Intelligent River® Bridge Flood Monitoring System to Improve Transportation Mobility

Final Report

by

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DISCLAIMER

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15. Supplementary Notes

16. Abstract

Bridge flooding can dramatically impact mobility, and climate change impacts are expected to increase flooding frequency in the future. There is an urgent need to develop technology to provide accurate, near realtime water level information from bridges. The Clemson Intelligent River® project has developed an innovative low-cost platform for water level monitoring from bridges. This "BridgeBox™" uses radar technology to measure water level and then sends this data over IoT cellular networks to a cloud-based system that can share water levels and flood to improve mobility during extreme precipitation and flooding events. Water level distance accuracy was validated through laboratory and field testing and bridge mounting systems have been developed to enable mounting on various bridge structures. Installation surveying methodology has been developed. Finally, multiple test deployments have been done in collaboration with local governments.

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EXECUTIVE SUMMARY

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CHAPTER 1

Introduction

1.1 Research Motivation

Climate change is predicted to dramatically alter temperature and precipitation regimes in the southeastern United States (US), with expected precipitation increases under many climate scenarios (Almazroui et al., 2021). Increased road and bridge flooding incidences, exacerbated by rising sea levels, will likely cause serious barriers to urban traffic flows, with wide-ranging traffic delays that could propagate throughout a region (Kasmalkar et al., 2020). Flooding will likely interfere with road functionality, preventing mobility and access to critical services in both large and small cities (Alabbad et al., 2021). Impacts of flooding can include damage to bridge infrastructure, which often lacks redundancy and has a high cost of repair (Pregnolato et al., 2022), so flooding can lead to longer-term barriers to mobility. Flooding impacts on bridge structures are attributed to hydrodynamic loading and bridge scour, which can be understood by evaluating flow velocity, flood height, obstructions to flow and type of sediment (Loli et al., 2022).

Realtime monitoring of river water height at bridge locations could serve as a warning system to provide alerts to possible bridge impacts caused by flood scouring (Koursari et al., 2020) and impassable roads, which require re-routing to maintain transportation mobility. Water-level and flow monitoring at bridge locations is most commonly done by the U.S. Geological Survey (USGS), which runs more than 10,300 stream gauges in the United States, which provides invaluable data to monitor water levels at mainly bridge locations (Normand, 2021). While the USGS provides professionally managed water-level monitoring with accurate data, the number of locations that can be monitored is limited by the high cost of installation (~$40,000) and maintenance at approximately $15,000 per location per year to monitor water level to estimate water flow and volume. It should be noted that the USGS systems are considered best in class because sensor systems deployed are supported by a large number of staff and processes to understand cross-sectional area to understand level and flow relationships.

1.1.1 Project Highlights and Impacts

- Climate change will increase the incidence of road flooding on bridges and it is critical that systems are developed to provide accurate, low-cost, and resilient water-level monitoring from bridges to improve mobility during these extreme weather events.
- This project supported the validation and testing of the Clemson Intelligent River® BridgeBox™ water level monitoring system that could scale to be deployed on thousands of bridges where flooding is likely.
- Monitoring realtime water level at flood-prone bridges could improve mobility by providing critical alerts to transportation authorities to aid in disaster response and transportation rerouting.

CHAPTER 2

Project Background

2.1 Background

South Carolina contains more than 30,000 miles of rivers and streams (SC DNR, 2023), so, unsurprisingly, the road network often intersects streams and rivers, with more than 8000 bridges over water in the state (Figure 1). According to the South Carolina Department of Transportation (SCDOT), there are approximately 1000 bridge locations concerned about bridge flooding. In addition to SCDOT managed bridges, there are many bridges in South Carolina that are managed by counties, cities, and private entities. It is important to develop procedures and processes that can support water level sensor deployment across bridges subject to flooding.

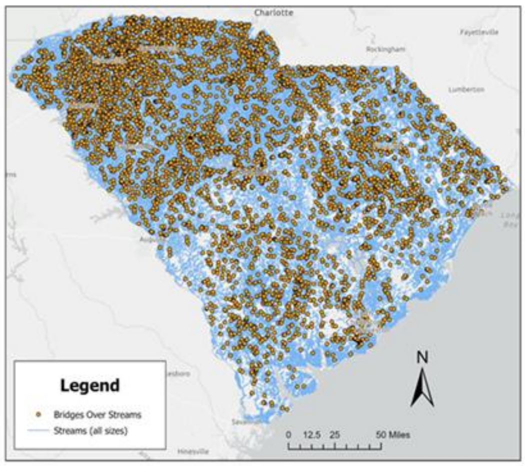

Figure 1: Bridges over streams/rivers in SC

Unfortunately, South Carolina has only 157 USGS watering measuring stations (Figure 2). This means that there is no realtime flood monitoring (or water level sensing of any type) on the vast majority of bridges over streams and rivers in South Carolina.

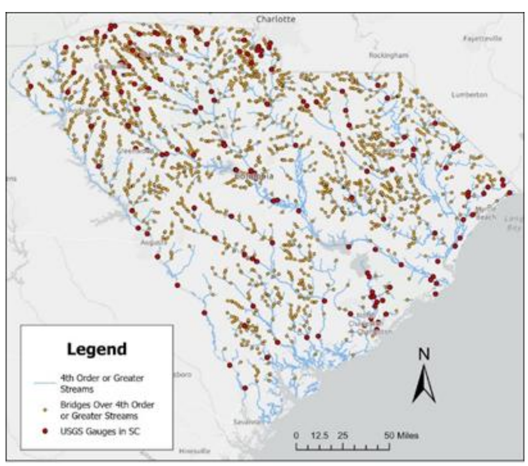

Figure 2: Current USGS gauges (red)

While bridges are commonly evaluated for flood risk based on historical flooding records, it is also important to note that with changing weather patterns associated with Climate Change (e.g., Almazroui et al., 2021) it is probable that a greater number of bridges will be subject to flooding in the future. It is also possible to prioritize bridges for monitoring based on available flooding hazard spatial data layers (Figure 3). Spatial data that represents future flood potential can include standard flood hazard maps as well as new and innovative modeling efforts such as the First Street Foundations flood factor data, which can provide depth of water predictions at a high resolution (3m) for various high water even scenarios, including scenarios that include climate change impact predictions (Cooper et al., 2022).

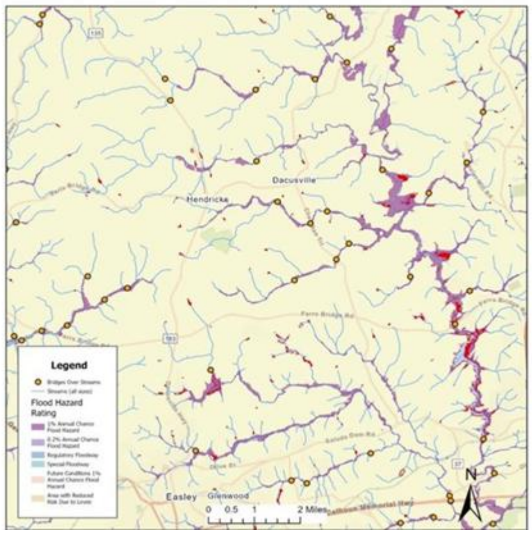

Figure 3: Example flood risk at bridges in SC

Transportation mobility is at high risk in South Carolina and beyond, given the likely increased bridge flooding as there are greater climate change impacts. There is an urgent need to develop technologies to monitor bridge flooding events in near real-time to improve data and response to bridge flooding and mobility. This is now possible because of IoT advances that enable the creation of low-power, resilient internet-connected water level monitoring systems at a much lower cost than existing commercial systems. It is not enough to develop low-cost and reliable systems, because it is also necessary to create rapid deployment mechanisms, including ways to transmit data during extreme weather events, and survey techniques that can accurately place the height of water in relation to existing bridges and other critical infrastructure. It is also important to work with state DOTs as well as county and local governments to find the most appropriate ways to share water level data and alerts related to high-water events.

CHAPTER 3
Methods

3.1 Intelligent River® System

The Clemson Intelligent River® platform, developed under the direction of Dr. Post, includes technologies, systems, and methods developed over the last four years to monitor water quantity using internet-connected devices that can stream data in near real-time to a cloud repository and securely, share data or alerts through web dashboards.

The data repository system is cloud-based based on redundant servers and is professionally managed for reliability and security (Figure 4). It integrates streamed sensor data in near real-time, a modern NoSQL database, and open-source management and presentation systems. The metadata system has the unique ability to track system-level information about both the sensing platform and each deployment site. This allows tracking of individual sensors and supporting hardware to link and track individual sensor performance and calibration through time. A custom application deployment manager is used on a cellphone or tablet with GPS to note all system components (and take a photo of installation) as they are deployed so that detailed information is tied to all recorded sensor data. This type of information, when combined with specific information about system deployment (e.g., water level at deployment, maximum and minimum expected water heights, height for water to overtop road surfaces, etc.) will be used in the future to develop systems that have the capacity to predict attributes associated with future system failure and anomaly detection for data.

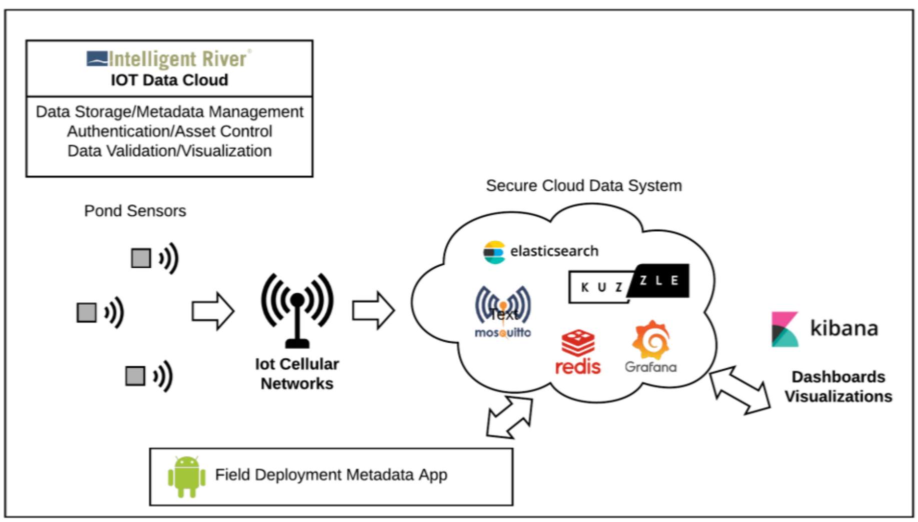

Figure 4: Intelligent River Cloud Repository

3.2 Intelligent River® BridgeBox™ System

The Intelligent River® project has recently developed its third-generation platform, which includes more than 15,000 lines of custom-embedded software as well as a custom circuit board that is used as part of the BridgeBox™ product (Figure 5). This system can record water levels using a 60 GHz radar at a distance of up to 20m. It also uses industry-leading power-saving techniques to enable the sampling of water distances every 10 minutes and transmission every hour while maintaining a battery life of greater than 2 years. Because the batteries, system main board and radar module are contained within one small enclosure, both construction and deployment are optimized for rapid and wide-scale deployment. The solar power requirement can often be a deployment limitation on many bridges over water in South Carolina because they characteristically have high levels of vegetation, so solar power may not provide sufficient power during summer months when trees and other vegetation can obscure bridge solar exposure. Construction of the BridgeBox™ is simplified because the custom-designed main board and radar modules have embedded connectors for rapid system assembly. Furthermore, the custom battery pack includes a custom connector, so that no soldering or wiring is necessary to minimize the time required to construct a system. The use of an IP68 waterproof enclosure that is waterproof, even when completely submerged, however water level readings and cellular data reporting is not possible when submerged. Because of this, device placement is optimized so that data is available, even if water levels rise above the roadbed.

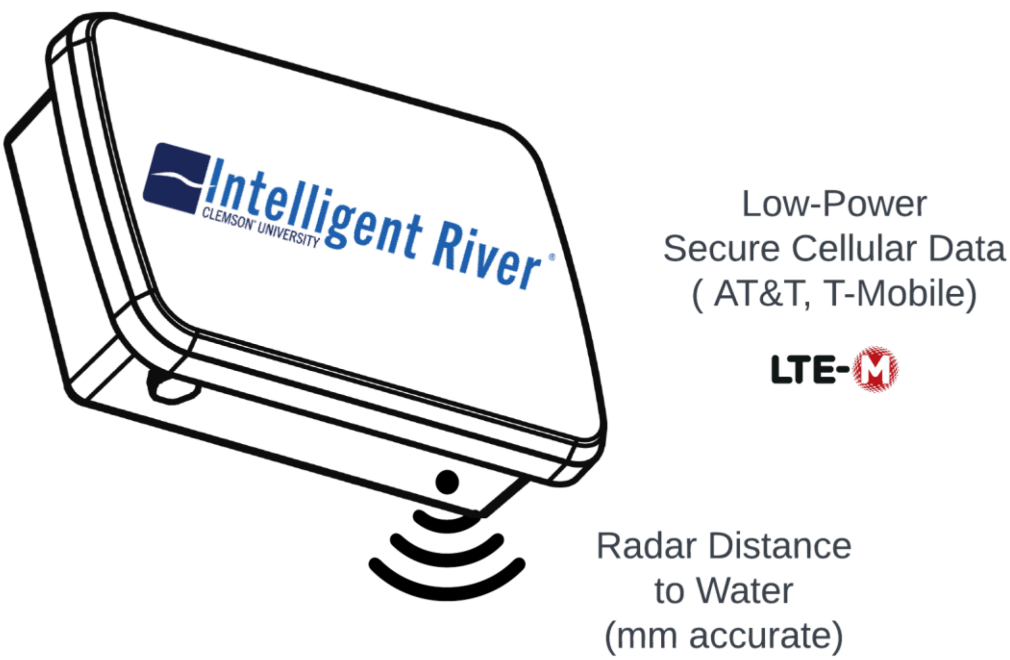

Figure 5: Intelligent River® BridgeBox™ Device

3.3 Project Objectives

3.3.1 Objective: Develop BridgeBox™ Mounting System

The Intelligent River® BridgeBox™ weighs approximately 4 lbs and measures 7 x 8 inches. The general practice in deploying sensors used by other projects in the past has been to drill into bridges directly to mount water-level boxes. However, this is both time and cost-prohibitive and could potentially lead to disruption of traffic. Invasive drilling into bridge structures has a slight risk of impacting bridge integrity and requires further coordination with bridge engineering staff, given the associated risks, which vary by type and age of bridge structure. Therefore, the focus of developing mounting mechanisms for the BridgeBox™ has been to limit any risk and standardize the installation (and approval process) as much as possible. The following design philosophy was developed for the design of the mounting system:

a) No drilling or invasive procedure to the bridge
b) Lightweight
c) Quick Installation
d) Sensors can be mounted or replaced for maintenance purposes.

An on-site survey of potential bridge installations revealed that almost all of the bridges that were identified as prone to flooding have a wall available for mounting with a concrete slab thickness of between 9-12 inches, depending on the size of the bridges. Further, it was decided to mount the BridgeBox™ on the sideway slab of the bridge to keep the instrument away from the commuter field of vision. This removes the chance that the box could distract drivers (because the mounted box is not visible from the roadways) and likely also limits chances for system vandalism.

To keep the mounting system and system replication costs low, it was decided to use off-the-shelf components combined with custom-designed 3D Printed parts. This served to allow rapid design iterations, as well as the opportunity to modify the design as needed for new deployments. The prototyping and mounting system replication costs were also minimized because there was no need to do custom machining, given our design philosophy. Carbon-fiber-infused 3D Printing was used because of the higher strength profile of the resulting designs. Figure 6 shows the thickness of the sideway slab of one of the bridges where the system was eventually mounted.

Figure 6: Typical Bridge Slab for Mounting

3.3.2 Objective: Optimization of Radar Performance

The Intelligent River® BridgeBox™ utilizes a 60 GHz radar, which is novel because most water-level radar systems use 78 to 80 GHz. While there is the possibility of signal attenuation during rain events and fog, operational experience over years of testing of Intelligent River® has shown it is possible to use 60 GHz radar for water level monitoring. Furthermore, the use of 60 GHz radar serves to reduce the overall system. The time elapsed between transmission and reception of the signal is used to calculate the distance from an object. Several parameters can directly influence the performance of the radar. For example, the input power injected directly correlates with the distance that the radar can measure. Additionally, on-site factors like rain or reflection of the radar signal from an object other than water can potentially result in erroneous readings.

To optimize the radar performance, an in-lab platform was developed, which can vary the height of the radar from a water surface. Figure 7 shows a measurement testing system with the ability to vary height of the radar sensor from the water surface using a motorized height system. This system was used for near-water system testing, while other telescoping pole-mounted systems (Figure 8) were used to test larger distances from water. It is important to test near-water radar performance because during flood events, it is critical to accurately measure water that is rising towards the radar sensor to report flood or near-flood events accurately. Using a fixed-level water pool allows the optimization of radar accuracy, however, the apparent water height variation during actual deployments will be evident because the water level in creeks, streams, and rivers is typically not flat but varies because of waves in the water surface.

Figure 7: Laboratory Radar Testing System

Figure 8: High Height Radar Testing System

Additionally, to facilitate testing, the cellular module was directly interfaced with the radar, with the radar parameters (to be tested) sent over the air via cellular networks (Figure 9). This included custom code on the cellular device that could take changes in radar parameters from the cloud interface and pass them to the radar module. Custom code on the radar module served to receive and update the available radar parameters. This system was necessary to speed the testing of different combinations of radar parameters, particularly when the system was mounted at a higher elevation (Figure 8). Radar parameters were systematically changed, based on information from the theory of radar operation, as well as the recommended settings from the radar module manufacturer. This kind of setup is not suitable for on-site deployment due to excessive power usage by cellular modem and power leakages and a high sleeping current of the cellular module. However, it facilitated rapid testing of different radar configurations. Radar performance was tested at various heights to simulate the typical heights of bridge deployments. The focus of the testing was to maximize the accuracy and stability of water distance measurements, while also minimizing the power needed to take those measurements.

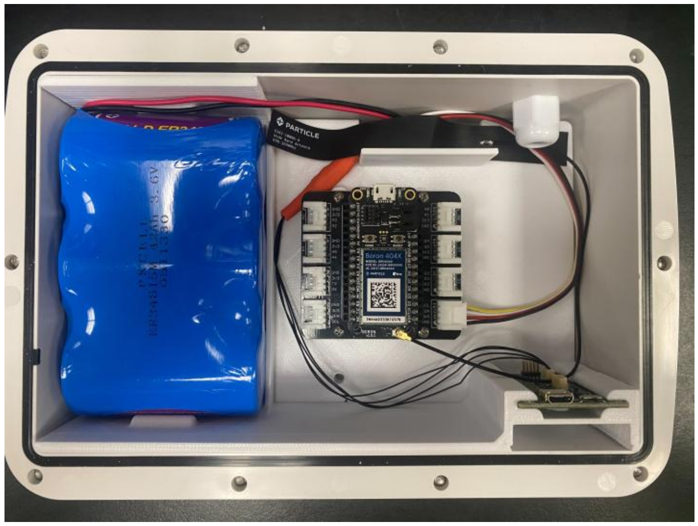

Figure 9: Radar Testing System

3.3.3 Objective: Develop Survey Techniques for On-Site Deployments

An important aspect of the deployment of water level sensing devices is to develop a procedure to identify their location in relation to bridges and other built infrastructure through accurately determining horizontal and vertical location within a recognized geographic coordinate system and datum(s). There is a long history of procedures to accurately locate water level sensing devices, with many of them based on traditional surveying techniques. Originally, this involved using vertical control networks to survey in monitoring locations (Schomaker and Berry, 1981). More recent surveying techniques for similar devices use a combination of existing geodetic benchmarks or long-GPS survey techniques to essentially create a series of new geodetic benchmarks to confirm RTK GPS positions (Dorton, 2023). These procedures require establishing a minimum of 3 benchmarks within 1 km of the gauging station (Dorton, 2023). The required accuracy for these SECOORA gauges is within 0.05 m for vertical elevation (Dorton, 2023), which is a lower accuracy standard compared to the rigorous USGS standard of 0.3048 cm (Kenney, 2010) in relation to a vertical datum. Most modern water level surveying techniques have relied on the vertical datum NAVD88; however, a new, more accurate, gravity-based datum is being introduced (NAPGD2022), which will serve to further improve the accuracy of GPS-based methods for determining vertical elevation (Ahlgren et al., 2017).

One of the key difficulties with using a series of complex, geodetic benchmark-based procedures is the time required when surveying the location of water level monitoring systems. With the urgent need to increase the density of water level sensing networks, the need to spend a day or more surveying newly installed stations impedes installation because it dramatically increases the overall cost of system deployment. Given these considerations, a surveying technique was developed for BridgeBox™ deployment that relies on the accuracy of RTK GPS utilizing the South Carolina Realtime Network (SCRTN) and a low-cost but professional-level GPS system that can use the GPS corrections from SCRTN to determine horizontal and vertical location accurately. The reported horizontal and vertical accuracy of GPS systems receiving the realtime correction from the SCRTN is 0.02m and 0.04m, respectively, which does not inherently meet the USGS standard but is within the SECOORA vertical standard used for similar systems (Dorton, 2023). An Emlid Reach RS2 RTK system was used for testing combined with a hot-spot cellular modem and account for the SCRTN provided through the Clemson Center for Geospatial Technologies. This GPS can process realtime differential corrections while receiving and processing signals from all of the global GNSS satellites.

3.3.4 Objective: On-Site Deployment to Test System Performance

To accelerate on-site testing, talks were initiated with Greenville and Anderson counties regarding potential deployment on flood-prone bridges. Greenville County identified ten flood prone locations where they were not planning on replacing bridges in the near future. Counties maintain and install a subset of the bridges over water in South Carolina, with an acute knowledge of which bridges in their county are subject to flood risk. We received support and written approval to install on as many as 10 bridges in Greenville County (Figure 10). The selected bridges included five bridges identified as high flood risk from Greenville County, and another five selected by our team that have high predicted flood risk in the area of the bridges. These five bridges may not be at risk for overtopping but have a high risk of flooding near the bridge locations.

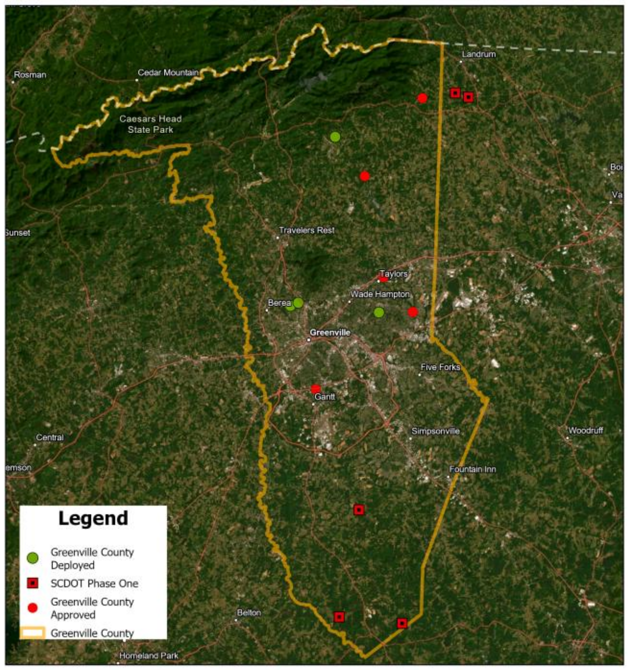

Figure 10: Approved and Greenville County Deployed Systems

An on-site survey methodology was developed to survey potential mounting sites before installation. The goal was to develop protocols that would assure the reliability of installation and the resulting data in a way that would scale in the future for large numbers of deployments. Using the developed methodology, on-site surveys were done by the Research Team to ensure the feasibility of installations (Figure 11). The key survey parameters included::

a) Height of the water surface from the potential installation point
b) The presence and location of a sideway concrete slab which would give a clear line of vision to the radar from the water surface.
c) Feasibility of different mounting strategies based on the slab presence and width.
d) Cellular Signal Strength for Cat M cellular networks.
e) Potential damage/erosion on concrete surfaces, which could result in poor adhesion.

Figure 11: Bridge Site Surveys

3.3.5 Objective: Addition of Communication Interfaces to the BridgeBox™ System

The BridgeBox™ currently has a cellular module that connects via an LTE-M network. The cellular chip can roam between AT&T and T-Mobile networks. In case of poor cellular connectivity, the main board can save accurately timestamped data in non-volatile internal memory and later send it when cellular reception improves. However, additional communication interfaces were explored which could enable Bridge box system to send data in locations, where cellular reception is weak, while the GPS module can validate the general loction where a system is deployed. The following protocols were explored:

a) Satellite: Low data throughput compared to cellular networks. Can send data in extremely remote locations.
b) GPS: Can be used to provide accurate data location of the exact sensor node for high density deployments. This could also be used to provision the onboard real-time clock. Importantly, large system deployments allows the initial and regular verification of

deployment location, which is an important component of IoT security and deployment process verification.

Hardware Modules were identified for Satellite telecommunications, and GPS and subsequently interfaced to the existing Bridge Box system.

CHAPTER 4

Results

4.1 Objective: Develop BridgeBox™ Mounting System

A complete non-destructive methodology was developed to deploy BridgeBox™ technology. Figure 12 shows the exploded view of the mounting assembly. An aluminum plate (detailed dimension in Figure 13) is attached to the bridge concrete slab using a construction adhesive. The construction adhesive is all-weather and has been tested in our lab to show excellent adhesion to concrete. A custom mount which is 3D printed using carbon fiber reinforced PET-G (detailed dimension in Figure 14), is attached to the aluminum plate using screws. This has been made easily removable to accommodate dimension changes in future iterations of the bridge box.

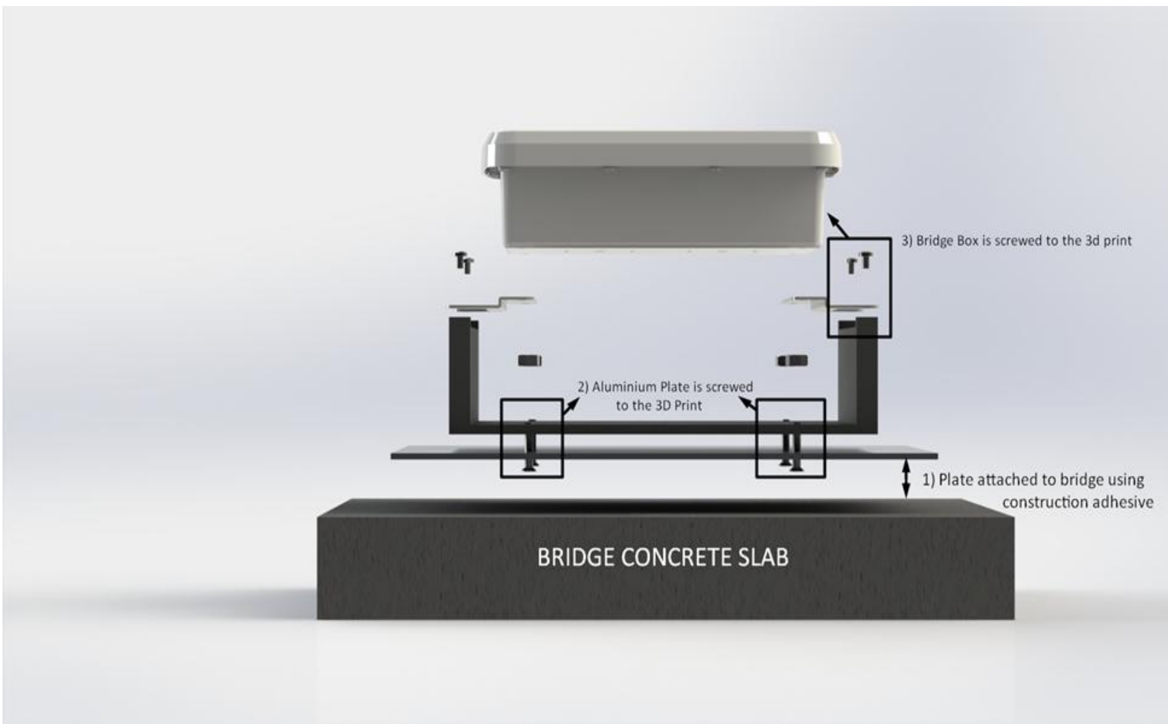

Figure 12: BridgeBox™ Mounting System

The construction adhesive requires 12 hours to achieve full curing strength, and as per site experience, 3-4 hours for holding strength. A holding fixture needed to be engineered to keep the mounting assembly attached to the concrete slab during the curing process. To keep costs low, a lead screw assembly with guide bars was purchased from amazon (see Figure 15). The total length of the lead screw assembly was enough to grab the concrete slab of bridges. A custom part was designed and 3D printed to cradle the complete mounting assembly including the bridge box. The holding fixture was printed with a carbon fiber PET-G with high infill percentage to achieve the required strength.

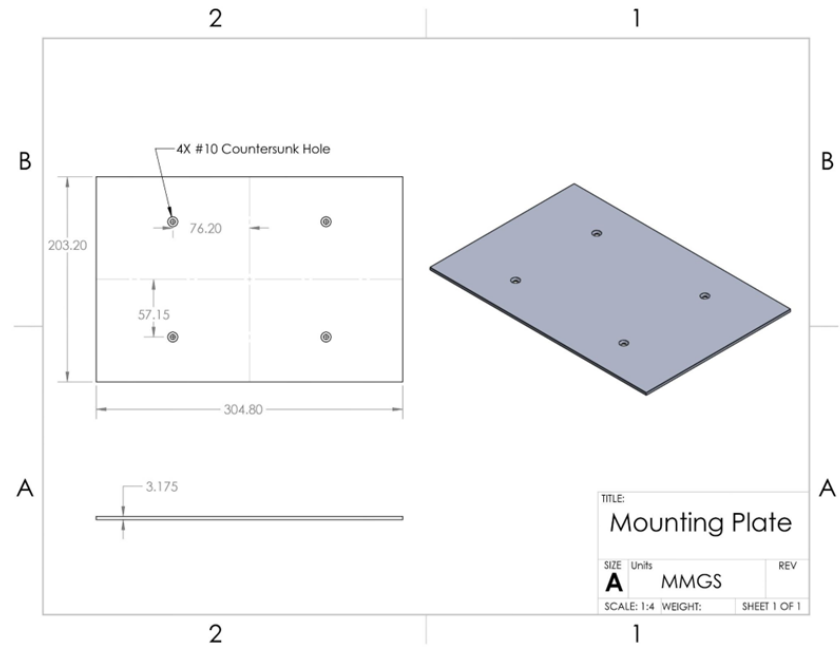

Figure 13: BridgeBox^{TM} Mounting Plate

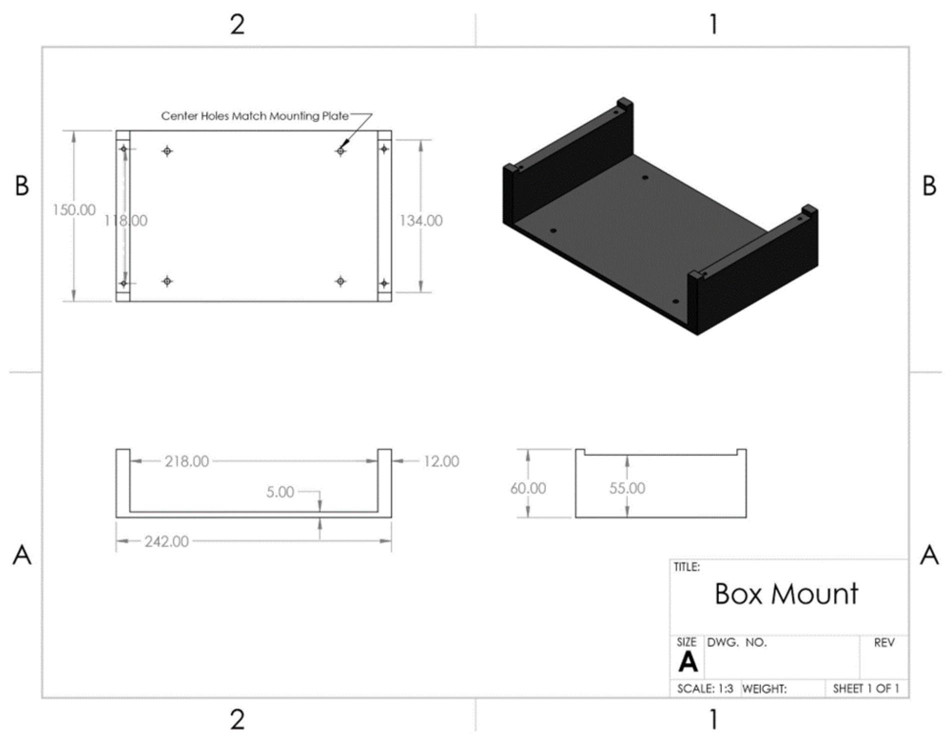

Figure 14: BridgeBox^{TM} Custom Mount

Figure 15: BridgeBox™ Custom Modified Vise

The innovative design led to a very simple four step installation process (Figure 15), with off the shelf parts purchased from Amazon, and any custom part 3D printed inside the Intelligent River lab, keeping the cost much lower than what would be expected from a traditional manufacturing workshop.

1) Assemble the aluminum plate, 3D printed mount and BridgeBox™ together using screws.
2) Put the mounting assembly inside the holding fixture.
3) Apply construction adhesive on the back of the aluminum plate
4) Put the holding fixture on top of the concrete slab and tighten the lead screw using hand.

The figure below (Figure 16) shows Step-4 being carried out. The whole mounting process takes less than 30 minutes to complete.

Figure 16: BridgeBox™ Mounting Process

4.2 Objective: Optimization of Radar Performance

The actual validation of Bridge Box system is subject to on-site validation, however, to optimize the radar's performance, a series of experiments were done in-lab and on near site deployments in Hunnicutt Creek, SC. There are two important factors associated with radar optimization. One is radar accuracy and the second is power consumption. The two are not necessarily inversely proportional. Below we discuss a few parameters that were important to optimize the performance of the radar.

4.2.1 Effect of Initial Power Input in Radar Pulse

The Bridge Box uses a pulsed coherent radar, which means that it emits radar pulses with a known starting phase. The known phase helps the radar identify the pulse when it gets reflected off the object. As the radar pulse travels through the surroundings, signal attenuation takes place. A longer pulse duration will be able to detect objects which are at longer distances, however resulting in higher power consumption. Figure 17 shows five different power profiles tested with the radar, with power profile 1 corresponding to the smallest power input (small pulse duration) and power profile 5 corresponding to the highest power input (large pulse duration). The experiment was done in-lab at a distance of 2.7m for an extended period of time. Figure 17 shows the cumulative error (in %) for the five power profiles. Interestingly, the smallest power profile corresponds to the smallest error. While the larger power profile corresponds to an increased range detection, it also results in erroneous reflection from objects in the surrounding environment. It was decided that from site to site, an initial testing would be done to determine the smallest power profile that could safely detect water surface at the lowest possible depth. This has two-fold advantages, first greater accuracy, secondly lower power consumption of the system.

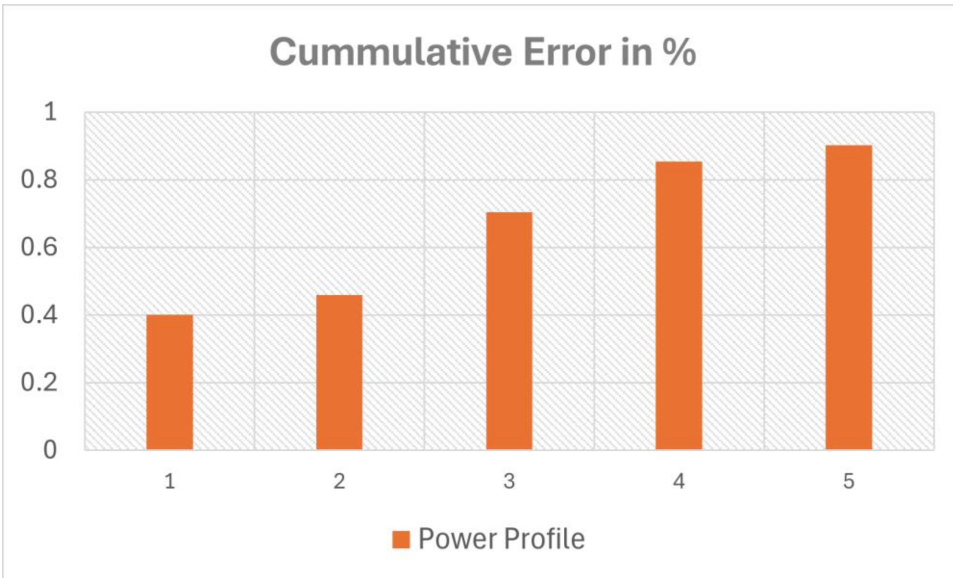

Figure 17: BridgeBox™ Radar Power vs. Error. Cumulative error (in %) for five power profiles, with power profile 1 having the least power output ranging to the highest power output at power profile 5.

4.2.2 Effect of Hardware Accelerated Averaged Sampling

Hardware Accelerated Averaged Samples (HWAAS) is a technique used in radar technology to detect objects when the received pulse is severely attenuated, and it becomes difficult to distinguish the object from surrounding noise picked up during signal propagation. The radar instead of emitting a single pulse, would emit several pulses. These pulses on reflection would then be averaged using hardware accelerators. One would expect the noise to be averaged to zero, while the actual object's reflection will become much larger than the surrounding noise. The more samples used in HWAAS, however, the higher power consumption will be. For Bridge Box four different sample counts were tested as seen in Figure 18. HW1 corresponds to the smallest number of samples, while HW4 corresponds to the highest number of samples. Figure 18 shows the cumulative error in % for two different heights that were tested. HW1 (lowest number of samples) corresponds to the largest error, however as the samples are increased the cumulative error reaches an asymptotic value. After a point, more number of samples did not significantly decrease the error. It was decided to use HW3 value for initial deployments. This is to balance both accuracy and power usage.

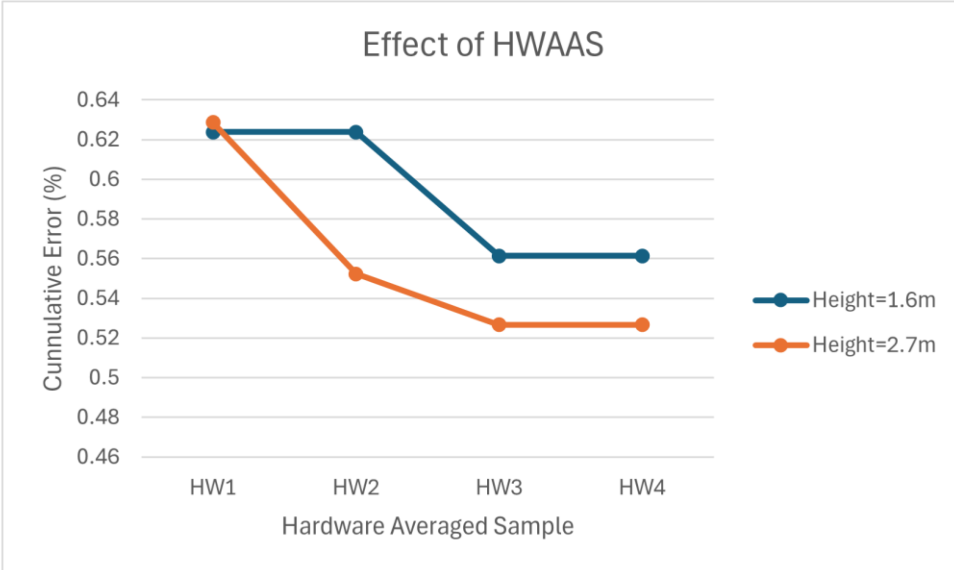

Figure 18: Error vs. Hardware Accelerated Averaged Samples. Four different Hardware Accelerated Averaged Samples (HWAAS) ranging from a lower number of samples (HW1) to the largest number of samples (HW4) were compared to understand the relationship between sample number and error.

4.2.3 Effect of Water Proofing Spray

On-site test deployments at Hunnicutt creek have shown that water accumulation at the box, specifically where the radar is located, can result in erroneous readings. Hydrophobic coatings have been used in telecommunication antennas to prevent water accumulation. These coatings are designed for specific frequencies, so signal attenuation at particular frequencies can be avoided. After a search for available commercial products we were unable to find hydrophobic coatings that reported to not interferior in the 60 GHz frequency however a cytothane coating (from cytonix : https://cytonix.com/products/cytothane-mw) was identified as a possible solution. This coating is designed to be used in Ku (2-18 GHz) and Ka (27-40 GHz) bands. Experiments were carried out at three different heights 1.6m, 2.0m and 2.7m. Figure 19 shows the cumulative error (in %) for the three different heights. In general, it was seen that the hydrophobic coating increased the error at all three heights, so it was determined that this coating was not a viable solution.

Application of hydrophobic coating was also a time-consuming process and requires safe handling procedures. It was decided to 3D-print a hood (see Figure 20), which can redirect the water flow and prevent the radar surface from accumulating water. In general, on-site deployments have shown this to decrease the error during major rain events and avoid erroneous readings.

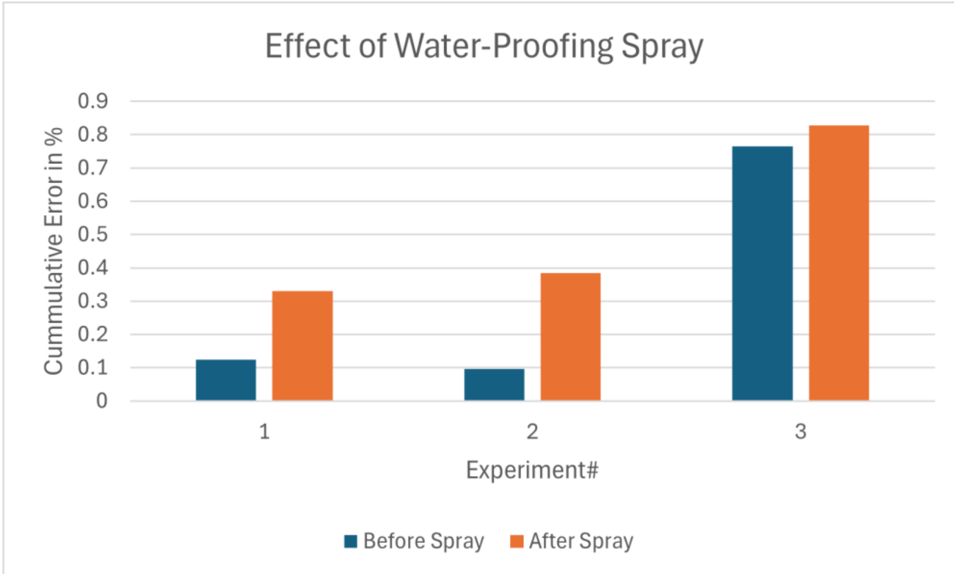

Figure 19: Effect of Water Proofing Spray

Figure 20: Radar Hood

4.2.4 Implementation of a Median Filter to Limit Sensor Anomalies

Initial test deployments of the Bridge Box at Hunnicutt Creek also revealed intermittent erroneous readings. This could be due to the intermittent reflection of random objects. Figure 21 shows an example of intermittent disturbance seen by the radar. This was more frequently observed during rain events. To resolve this, a median filter incorporated into the radar algorithm. This is not to be confused with HWAAS, which constitutes a single reading. A greater number of medians results in higher power consumption. After several trial tests, it was decided to cap the number of medians to five. This value, while resulting in higher power consumption, has resulted in a reduction of erroneous readings. Figure 22 shows a rain event captured in Hunnicut Creek with five sample medians used to filter the data. In general, one can see that Bridge Box was able to capture the rain event without any intermittent erroneous jumps qualitatively.

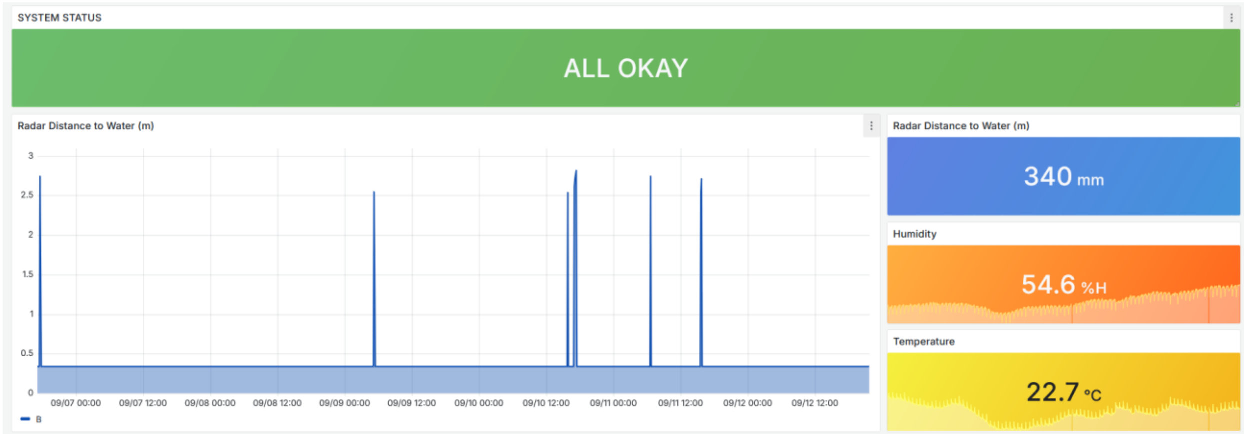

Figure 21: Data Errors with No Medians

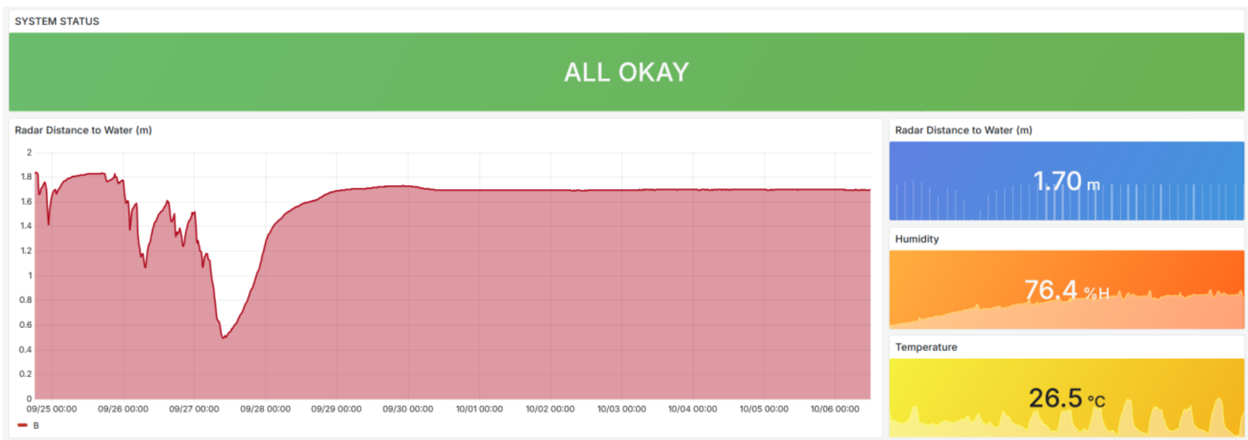

Figure 22: Smooth Data with Medians

4.2.5 Minimizing Disturbance from Bridge Concrete Slab

The radiation pattern for the radar is constrained to emit max power within +- 20 degrees horizon. An internal lens is also used to focus the beam. However, to reduce disturbance from the concrete bridge slab, it was decided to design the mechanical mount with a given offset. This was done by trial, and in the offset distance was deemed enough to prevent any erroneous readings (Figure 23).

Figure 23: Mounting System Showing Distance from Slab

4.3 Objective: Develop Survey Techniques for On-Site Deployments

Deployment trials using RTK GPS relying on the SC Realtime Network for differential GPS showed horizontal and vertical accuracies within 1 cm, and 2 cm, respectively using an Emlid RS2 RTK GPS. To facilitate surveying, a permanent survey location, in the form of a notch, was added to the BridgeBox™ mount (Figure 24). The survey notch is a known distance from the radar sensor and allows simple re-surveying of deployed sensors over time.

Figure 24: Field Surveying System

4.4 Objective: On-Site Deployment to Test System Performance

The following 5 bridges were identified by Greenville County to be prone to flooding risk, and which lacked USGS instrumentation for emergency preparedness.

A) 309 Scotswood Rd, Taylors, SC (GVC-BR388)
B) Aiken Chapel Rd · Taylors, SC 29687 (Not Installed)
C) 50 School Rd, Greenville, SC 29617 (GVC-BR391)
D) 155 Webb Rd, Seneca, SC (GVC-BR2728)
E) 298 Langston Dr, Greenville, SC 29617 (GVC-BR393)

Site-A has a pre-existing USGS installation, which helped verify the accuracy of the BridgeBox™ for Greenville County and Intelligent River® Team. The site also now serves as a purpose for algorithm testing with the reference USGS gauge. On-site survey revealed Site-B bridge structure to be missing due to a prior flooding event. The missing bridge structure and the resulting disruption to mobility underscored the need for such low-cost instrumentation.

4.4.1 GVC-BR388 Installation and Comparison with USGS Gauge

Figure 25 shows the installation at Site-A. As can be seen in the picture, the mounting methodology has been successful, with the total installation time of device on-site less than 30 minutes. This site has a pre-existing USGS instrumentation which was used to cross-verify the accuracy of BridgeBox™.

Figure 25: Greenville County, SC Site: GVC-BR388

Figure 26 shows a side-by-side comparison of the USGS site and BridgeBox™ between August 3, 2024, and August 10, 2024. While the two instruments are at slightly different locations, it can be seen qualitatively that BridgeBox™ was able to capture the rain events quite accurately. The difference between the normal expected water level and what was seen during a rain event on August 10th was calculated to be exactly the same by both the instruments. This helped reinforce confidence in the accuracy of BridgeBox™.

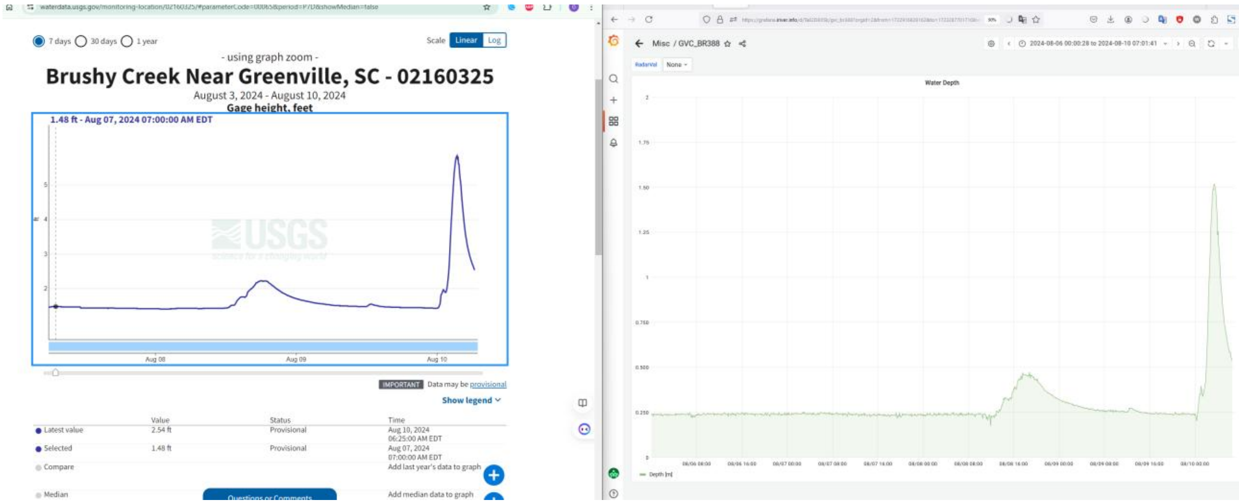

Figure 26: Greenville County, SC Site: GVC-BR388 Data Comparison. Data from an existing US Geological Service (USGS) sensor on the left and data from the BridgeBox™ system on the right.

A more severe test of BridgeBox™ accuracy and resilience happened during the recent Hurricane Helene. Figure 27 shows a scaled comparison between the Intelligent River Bridge Box and USGS gauge. The accuracy of the BridgeBox™ during a severe flooding event was shown to be very favorably comparable. Interestingly, this site normally has a water level of around 0.8-1.2 ft. However, during the recent Hurricane the water level at the site rose to approximately 15 ft. These water levels correspond to severe flooding risk for this site, as the distance of the radar from the water surface during peak level was only about 0.3 meter or 1 foot (as seen in Figure 27). The photos of the site shown in previous figures underscore the alarming need of low-cost accurate instrumentation at these flood prone sites.

It is important to note that the slight difference between the BridgeBox™ and the USGS data can be attributed to the differences in deployment location between the two sites, which showed minor differences at lower water levels and no difference during flood conditions.

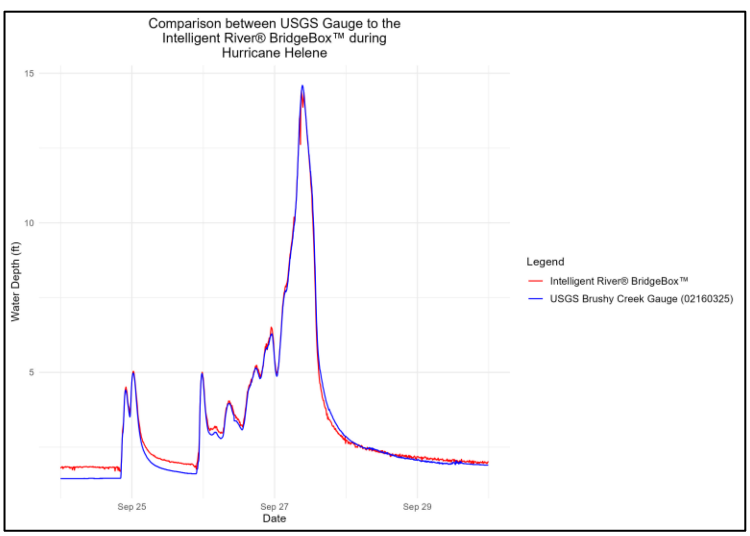

Figure 27: GVC-BR388 Data Comparison with USGS Site

4.4.2 GVC-BR391 Installation

Figure 28 shows the installation of Site-C (BR-391). Again, the mounting method has proved to be quite successful. Notably this was the first installation done by the Intelligent River® team (July-30-2024).

Figure 28: Greenville County, SC Site: GVC-BR391

Figure 29 shows the depth of water measured by BridgeBox™ since its initial installation. The BridgeBox™ was able to capture several minor and major rain events. The major rain event seen in Figure 29 again corresponds to Hurricane Helene. At peak water levels the distance between the bottom of radar and water surface was only about 5-6 foot.

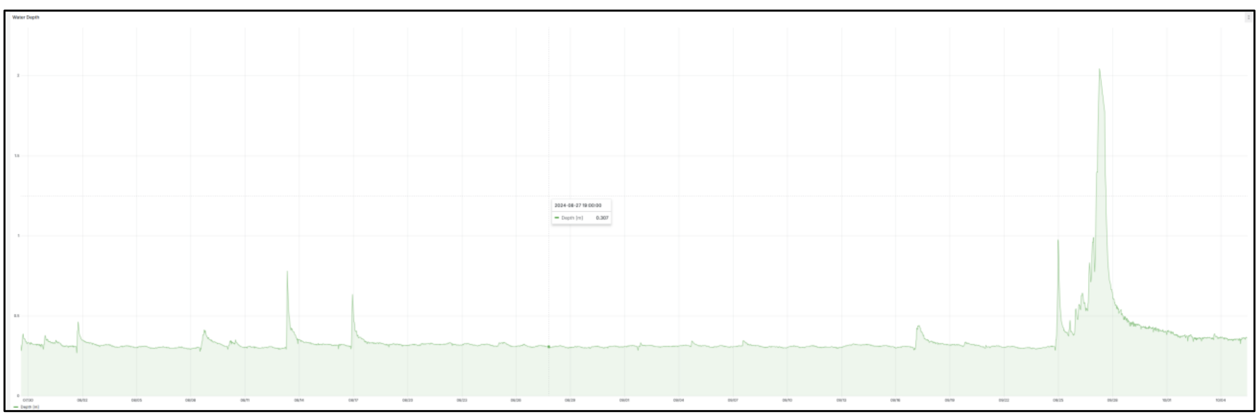

Figure 29: Greenville County, SC Site: GVC-BR391 Data

4.4.3 GVC-BR2728 Installation

Figure 30 shows the installation at Site-D (BR-2728). There are a lot of rocks directly underneath the field of vision of BridgeBox™. This resulted in some choppy disturbances during normal water levels (as seen in Figure 30). However, the instrument was able to accurately capture the Hurricane Helene water event, as the water levels rose above the rocks during severe rainfall event. This does, however, underly the effect of surrounding physical environment, during normal operation of the instrument.

Figure 30: Greenville County, SC Site: BR-2728

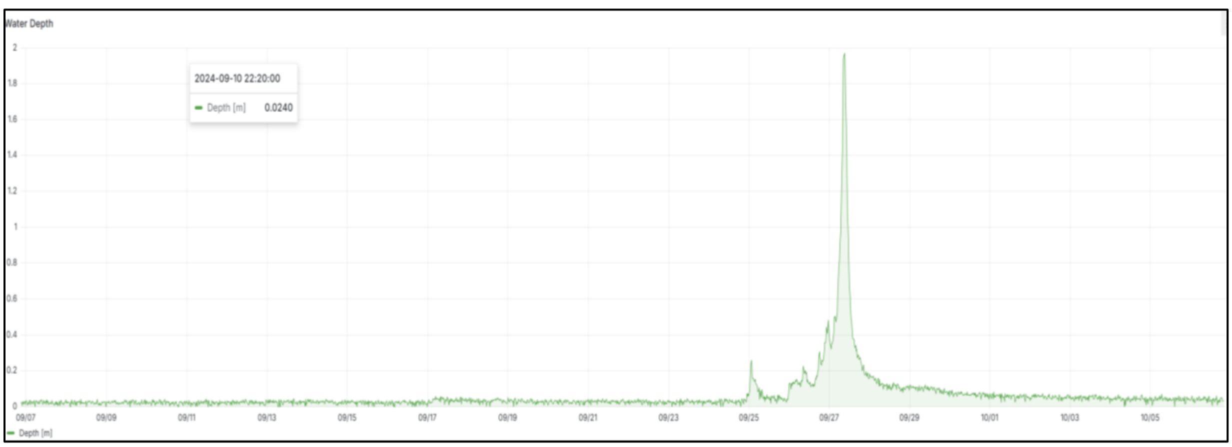

Figure 31: Greenville County, SC Site: BR-2728

4.4.4 GVC-BR393 Installation

Figure 32 shows the installation at Site-BR-2728. As in previous example, Figure 33 shows the rain events detected by the instrument since its installation, with the largest major rain event occurring during Hurricane Helene.

Figure 32: Greenville County, SC Site: BR-393

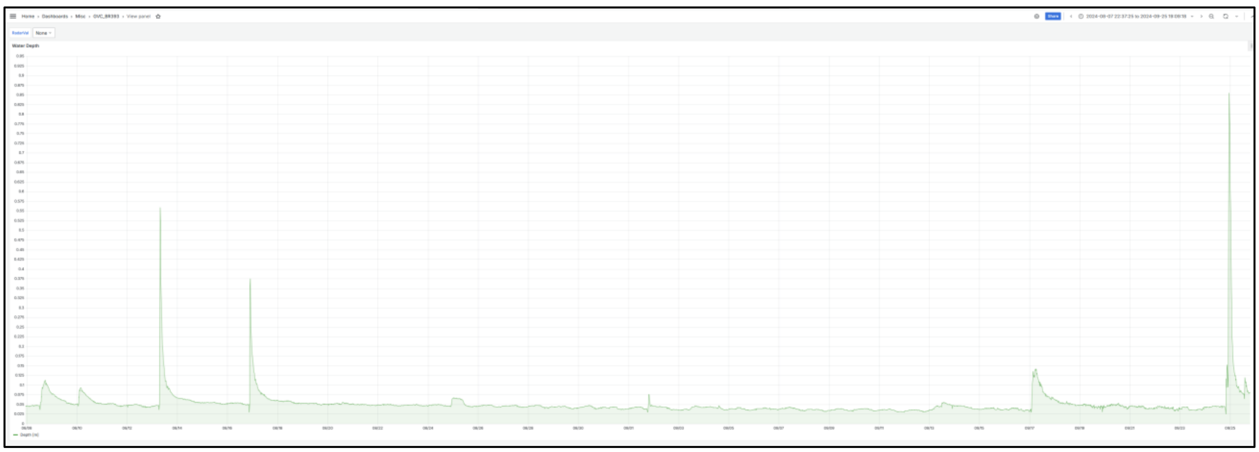

Figure 33: Greenville County, SC Site: BR-393 Data

4.5 Objective: Addition of Communication Interfaces to Bridge Box System

As described in Section 3.3.5, several communication interfaces were added to Bridge Box in the duration of the project. Reasons included communication in very rural areas where cellular connectivity can be patchy and having the capability to form sensor networks with independent sensor nodes connecting to a single cellular box.

4.5.1 Satellite and GPS Connectivity

For satellite connectivity, an Iridium satellite modem was integrated with Bridge Box. The iridium satellite network is a Low Earth Orbit (LEO) network, approximately 490 miles above the surface of Earth. Figure 34 (Part-A) shows the modem connected to the Bridge Box. Bridge Box was able to send emails to configured email addresses with a text string. The data rates, as compared to an LTE-M network, are quite slow, so use case is only envisioned in emergencies when cellular networks are down or unavailable.

Additionally, a GPS module from U-blox (Neo-8 Series) was also integrated (Figure 34). This has added the ability to identify its current location for Bridge Box. Bridge Box also uses cellular network to resynchronize its internal clock. Internal time synchronization is important for the sanctity of data. The GPS time signal can now be used as a backup for clock synchronization in case of cellular network unavailability.

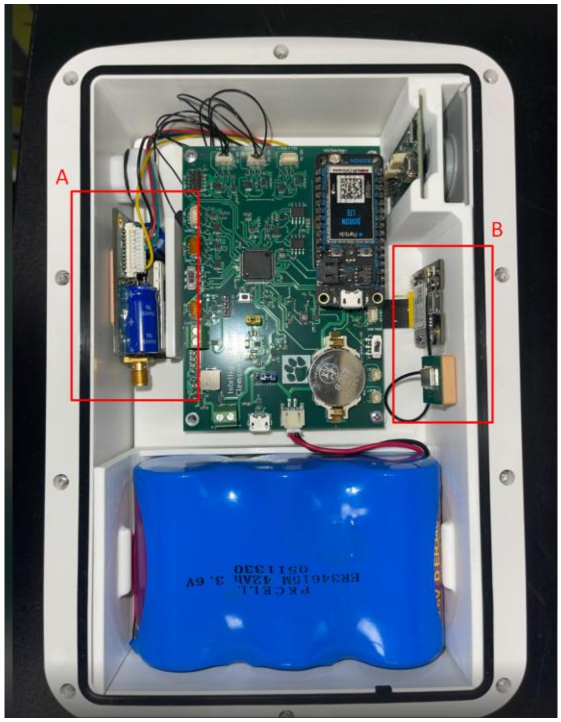

Figure 34: Interfaced Satellite and GPS Module

CHAPTER 5

Conclusions

Bridge flooding can dramatically impact mobility, and climate change impacts are expected to increase flooding frequency in the future. There is an urgent need to develop technology to provide accurate, near real-time water level information from bridges that can be deployed at thousands of bridge locations. The Clemson Intelligent River® project has developed an innovative low-cost platform for water level monitoring from bridges. This “BridgeBox™” uses radar technology to measure water levels and then sends this data over IoT cellular networks to a cloud-based system that can share water levels and flood alerts with DOT professionals to help improve public safety and vehicle flow to improve mobility during extreme precipitation and flooding events. Project funding from the Center for Connected Multimodal Mobility enabled critical testing and deployments to improve the system and deployment system. Water level distance accuracy was validated through laboratory and field testing, showing that this system was as accurate as the USGS system, which cost approximately 80 times more to install. A GPS was integrated to help validate the installation location, and a satellite module was integrated as a proof of concept for extreme event follow-over (transition from cellular to satellite telemetry) if cellular networks become unavailable. Multiple bridge mounting systems have been developed to enable rapid, non-destructive mounting on various bridge structures. Installation surveying methodology was developed. This grant supported and enabled the presentation of the device at the USDOT's Future of Transportation (FoT) Summit in August 2024, where it was well received by the DOT community. Finally, multiple test deployments were completed in collaboration with local governments, and more are planned in the near future.

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