 34. Frequency content of a simulated GPR response to a 1 cm diameter water feature (low moisture content) in a tunnel liner.

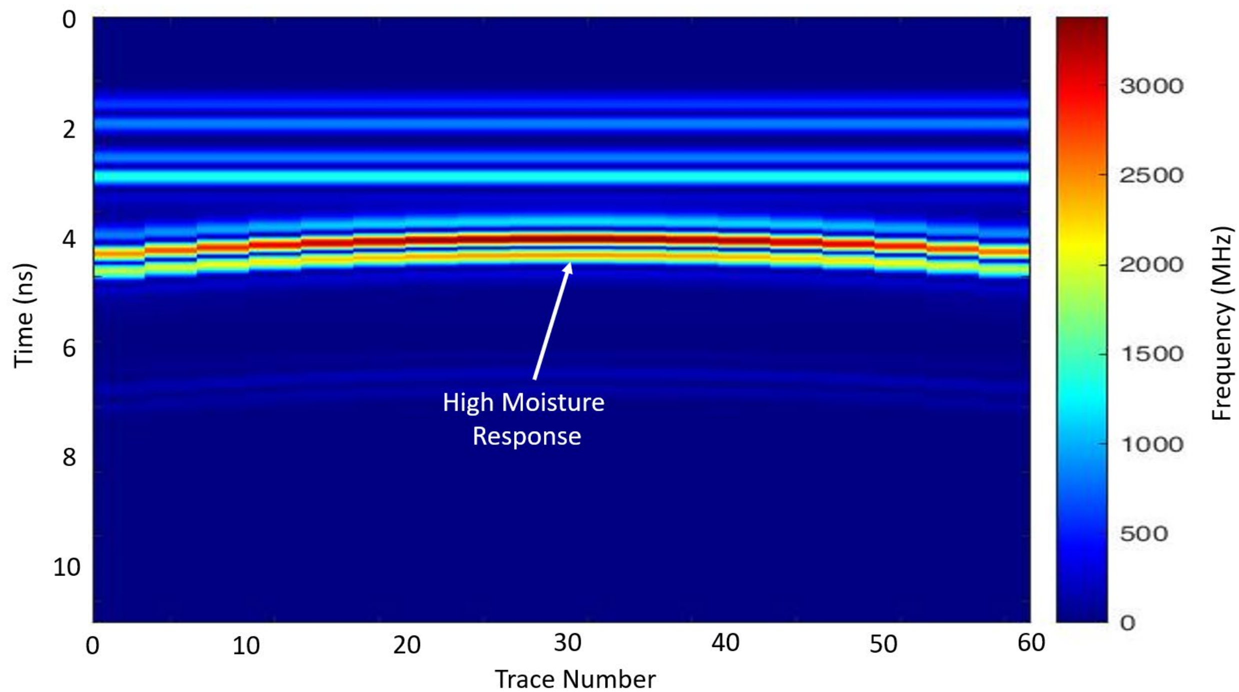


Figure 35. Frequency content of a simulated GPR response to a 6 cm diameter water feature (low moisture content) in a tunnel liner.

difference between the frequency transformed response to a 1 cm water filled void versus a 6 cm water filled void. Fundamentally, the Figure 35 simulation verifies high magnitude responses observed in Figure 22 results. Where depth calibration is achieved by reference measurements, the rough volume of concentrated water per unit volume in a given field location can be determined by scaling to modeled results as shown here by corresponding color codes.

Water intrusion conditions and large-scale deterioration phenomena detected by SATES (such as cracking and spalling) were consistent with contemporary Norfolk Southern Railroad tunnel visual inspection reports at a high level. Detailed inspection correlations (between visual inspection and SATES) on a feature by feature basis were beyond the scope of the current research project. Future SATES research will benefit from correlating detailed feature responses to detailed categories via Artificial Intelligence [AI] analysis techniques.

Conclusion

A safe, airborne railroad tunnel inspection technology called SATES was developed and successfully field tested by the RS42 Project Team. SATES demonstrated unprecedented tunnel material inspection capabilities (surface and subsurface) via a novel UAV system and analysis package. SATES field test data was collected from railroad tunnel liners and analyzed to meet the following Project objectives:

- World’s first surface + subsurface UAV measurements in a tunnel
- Detected and located subsurface water in concrete tunnel liners
- Detected concrete tunnel deterioration features (spalls, cracks, etc.)
- Virtualized 3D tunnel geometry

SATES technology successfully demonstrated untethered, contact-free, reference-free UAV measurement techniques and capabilities at multiple field test sites. SATES detected moisture and deterioration phenomena in concrete tunnel liners, consistent with conventional observations. Stage 2 improvements in hardware and software also show feature detection benefits to further improve SATES accuracy and convenience versus competing techniques.

Stage 1 Report Note on a Correction/Revision to QPR2:

On review of the Conclusion Section of QPR2, we note integrated SATES measurements at Blair Tunnel and integrated SATES measurements at the Silver Run Tunnel in Cairo, WV. The substitution of the Silver Run Tunnel was made because access to the Cregan Tunnel was unexpectedly denied by Norfolk Southern Corp. on January 10, 2020 (when Cregan Tunnel testing was planned). The project Team traveled to Cairo, WV and performed data collection at the Silver Run Tunnel as a result. The Conclusion Section of QPR2 made an error in stating which tunnel was scanned with SATES in addition to Blair Tunnel (where the majority of SATES field work was performed). We are clarifying and correcting this error here.

Appendix A

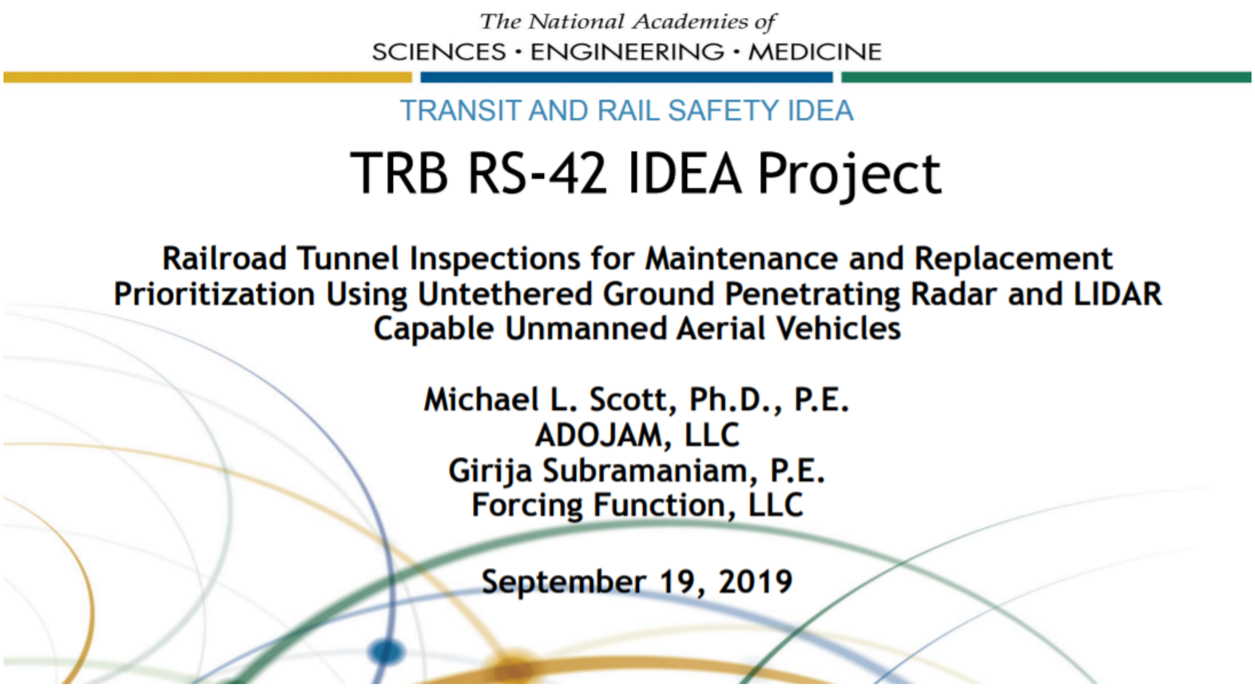


Figure A1. Kick-off meeting cover slide.

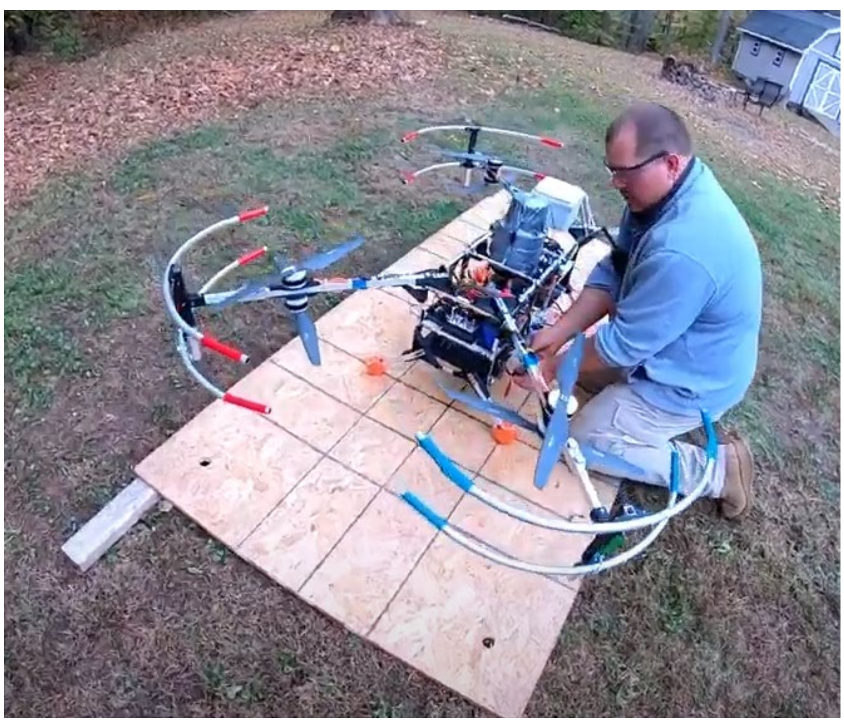


Figure A2. Dummy payloads and prop guards shown installed.

Figure A3. Successful test flight with dummy payloads.

Figure A4. Completed test flight with dummy payloads.

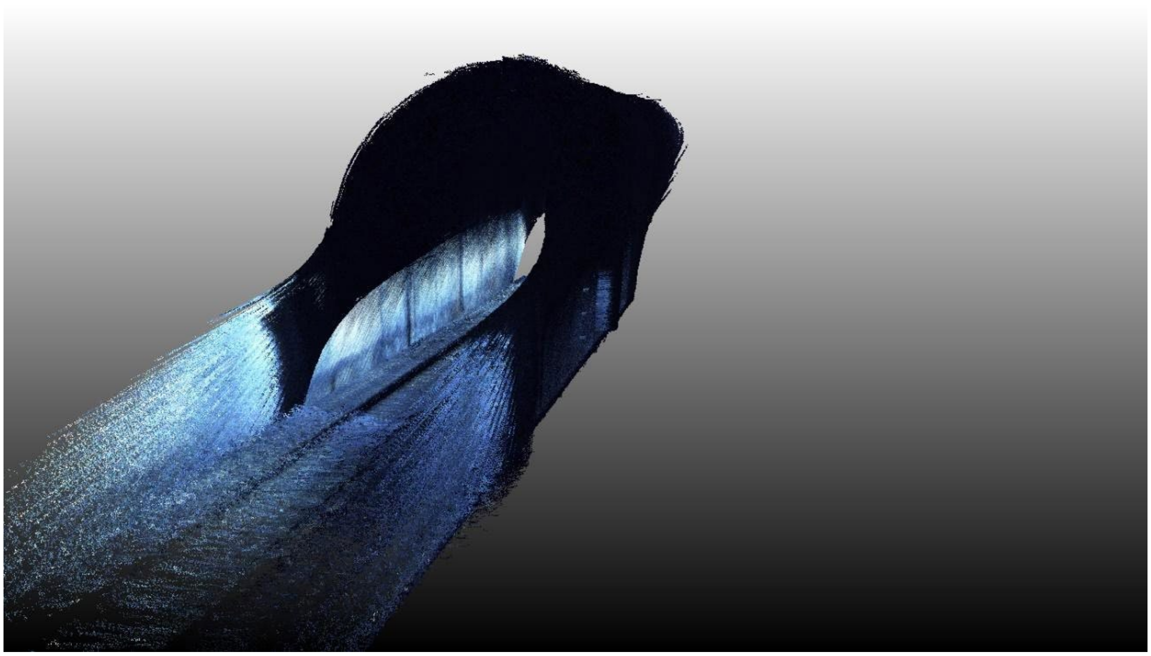


Figure A5. SLAM LIDAR data showing lighting issues (dark/black areas).

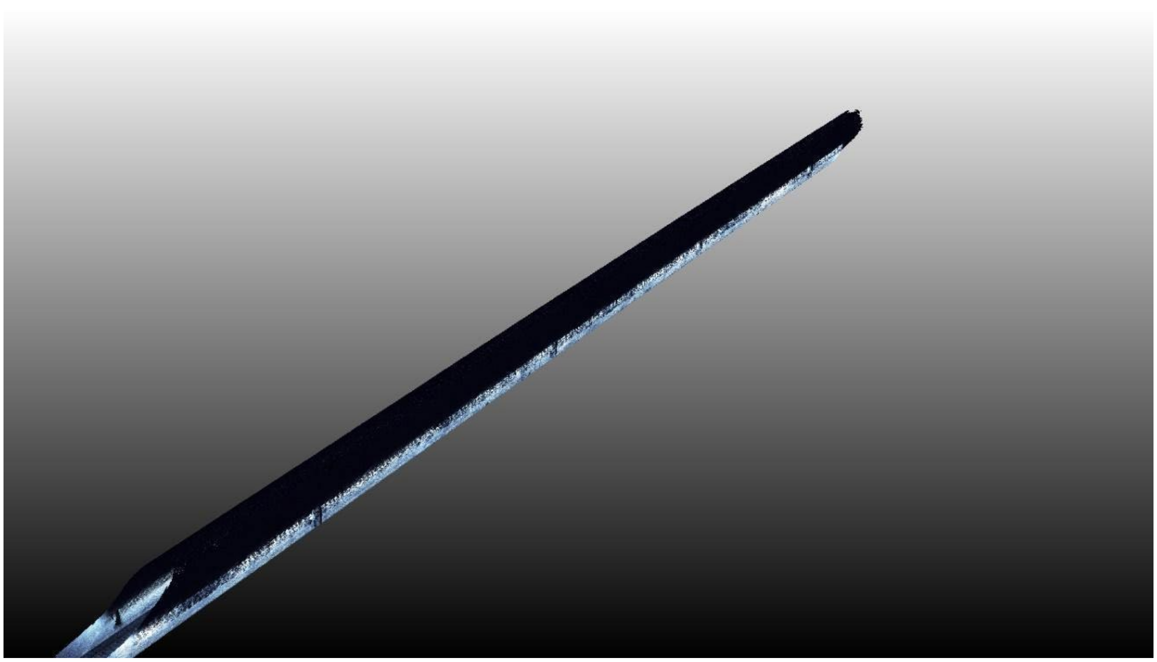


Figure A6. SLAM LIDAR data showing lighting challenges (dark/black areas).

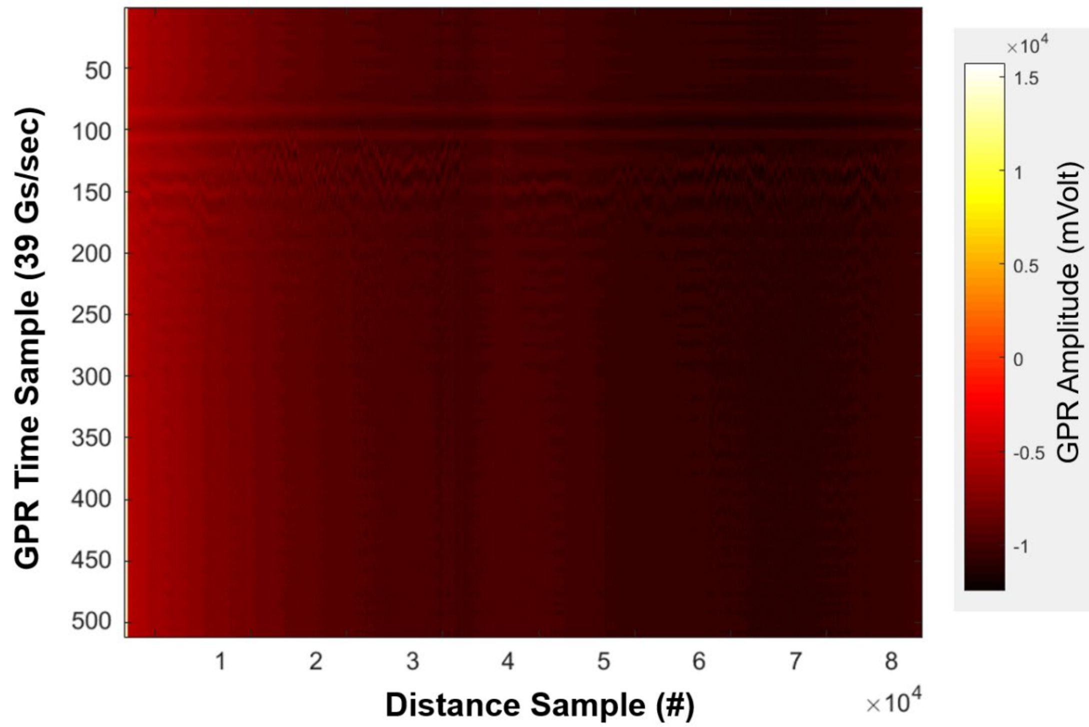


Figure A7. Example raw Ground Penetrating Radar [GPR] data requiring equalization.

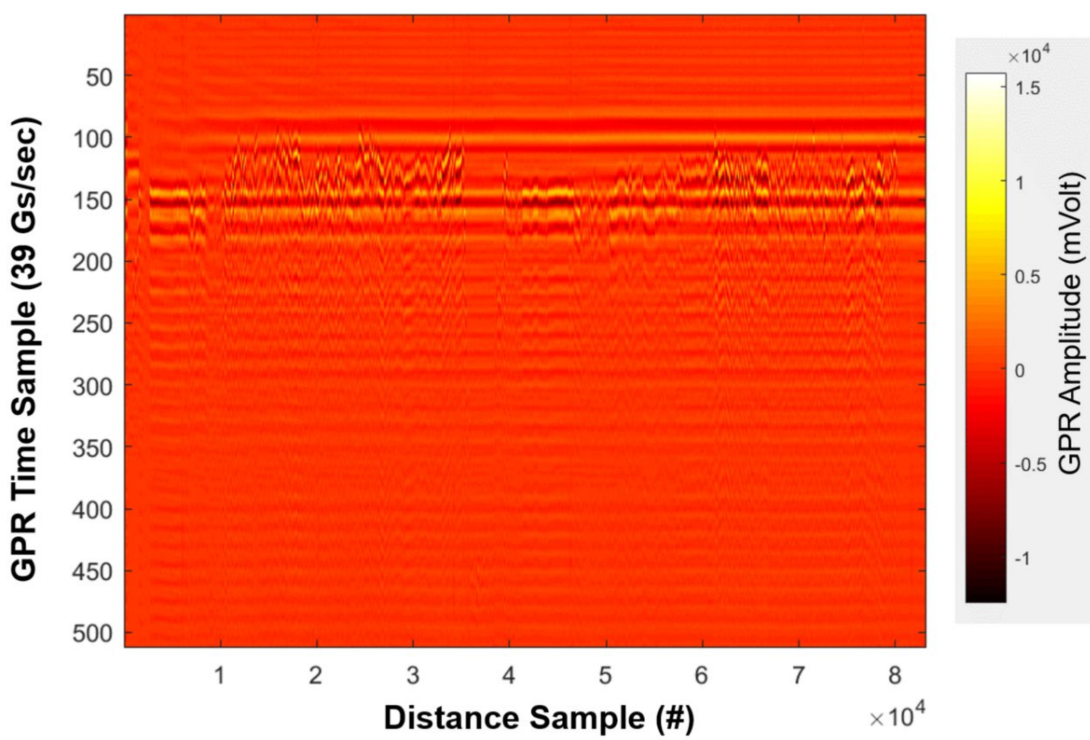


Figure A8. Example equalized Ground Penetrating Radar [GPR] data.

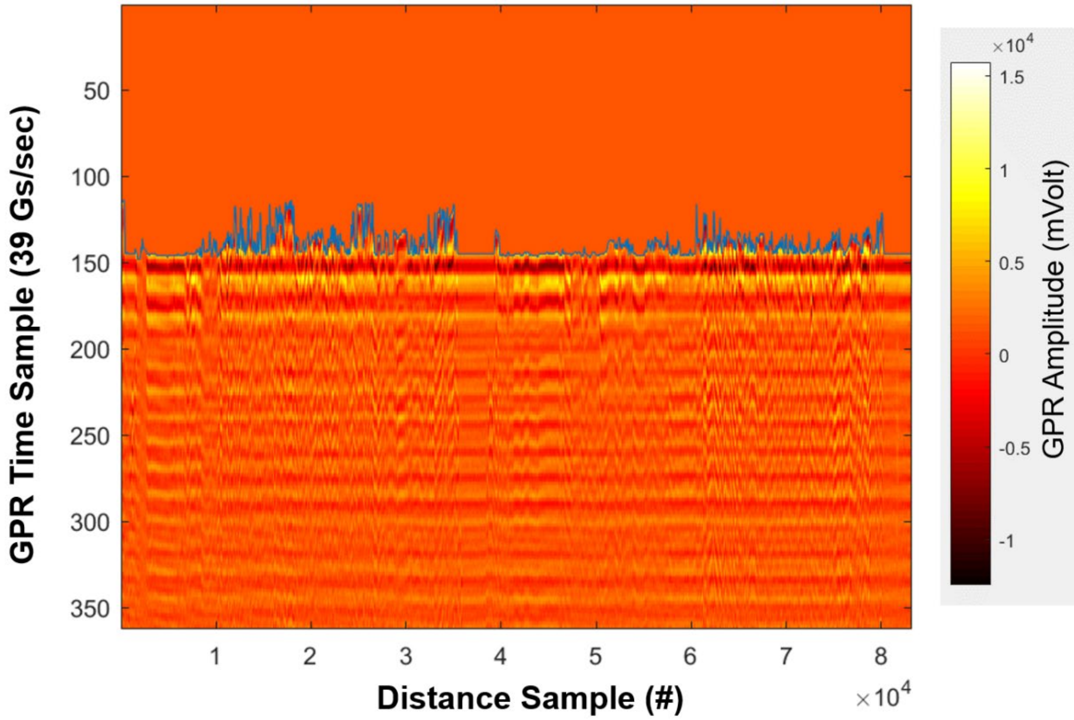


Figure A9. Equalized Ground Penetrating Radar [GPR] data with concrete surface reflection labeled/identified.

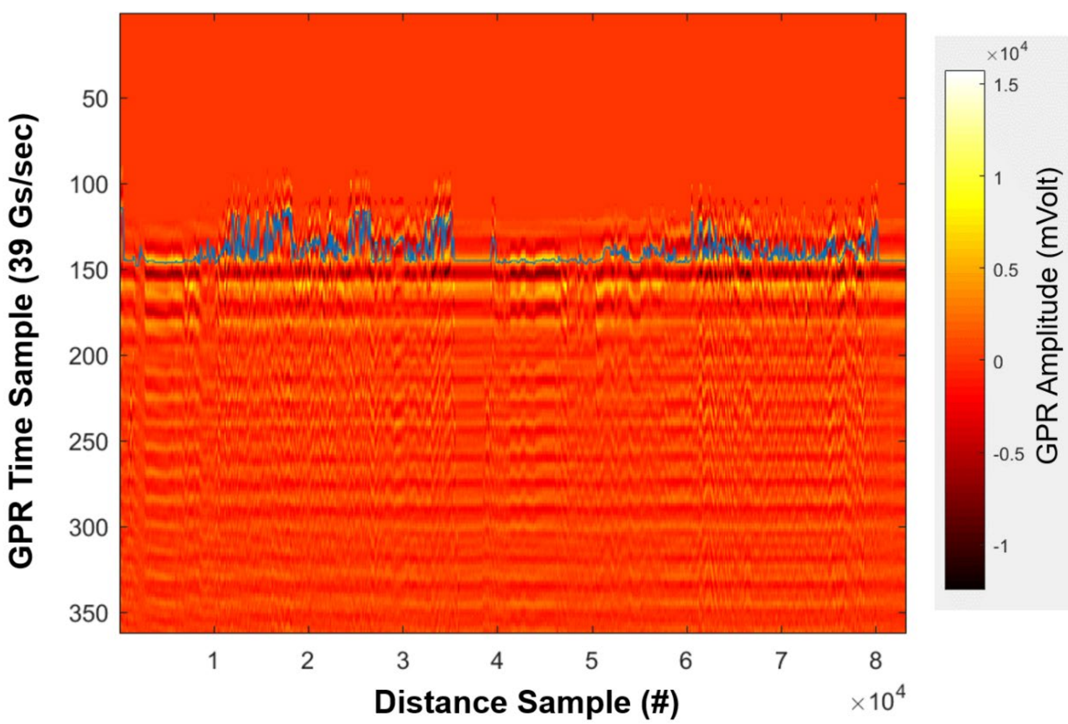


Figure A10. Equalized Ground Penetrating Radar [GPR] data with concrete surface reflection labeled/identified and near surface response.

Figure A11. Blair Tunnel interior illuminated by LED panel source (showing PI and Co-PI at the field test site.

Figure A12. SATES data collection at the Silver Run Tunnel (SLAM LIDAR mounted)

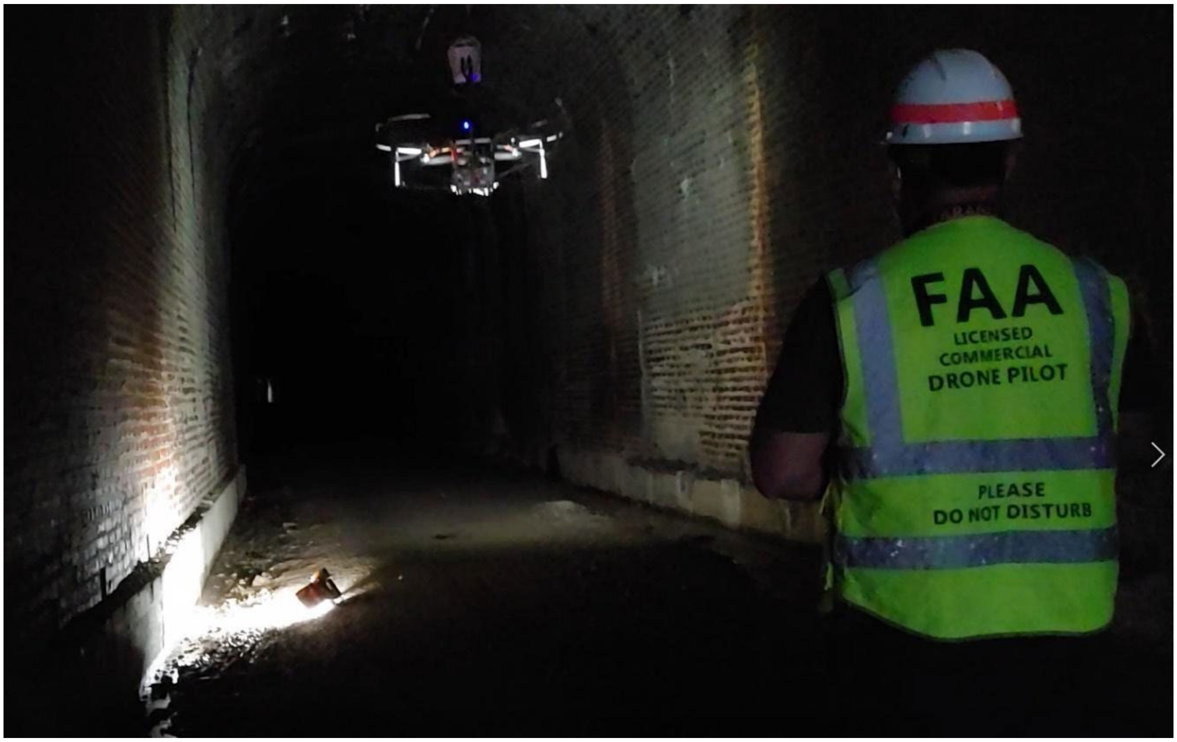


Figure A13. SATES data colleciton at the Silver Run tunnel (SLAM LIDAR and GPR mounted).

Figure A14. Data collection Team at the Silver Run tunnel in West Virginia.

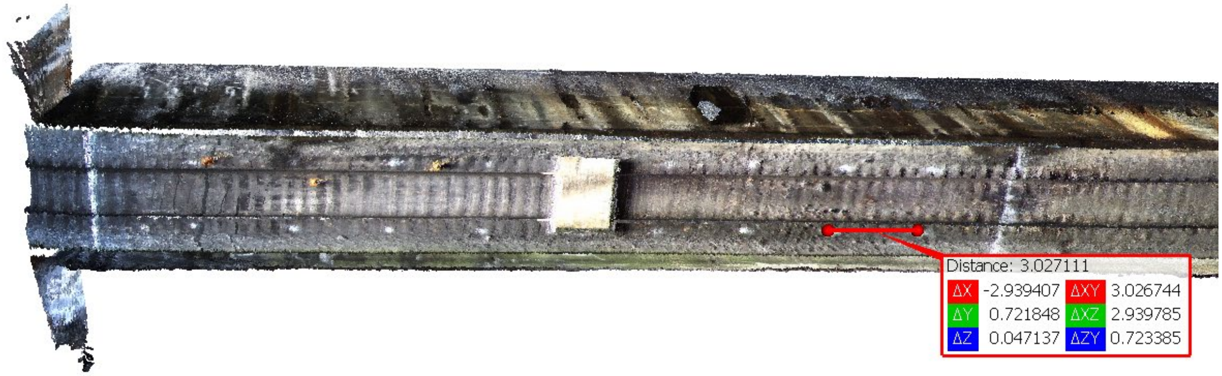


Figure A15. A “bottom view” of tunnel data is shown, including paint marked dots at 10-foot intervals (within a 100 foot section bounded by two prominent white stripes). A scaled measurement is shown between the marked dots. A manual reference measurement between the marked dots was 120 inches long, while LIDAR data showed a 119.2 inch length.

Appendix B

PX-80™

FEATURES & TECHNICAL SPECIFICATIONS

SPECIFICATIONS

PX-80

Weight	6.4 lbs / 2.9 kg
Height	26.7 cm
Diameter	16.2 cm
Extension rod	43-67 cm

Color Camera

Resolution	2048 x 1536 px
Megapixels	3.2 MP
Maximum frame rate	50 fps
FOV horizontal / vertical	360° x 250°

Lidar Velodyne LiDAR

Laser type	VLP-16, Class 1 (Eye Safe)
FOV horizontal / vertical	360° x 30° (±15°)
Acquisition rate	300,000 pts/sec
Range	0.5 m - 100 m
Relative accuracy	±1-3 cm
Global accuracy	±3-30 cm (10 min scan, 1 loop)
Environment	Indoor / outdoor

Note: Accurate scans are captured by using a steady and smooth walking pace. A variety of factors can negatively influence tracking, including: rotating 6-DoF very quickly (fast 180° turns), extreme motion in the environment (a few people or vehicles in an open space are not a problem, however, scanning in a narrow hallway with multiple people is not recommended).

CLASS 1 LASER PRODUCT

PARACOSM™

Appendix C

ADOJAM Low Frequency Ground Penetrating Radar [GPR] – TYPE 1 SATES Deployment

The ADOJAM GPR – TYPE 1 for SATES deployment features Radar on a Chip [RoC] technology. It performs under demanding field conditions and penetrates many civil engineering materials, including concrete and other dielectrics. It does not penetrate metals/conductors. The system is robust, yet very precise and accurate. Please contact Adojam for system deployment terms and conditions, including Unmanned Aerial Vehicle [UAV] mounted services.

System Specifications:

30 mA @ 3.3 Volts (450 mW)
Operating Temp (Range): -40 to 85 ºC
Dimensions: 8 x 8 x 9.5 inches

Radar Details:

Range Accuracy:
    4 mm (~39 GS/s)
Pulse Repetition Frequency (PRF)
    Up to 100 MHz
Frame Size
    2 meter window
Average Tx Power
    -19 dBm
Operating bandwidth (Frequency Range)
    0.9 to 3 GHz (-10 dB)
    0.7 to 3.2 GHz (-12 dB)
Integrated LNA
    NF = 2 dB (@ 6 GHz)
    Gain = 16 dB (@ 6 GHz)

Memory:

32 KB of EEPROM
64 KB of Flash
Built in MicroSD card slot

Physical Interfaces:

1 CAN Bus
1 I^2C Bus
4 User Controllable LEDs
2x46 PIN Expansion Headers
1 Temperature Sensor (±1 ºC)