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THESIS

**ANALYZING CELL PHONE NETWORK RESILIENCE
IN THE U.S. VIRGIN ISLANDS**

by

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June 2020

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**ANALYZING CELL PHONE NETWORK RESILIENCE
IN THE U.S. VIRGIN ISLANDS**

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

This thesis assesses the operational resilience of the wireless communication system in the U.S. Virgin Islands (USVI) and provides recommendations to protect this system from future disasters. We develop a model of the cellular phone network coverage in the USVI with the Terrain Integrated Rough Earth Model (TIREM)—a Department of Defense and industry standard model for wireless signal assessment. We generate individual and composite coverage maps for each tower and each island to conduct parametric "what-if" analysis of tower failure on cellular service to geographic regions, critical facilities, and communities. Results estimate cell phone coverage during normal operations and in future disaster scenarios. We conclude with recommendations for hardening existing systems to improve network resilience to future disruptions.

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List of Acronyms and Abbreviations

4G	4th Generation Mobile Networks
5G	5th Generation Mobile Networks
BBVI	Broadband VI
CAI	Community Anchor Institution
CI	Critical Infrastructure
CRS	Coordinate Reference System
CSV	Comma Separated Values
DAD	Defender-Attacker-Defender
DEM	Dynamic Elevation Model
dBm	Decibel-milliwatt
DLL	Dynamic Link Library
DoD	Department of Defense
DOE	Department of Energy
DPW	Department of Public Works
FAP	Fiber Access Point
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
GDAL	Geospatial Data Abstraction Library
GHz	GigaHertz

GIS	Geographic Information Systems
HFC	Hybrid Fiber Coaxial
ILEC	Incumbent Local Exchange Carrier
IP	Internet Protocol
ISP	Internet Service Provider
LOS	Line of Sight
LTE	Long Term Evolution
MASINT	Measurement and Signature Intelligence
MHz	MegaHertz
MW	MegaWatts
NGO	Non-Governmental Organization
NOAA	The National Oceanic and Atmospheric Administration
NPS	Naval Postgraduate School
NTIA	National Telecommunications and Information Agency
RF	Radio Frequency
RMD	Reflection plus Multiple Diffraction loss
SPEED	Systems Planning, Engineering and Evaluation Device
SRWBR	short range wide band radio
STJ	St. John
STT	St. Thomas
STX	St. Croix
TCP	Transmission Control Protocol

THz	TeraHertz
TIFF	Tagged Image File Format
TIREM	Terrain Integrated Rough Earth Model
UDP	User Datagram Protocol
U.S.	United States
USG	U.S. Government
USGS	U.S. Geological Survey
USN	U.S. Navy
USVI	U.S. Virgin Islands
UVI	University of the Virgin Islands
VI	Virgin Islands
viNGN	Virgin Islands Next Generation Network
VIPA	Virgin Islands Port Authority
VITEMA	Virgin Islands Territorial Emergency Management Agency
VIWAPA	Virgin Islands Water and Power Authority
VIWMA	Virgin Islands Waste Management Authority
W	Watts
WMN	Wireless Mesh Network

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Executive Summary

In September 2017, Category-5 Hurricanes Irma and Maria struck the U.S. Virgin Islands (USVI) within a two-week period and collectively devastated homes, businesses, and infrastructure throughout the territory. The impacts to USVI infrastructure showed compounding effects when critical services (e.g., electricity, water, transportation, and communications among others) were lost and impacted the functioning of interdependent services and the communities that depend on them. These compounding effects were particularly acute when critical wireless communications services like cellphone signal and WiFi were lost. This inhibited effective communication within local communities and among emergency responders, exacerbating the impacts of the hurricanes and slowing recovery efforts.

This thesis assesses the operational resilience of the current wireless communication system in the USVI and provides recommendations to protect this system from future disasters. The goal is to conduct analysis for the U.S. federal government and USVI territorial stakeholders to guide Irma and Maria recovery and mitigation efforts. This thesis achieves this goal by curating new infrastructure datasets useful for assessing the function the USVI cellular infrastructure system, conducting analysis of the robustness of this system to infrastructure failures, and providing recommendations for how to improve system design and operation to be resilient. Specifically, this thesis completes four tasks that help guide future decisions about wireless infrastructure resilience in the territory. This thesis:

1. Curates infrastructure data for the territory to map and assess cell phone coverage;
2. Develops a model of current cellular phone network coverage in the USVI with the Terrain Integrated Rough Earth Model—a Department of Defense and industry standard model for wireless signal assessment;
3. Conducts parametric, “what-if” analysis of tower failure to identify what cell phone coverage may look like in future disaster scenarios; and,
4. Produces coverage maps and recommendations for hardening existing systems to future storms.

Results presented in this thesis support disaster response and system protection in three ways. First, we generate maps that show the composite coverage from all towers in the

USVI to identify regions on each island with limited to no cell phone signal. Results demonstrate that each island has regions with no signal that may impede communications even when all towers are operational. Second, we measure the number of critical facilities covered by each tower. Results identify which towers provide cellular service to the greatest number and diversity of critical facilities to inform effective disaster response operations. Third, we measure how communities are covered by each tower. Results show which towers cover the greatest number of buildings and which towers, if lost, lead to the greatest increase in coverage shortfalls. Stakeholders can use this result to prioritize tower hardening and recovery for disaster-stricken communities.

Ultimately, this thesis develops data, models, and analyses that can be used by project partners to build a more resilient cellular phone network. The model presented in this thesis can serve as a decision tool to quickly identify which towers are more critical to harden or where additional towers may be needed. This includes recommendations as to where to construct new towers or where existing towers should be hardened to better survive hurricanes. Thus, the output of this thesis will assist the Federal Emergency Management Agency, the Virgin Islands Territorial Emergency Management Agency, and the University of the Virgin Islands in further research and decision making about wireless communications networks to lessen the impacts of future storms. This will reduce disaster impacts by allowing first responders to more rapidly and effectively communicate and reduce the need for communities to leave their homes seeking cellular signals.

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CHAPTER 1: Introduction

In September 2017, Category-5 Hurricanes Irma and Maria struck the U.S. Virgin Islands (USVI) within a two-week period and collectively devastated homes, businesses, and infrastructure throughout the territory (Alderson et al. 2018; USVI Hurricane Recovery and Resilience Task Force 2018). The impacts to USVI infrastructure systems showed compounding effects when critical services (e.g., electricity, water, transportation, and communications among others) were lost and impacted the functioning of interdependent services and the communities that depend on them. These compounding effects were particularly acute when critical wireless communications services like cellphone signal and WiFi were lost. This inhibited effective communication within local communities and among emergency responders, exacerbating the impacts of the hurricanes and slowing recovery efforts. The focus of this thesis is to assess the operational resilience of the current wireless communication system in the USVI and provide recommendations to protect this system from future disasters.

This thesis is part of a number of interrelated federal and territorial efforts to assess the vulnerability of USVI critical infrastructure systems and determine effective ways to recover and mitigate the impacts of future disasters. In particular, this work is part of a funded effort by the Federal Emergency Management Agency (FEMA) to connect work by FEMA, the Naval Postgraduate School (NPS) the US Department of Energy (DOE), DOE National Labs, the University of the Virgin Islands (UVI), and USVI Territorial government agencies and utilities among others.

1.1 Overview of U.S. Virgin Islands

The USVI is a territory in the Leeward Islands of the Lesser Antilles approximately 40 miles east of Puerto Rico and 1100 miles southeast of Miami, Florida. The territory has three main islands: St. Croix (STX), St. Thomas (STT), and St. John (STJ) (shown in Figure 1.1).

STX, STT, and STJ share some similar characteristics due to their isolated geographic



Source: Encyclopædia Britannica Inc. (2010).

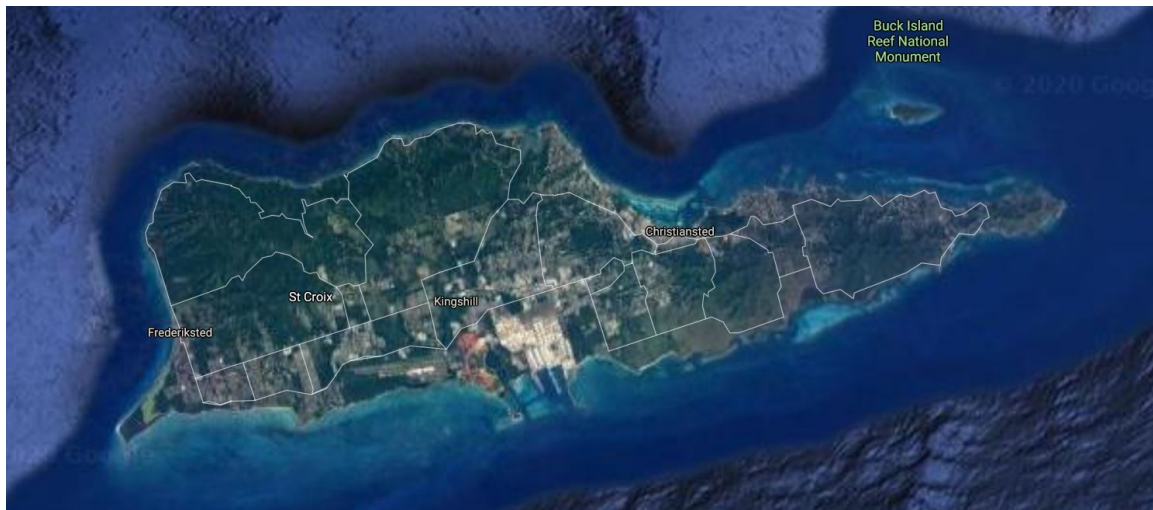
Figure 1.1. The U.S. Virgin Islands

location. The USVI has a tropical climate with temperatures that range from lows of 75° F at night to highs of up to 90° F during the day and both rainy and dry seasons that can sometimes result in flooding or drought (Evans 2017). The USVI has limited natural resources and only a modest amount of local agriculture and industry, so a majority of everyday goods such as food and fuel have to be imported (Alderson et al. 2018).

However, STX, STT, and STJ each have a unique subculture and economy, mostly related to their history and how they were colonized.

1.1.1 St. Croix

STX is the largest island in the USVI with respect to total landmass, has a total population of approximately 50,000 people, and is located about 65 miles southeast of Puerto Rico and about 40 miles south of STT. The two main towns on the island are the capital of Christiansted on the northeast coast and Frederiksted on the western coast. The remainder of the island is divided into sub-communities called estates (similar to census tracts), still named as they were during the colonial era. While the ruling nation of STX changed numerous times during the colonial period, all countries that owned STX recognized the most profitable product at the time was sugar cane which the flat land and climate were perfect for growing. After becoming a U.S. territory, STX also became the location of the Hovensa refinery—one of the largest oil refineries in the western hemisphere. The economy in STX now revolves around tourism and rum distilling; the closure of the Hovensa oil refinery in 2012 left only those two pillars and caused a significant economic decline for the island (Good 2019).



Source: Google (2020a).

Figure 1.2. St. Croix, USVI

1.1.2 St. Thomas

STT is a volcanic island that lies 40 miles east of Puerto Rico and is considered the chief island of the USVI with a total population of approximately 51,000 people, and has one of the most popular cruise ship docks in the Caribbean. The capital of STT, and the USVI as

a whole, is Charlotte Amalie which is in the center of the island on the southern coast. The rest of the island is divided into estates whose names date back to the colonial era similar to STX. Tourism is the primary industry for the island, giving it one of the highest per capita incomes in the Caribbean. The deep port also has some strategic significance because the U.S. originally purchased the island in 1917 to be used as a naval base (Good 2019).

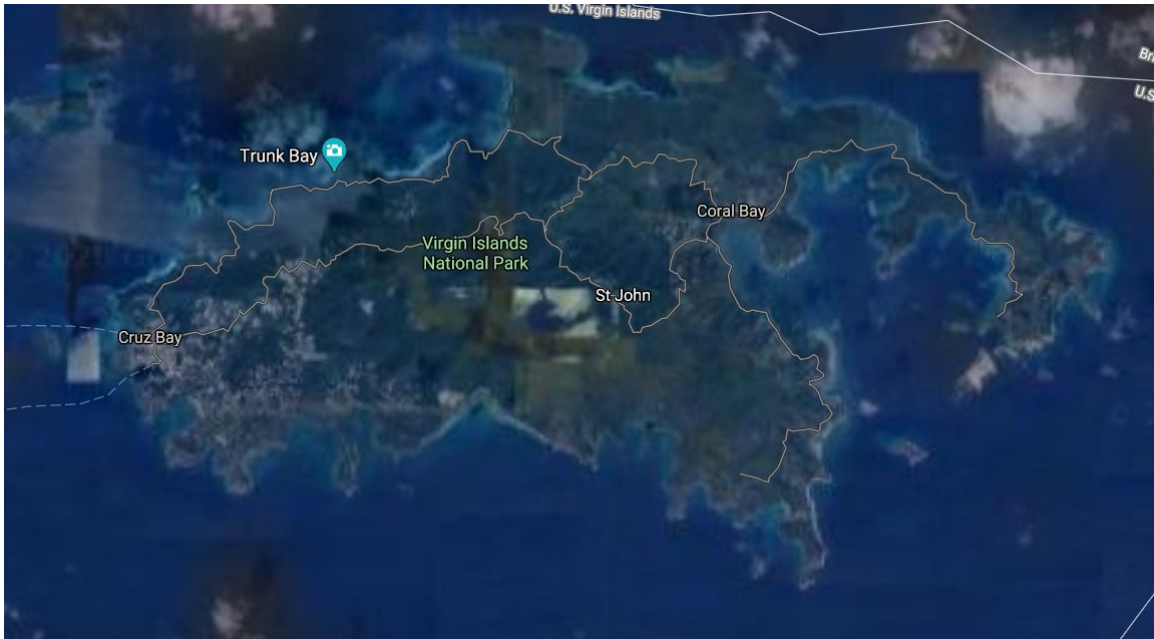


Source: Google (2020c).

Figure 1.3. St. Thomas, USVI

1.1.3 St. John

STJ is the smallest of the main islands in the USVI with a population of approximately 4,100 people. STJ is located directly east of STT and has two major towns, Cruz Bay on the west coast (with ferries to STT) and Coral Bay on the southeast coast. A majority of STJ is tropical vegetation and second-growth trees (after originally being cleared to grow sugar cane) that were designated as Virgin Islands National Park in 1956. The economy for STJ is centered on cattle raising, bay leaves, and as with the rest of the territory, tourism. The terrain is significantly more mountainous than the other two islands, making travel across the island a time-consuming process (Good 2019).



Source: Google (2020b).

Figure 1.4. St. John, USVI

1.2 Critical Infrastructure and Cellular Communications in the USVI

Critical Infrastructure (CI) refers to all physical and cyber-based systems that are essential to the minimal operation of economic and government entities (Wille 2019). In the USVI, these systems span 16 sectors defined by the U.S. Department of Homeland Security (Department of Homeland Security 2013), including telecommunications, water, power, sewer, and transportation among others. As a start to looking at CI, there are some definitions that should be stated for the sake of clarity and understanding:

- **Critical Infrastructure:** systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters (Clark et al. 2018; The White House Office of the Press Secretary 2013a,b).
- **Dependent Failures:** challenges that may result in a cascade of failures (e.g., power failures causing communications failures) (Mauthe et al. 2016).

- **Hardening:** preparing existing assets for the impacts of natural disasters by strengthening the structure or adding physical barriers (e.g., elevating a transformer substation) (USVI Hurricane Recovery and Resilience Task Force 2018).
- **Interdependency:** A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other. (Rinaldi et al. 2001).
- **Mitigation:** lessening the impact of disasters on systems by hardening existing assets, by ensuring those assets are not damaged in the first place (e.g., by moving them), or, if they are damaged, ensuring the systems have enough redundancy to keep working (e.g., by making sure a segment of a power system does not have a single point of failure) (USVI Hurricane Recovery and Resilience Task Force 2018).
- **Resilience:** engaging in mitigation, while also ensuring systems can recover quickly even if they are disrupted, and minimizing the impact of a disruption so the impact on the communities they serve is as small as possible. Also phrased as: the capacity of individuals, communities, institutions, businesses and systems to survive, adapt, and thrive no matter what kinds of chronic stresses and acute shocks they experience (Eisenberg 2018).

Each CI system in the USVI has a different structure and operations than normally found in other parts of the U.S. For example, the energy systems in the Territory are comprised of a similar combination of fuel delivery systems and electric generation, transmission, and distribution systems found across the U.S. However, energy systems in USVI are separated into two isolated grids, one on STX and one connecting STT and STJ through undersea cables. All power infrastructure is owned, operated, and maintained by the Virgin Islands Water and Power Authority (VIWAPA), which is an autonomous government public utility for the Territory (Alderson et al. 2018).

Water systems in the USVI are similar to mainland U.S. systems by managing three different sources: storm water, potable water, and wastewater. However, most houses also have cisterns to collect rainwater for home use. Potable water distribution services are provided via pipes owned and operated by VIWAPA alongside private water hauling companies that sell water to houses via trucks. Wastewater management is run by the Virgin Islands Waste Management Authority (VIWMA), a semi-autonomous agency mandated to operate and

maintain wastewater infrastructure in the Territory (Alderson et al. 2018).

Transportation systems in the Territory include ports and airports that connect between islands and surface roads that connect areas within each island. All port operations are managed by the Virgin Islands Port Authority (VIPA), a non-profit organization that relies on revenue from services and user fees (Alderson et al. 2018). Surface roads, railroads, transit, bridges, sidewalks, and other public pathways are engineered, constructed, and maintained by the Department of Public Works (DPW) (Alderson et al. 2018).

This thesis focuses on wireless communications in the territory, and the rest of this thesis is organized to model and analyze wireless cellular communications. However, wireless communications are interdependent with energy, water, transportation, and other telecommunications systems (e.g., the Internet). For more information regarding these interdependent systems, we direct the reader to the following studies:

- Energy: Bunn (2018); Wille (2019);
- Water: Wille (2019); Borgdorff (2020);
- Transportation: Good (2019); and,
- Communications: Moeller (2020).

1.2.1 Telecommunications and Cellular Infrastructure in the USVI

Telecommunications infrastructure in the USVI is owned and operated by a variety of companies that are in competition with each other (Alderson et al. 2018). The primary communications link for the USVI is provided by undersea cables, owned by AT&T and CenturyLink that land at different locations in the Territory (i.e., Butler Bay, STX near Frederiksted and Magen's Bay, Peterborg, STT). These landing sites supply approximately 8-10 Terabits of telecommunications capability to the islands through the primary public sector provider, Virgin Islands Next Generation Network (viNGN) (Alderson et al. 2018). Wired communications is from a combination of buried and aerial (utility pole) Hybrid Fiber Coaxial (HFC) cables throughout the islands and distributed by a series of Fiber Access Points (FAPs).

Wireless communications in the territory come from three primary companies: AT&T, Sprint, and Viya (formerly VI PowerNet). The primary wireless communications infras-

structure enabling cell phone coverage are cellular towers and antennas located across all three islands. Cell towers received communications signal via wireless, microwave transmitters that connect into the hard-line Internet. Each tower has wireless communications transmitters that amplify cellular signal from providers to individual users. AT&T is reported to have the best coverage throughout the territory and has physical assets in the territory providing 4G coverage. Sprint also has assets in the territory but they have a majority of assets focused primarily in the popular tourist areas. Viya is a fairly new company that provides wireline, mobile, internet, and cable television across the territory, and also serves as the Incumbent Local Exchange Carrier (ILEC) which provides the dial tone for the territory (Alderson et al. 2018).

There are also two other main Internet Service Providers (ISPs) in the islands: Broadband VI (BBVI) (primarily in STX) and SmartNet (primarily in STT), along with 12 other small service providers. AT&T was awarded a contract to create FirstNet in 2017 which will be a separate public safety network for public service providers to communicate in the event of another disaster (Alderson et al. 2018). Cell phone coverage varies throughout the territory with many dead spots along major roads, especially in STJ. These areas of no service were further amplified by hurricanes Irma and Maria in 2017.

1.3 Hurricanes Irma and Maria

In September 2017, Hurricanes Irma and Maria caused significant damage to cellular infrastructure, hindering Territorial response and emergency operations.

1.3.1 Hurricane Irma

Hurricane Irma hit the USVI as a Category-5 storm on September 6-7, 2017 and caused catastrophic damage to STT and STJ with maximum sustained winds of 180 miles per hour (Schott et al. 2019; Alderson et al. 2018). People on STJ and other smaller islands were stranded for days because of the damage causing ports to be closed and stopping ferry traffic. The populations of STT and STJ were stranded because of damage to the airports that prevented outbound flights for weeks (USVI Hurricane Recovery and Resilience Task Force 2018). The heavy winds, rain, and flooding resulted in damages to water, wastewater, telecommunications, and power across the territory (Alderson et al. 2018). Utility poles

being knocked down resulted in a blackout for both power and communications across the territory (USVI Hurricane Recovery and Resilience Task Force 2018).

1.3.2 Hurricane Maria

Hurricane Maria hit the USVI as a Category-5 storm on September 20, 2017, and caused the most catastrophic damage to STX, but STT and STJ sustained additional damage during the storm. Many of the gauges on STX were damaged and therefore unable to accurately record storm data but the max recorded wind gusts were 240 miles per hour and the recorded peak water level was 2.8 feet (USVI Hurricane Recovery and Resilience Task Force 2018). Just like Hurricane Irma, Hurricane Maria's heavy winds, rain, and flooding caused significant damage to critical infrastructure and resulted in blackouts of power and communications throughout the territory.

1.3.3 Hurricane Impacts to Telecommunications Infrastructure

After hurricanes Irma and Maria tore through the USVI, much of the critical infrastructure was left damaged, especially the cellular towers and antennas used by AT&T and Sprint. This damage exposed many vulnerabilities in the communications capabilities of the Territory (Alderson et al. 2018). The hurricanes showed that towers, antennas, and internet fiber lines are vulnerable to high winds, copper wire is susceptible to flooding, all cellular network structures are dependent on the power grid, and backup generators depend on unpredictable fuel deliveries to operate (Alderson et al. 2018; USVI Hurricane Recovery and Resilience Task Force 2018). Cellular service also depends on the local ISP for backhaul services that are not always owned by the cellular service provider and are also dependent on the power grid.

These direct failures also revealed interdependent effects across CI systems. In particular, the lack of cell phone service in many areas of the islands resulted in additional traffic congestion on surface roads, because of an increased number of people who were trying to get enough cell phone service to call family and friends. This impeded recovery operations of failed power grid and water systems, as additional traffic slowed infrastructure recovery crews. Together, telecommunications infrastructure, and cellular networks in particular, must be improved to mitigate future damages and support faster recovery to disasters.

1.4 Thesis Goals

The overarching goal of this thesis is to conduct analysis for the U.S. Federal government and USVI Territorial stakeholders to guide Irma and Maria recovery and mitigation efforts. This thesis achieves this goal by curating new infrastructure datasets useful for assessing the function the USVI cellular infrastructure system, conducting analysis of the robustness of this system to infrastructure failures, and recommendations for how to improve system design and operation to be resilient. Specifically, this thesis completes four tasks that help guide future decisions about wireless infrastructure resilience in the Territory. This thesis:

1. Curates infrastructure data for the territory to map and assess cell phone coverage;
2. Develops a model of current cellular phone network coverage in the USVI with Terrain Integrated Rough Earth Model (TIREM)—a Department of Defense (DoD) and industry standard model for wireless signal assessment;
3. Conducts parametric, “what-if” analysis of tower failure to identify what cell phone coverage may look like in future disaster scenarios; and,
4. Produces coverage maps and recommendations for hardening existing systems to future storms.

Ultimately, this thesis develops data, models, and analyses that can be used by project partners at the UVI and at FEMA to build a more resilient cellular phone network. This includes recommendations as to where to construct new towers or where existing towers should be hardened to better survive hurricanes.

CHAPTER 2: Literature Review

This chapter summarizes research on the resilience and hardening of telecommunications infrastructure to hurricanes and other natural disasters. In general, there is significant work analyzing the effects of hurricanes and natural disasters on critical infrastructure. However, the majority of studies tend to focus on other systems, such as electric power generation and distribution or on water distribution pipelines. Communications infrastructure is included in some studies, with the majority of work focused on building more robust and resilient system architectures.

2.1 Telecommunications Infrastructure Resilience

Resilience has a variety of definitions depending on the application. For example, definitions can be as broad as "the capacity for an entity to survive, adapt to and change in the face of disruptions" (Wang and Reed 2017), or as specific as "the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation" (Mauthe et al. 2016). Resilience research covers this breadth of perspectives across all CI systems, including electric power delivery, water distribution, transportation, and telecommunications. Several reviews exist that provide detailed overviews of resilience definitions and measures (Martin-Breen 2011).

A more specific definition for resilience as it relates to telecommunications systems is found in Sterbenz et al. (2013) and is defined as "the ability of the network to provide and maintain an acceptable level of service in the face of various faults and challenges to normal operation." It is widely thought that the current internet structure is not resilient enough to handle current demands in modern society and future designs for internet systems need to be much more resilient. The paper also mentions four key components of internet resilience that are necessary in future internet constructs: dependability, performability, survivability, and disruption-tolerance. Dependability refers to the network working in normal operations, performability refers to the level of performance of the network when it is stressed, survivability refers to the network's ability to tolerate failures from attacks or natural disasters, and disruption-tolerance refers to the ability of the network to communicate even when

network paths are lost or connection is weak (Sterbenz et al. 2013).

2.2 Telecommunications Infrastructure in Disasters

Communications networks have shown to be critical in times of natural disasters and disruptions to them can significantly affect local societies and economies afterward. Network challenges can take a variety of forms, from the obvious large natural disasters like hurricanes or earthquakes, to social and/or political challenges that can arise from malicious military acts or from acts of terrorism, to unusual network traffic volumes that cause certain parts of the network (e.g., a cell phone tower) to be overloaded (Mauthe et al. 2016). Mauthe et al. (2016) describe challenges to communications networks and their dependency on other civil infrastructure to function, specifically noting power generation systems as a dependency. Alderson et al. (2014, 2015) further suggest that resilience must be understood in a structural and operational manner. From a structural view, a resilient network should have redundancy and diversity to provide alternate routes for network traffic. In practice, this means deploying additional cell phone towers and a variety of antennas because some may survive certain conditions better. From an operational view, a network needs anomaly detection capabilities and a way to rapidly recover from an anomaly so service levels remain the same (Mauthe et al. 2016).

Khaled and Mcheick (2019) provide an overview of how the lack of communications in extreme environments, such as immediately following natural disasters, amplifies disaster impacts and slows down or stops recovery efforts. Failure of communications can result in several ways, such as physical damage or from increased network traffic causing an unintended denial of service attack — when the network can't handle the increase of post-disaster traffic even if the system is not physically damaged. Khaled and Mcheick (2019) describe this scenario by defining the potential risks and consequences from extreme dependence on communications infrastructure, examining communications during different extreme conditions, and recommending actions for infrastructure improvements. According to Khaled and Mcheick (2019), the top three ways communications infrastructure fail are:

1. destruction of the systems themselves,
2. damage to infrastructure supporting the systems, and
3. congestion from increased network traffic.

All these failure types can also occur in combination and can become a significant hindrance to recovery efforts.

Khaled and Mcheick (2019) also provide a general discussion of diverse emergencies on telecommunications infrastructure, including the attack on the World Trade Centers in New York in 2001, the Indian Ocean earthquake in 2004, the Haiti earthquake in 2010, the eastern Japan earthquake in 2011, and the Nepal earthquake in 2015. All disasters reduced the function of telecommunication systems in three common ways: destruction of systems, power outages, high congestion on the remaining functional parts of the network (Khaled and Mcheick 2019). Primary recommendations for most cases was hardening of structures. Additional disaster-specific recommendations for earthquakes (that could also be beneficial for hurricanes) was an early warning system that could alert prior to disasters.

Beyond broad case studies across telecommunications systems, research also focuses on the idiosyncratic differences in the effects of disasters on wired and wireless systems.

2.2.1 Wired Communications

Research shows that disasters can have significant impacts on wired communications networks, with specific attention on fiber optic (optical) networks. In general, optical networks are the network backbone for the world and carry 99% of internet traffic. Disaster models are used for optical networks to assess possible risks and translate those into financial impacts and recommendations for network improvement before a disaster strikes (Ashraf et al. 2018).

One important avenue of research in wired communications is measuring cascading failures that involve infrastructure losses in one network layer, e.g., physical failures (layer 1), cascading into higher-level network layers, e.g., the Internet Protocol (IP) link (layer 3). An increasingly complex optical network (layer 1) is more susceptible to local failures that can quickly propagate across geographic regions and into upper network levels. The risks of natural disasters worldwide have led to an increase in the need for resilient network infrastructures that can adapt to spatial disaster-based failures. Ashraf et al. (2018) summarize various issues that affect optical networks in the event of disasters, with emphasis on cascading failures. The authors determine that predicting the spatial impact of disasters enables better protective measures to prevent cascades in the digital stack (Ashraf et al.

2018). Simple optical networks are particularly prone to cascades across layers, such as the fiber optic network in the USVI where all FAPs are connected in a series so one failure breaks the chain and causes a failure in all successive FAPs (for a contemporary discussion relevant to the USVI, see Moeller 2020). Ashraf et al. (2018) also identify that network traffic congestion after a natural disaster is a common issue. The authors recommend having spare capacity and/or new routing protocols in place to handle the excess traffic experienced after a disaster. Moreover, there need to be plans in place to support network recovery and to reduce network congestion (Ashraf et al. 2018).

2.2.2 Wireless Communications

Significant research shows the similarities and differences in how disasters affect wireless networks from other telecommunications systems. Wireless networks are unique because their function is based on signal coverage rather than physical connection. Thus, wireless networks are impacted directly by physical damage to transmitters and towers (similar to optical networks), but are also impacted by changes in the local environment that change line-of-sight to receivers or lead to novel customer demands (e.g., due to population displacement). Moreover, wireless systems are perhaps more important for immediate disaster response to support emergency operations communications than any other telecommunications system.

Some research focuses on the response of particular wireless technologies to disasters. For example, several authors study the resilience 5th Generation Mobile Networks (5G), because they are designed to provide reliable, low-latency communications compared to current mobile networks. Esposito et al. (2018) show that the perceived benefits of 5G do not prevent communications loss and can still lead to cascading effects. For example, 5G utilizes millimeter-wave bands, which can offer large bandwidths and facilitate the implementation of complex antenna arrays, but millimeter-waves have poor propagation resulting in shorter coverage range compared to current 4th Generation Mobile Networks (4G). The safety of a network relies heavily on the physical infrastructure, which will likely require more infrastructure to handle the shorter propagation ranges. In contrast, so-called “softwarization” of the network is one of the new capabilities of 5G that seems to provide self-healing network options that allow networks to recover quickly after disasters to provide vital communications for the post-disaster environment. Still, with increased

softwarization security becomes a greater concern for 5G as there is greater potential for non-physical vulnerabilities to be exploited to attack the network (Esposito et al. 2018).

2.3 Model-Based Approaches to Estimate Wireless Communications during Disasters

This thesis focuses on model-based approaches to estimate cellular network coverage during normal operations and disaster scenarios. During normal operations, the most common way to estimate wireless network coverage is to use radio frequency models of *path loss* to measure the wireless signal strength from a given transmitter (e.g., cell tower) to a receiver (e.g., cell phone). Kumar (2011) defines path loss as the reduction in power density of an electromagnetic wave as it propagates through space. In essence, path loss refers to the loss of signal over a given path between transmitter and receiver, where wireless communications become impossible once signal drops below a certain threshold. Path loss is dictated by a number of physical factors, including Line of Sight (LOS), the electromagnetic characteristics of the earth, and the interaction between radio waves and air. In general, path loss calculation focus on measuring two values:

1. *Free space path loss*: path loss between transmitter and receiver without any obstructions, i.e., based entirely on radio propagation models and local geologic and electromagnetic characteristics.
2. *Excess path loss*: path loss between transmitter and receiver caused by obstructions in LOS and/or additional factors that impede wireless signals.

There are a variety of different path loss models that can be characterized based on their input parameters and use. For example, Kumar (2011) classifies different path loss calculation software by separating them into two categories: empirical models and physical models. Empirical models use measurement data to develop a path-loss equation to then calculate path loss. Empirical models generally have faster execution and do not rely on detailed knowledge of the terrain. Examples of empirical models include Free Space + Reflection plus Multiple Diffraction loss (RMD) and the Okumura (Hata) Model (Kumar 2011). Physical models use the laws of physics that govern electromagnetic wave interaction combined with physical elements of the propagation environment and because of this require extensive databases of information; examples include: TIREM and LOS or obstructed path

models (Kumar 2011).

Siraj and Kanrar (2012) also characterize various propagation models based on data inputs and how they consider the physical characteristics of radio waves. Specifically, Siraj and Kanrar (2012) describe path loss models with increasing complexity, from preliminary, physics-based models, to simulation-based models that incorporate detailed information about transmitters and receivers. For example, “simple” path loss models include the free space model which solely looks at wave propagation if LOS exists and the two ray ground model that includes LOS and ground reflection in signal calculation. More complex models include total path loss (i.e., free space path loss + excess path loss) that combines LOS propagation, troposcatter loss, and diffraction loss. Examples of these more complex models include the Rician Fading Model, the Longley Rice Model, and TIREM. Finally, simulation models are the most complex which simulates the transmitter and receiver for an electromagnetic wave propagation.

2.3.1 Wireless Mesh Networks

The function of a wireless network after a disaster depends on both existing infrastructure systems (e.g., cell towers) *and* rapidly deployed transmitters to form new networks and recover failed systems. These ad-hoc networks form a novel way wireless communications can respond to disasters that is unavailable to many other CI systems. In particular, several authors have used models for path loss to inform the design and robustness of Wireless Mesh Networks (WMNs).

Nicholas (2009) defines WMNs as systems of wireless access points interconnected in a mesh to provide digital services to client devices via radio transmission. The author used physical models to maximize client coverage given constraints on network service, quantity and technical capabilities of access points, the environment, and radio propagation over terrain. The first major subproblem in Nicholas (2009) calculates client coverage utilizing TIREM given the access point (cell tower) locations, operating characteristics, and terrain and environment information.

Nicholas and Alderson (2018) expand on the discussion of WMNs and look at their robustness to infrastructure failures with a Defender-Attacker-Defender (DAD) model. The DAD model estimates worst-case coverage failures for a WMN when the networks are op-

erating in hostile environments filled with jamming and interference. The model developed by Nicholas and Alderson (2018) minimizes the worst-case coverage short-falls given an intelligent adversary trying to maximize path loss. While the basis for this model is to minimize the effects of intelligent adversaries, the results of this model provide general guidance on the robustness of WMNs. Thus, although the USVI is primarily threatened by natural disasters, DAD modeling can determine worst-case combinations of infrastructure failures and vulnerabilities in existing network architecture. Nicholas and Alderson (2018) also produce coverage maps relevant to help stakeholders identify coverage shortfalls and areas that require network improvement.

2.4 Our Contribution

We build on the work of Nicholas (2009) and Nicholas and Alderson (2018) to assess the robustness of cellular networks in the USVI. We model the path loss between cell phone towers and customers in the Territory using the physics-based model TIREM. We use an algorithm to determine coverage maps for each cell tower on each island in the Territory. The combined coverage maps give a snapshot of current cell reception in the territory when all infrastructure is available. Then, we estimate the impacts of disasters by measuring coverage shortfalls on STX, STT, and STJ given the loss of a single cell tower at a time on each island. Together, this analysis provides important information on which cell towers are critical for cell phone reception and should be hardened to survive future disasters. Moreover, it provides an important foundation to estimating the optimal deployment of WMNs in the territory after a disaster strikes and damages infrastructure.

Overall, the contributions of this thesis are (i) development of a novel data set to assess cell phone coverage in the USVI, (ii) algorithms to use the TIREM path loss model in the Python Programming Language and generate cell coverage maps, (iii) coverage maps for the USVI Territory when all infrastructure is available and during disasters, and (iv) recommendations to improve the robustness of the wireless network in the USVI to large-scale disasters.

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CHAPTER 3: Methods

This chapter provides an overview of the methods used to model cell phone coverage in the USVI.

3.1 Terrain Integrated Rough Earth Model (TIREM)

To calculate the wireless coverage at any given point in the USVI, we use the TIREM software library (Alion Science 2017). TIREM was originally created in 1967 and has continued to be enhanced, maintained, and updated by Alion Science (2017) since that time. TIREM is currently the de facto Radio Frequency (RF) propagation software for the U.S. Government (USG) (Alion Science 2017). The primary purpose of TIREM is to estimate RF propagation loss from 1 MegaHertz (MHz) to 1 TeraHertz (THz) over varied terrain for both ground and air-based receivers and transmitters utilizing techniques of free-space spreading, reflection, diffraction, surface-wave, tropospheric-scatter, and atmospheric absorption (Alion Science 2017). TIREM provides the foundation for the Advanced Systems Planning, Engineering and Evaluation Device (SPEED) developed by Northrop Grumman for the U.S. Marine Corps in 2013.

Figure 3.1 illustrates the basic input-output relationship for TIREM. Essentially, TIREM takes a variety of factors such as elevation, environment data, and technical data from the antennas as inputs and generates total path loss, total free space loss, and received signal strength as outputs. The following subsections describe the inputs and our assumptions about them in more detail.

Input 1: Antenna Height Transmitter. According to the Department of Defense (1994), the acceptable inputs for transmitter antenna height are heights up to 30,000 meters and the values must be non-zero. The data from the Federal Communications Commission (FCC) has all the heights of the registered antennas, listed as the height above ground level. There is enough variation in these values that assumptions can be made for heights for future antenna locations for the disaster scenario analysis based on where the antennas are located and how large of an area needs service. For other towers added to the FCC data, we assume

Terrain Integrated Rough Earth Model (TIREM)

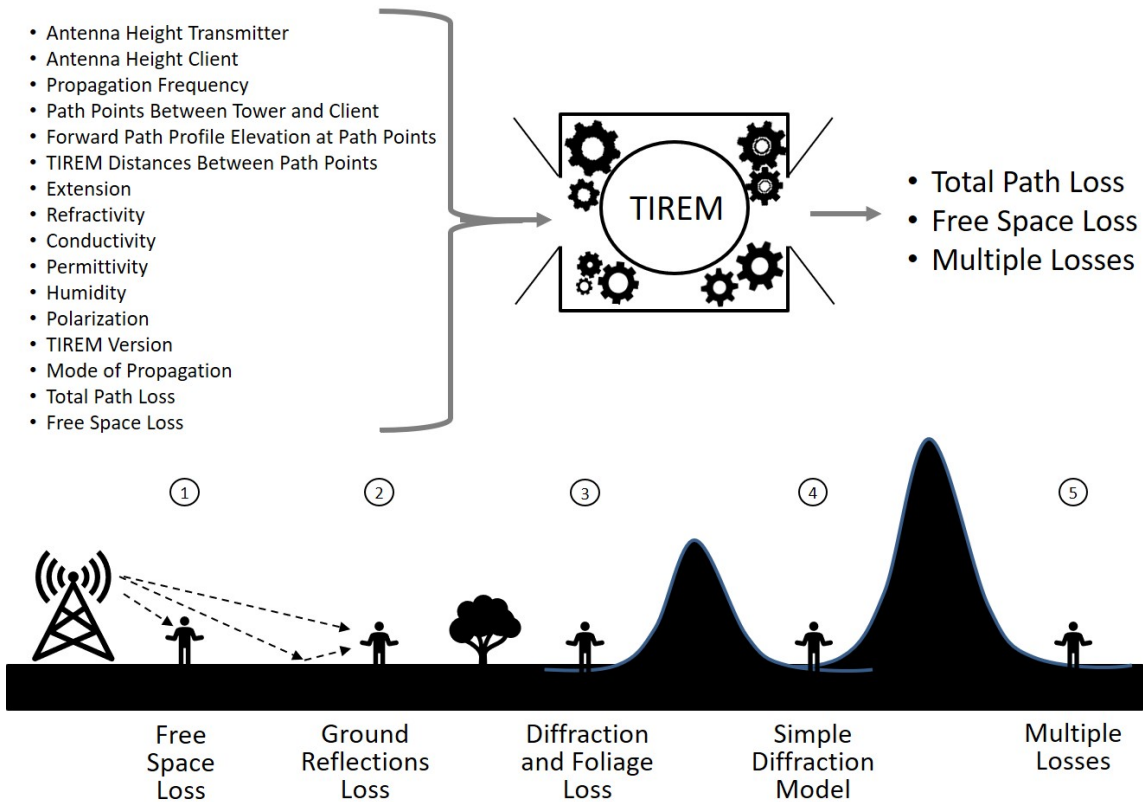


Figure 3.1. Overview of TIREM. Given a multitude of inputs, the model computes signal losses in a variety of scenarios: (1) direct LOS, (2) direct LOS with ground reflections, (3) losses due to diffraction and foliage, (4) losses due to elevation obstruction, and (5) combinations of all these.

a height of 50 meters and keep other parameters (polarization, frequency, etc.) the same as other towers. Another assumption we make is that the antennas are at the top of the towers, this allows us to use the total tower height and removes the estimation of how far below the top of the tower the antennas are mounted which varies by tower, service provider, and antenna type (cell phone antennas are not the only antennas on most of the towers).

Input 2: Antenna Height Client. The client antenna height is the network user; usually, this would be a person holding a cell phone, tablet, or other mobile device. This would vary depending on a person's height, but for the sake of simplicity we assumed 1.7 meters to make an average height because in the end, the client height will likely not affect the

received signal strength as significantly as distance from the transmitting antenna and the elevation profile between transmitter and client.

Input 3: Propagation Frequency. Current cell phone networks are classified as 4G Long Term Evolution (LTE) and have a range of propagation frequencies that they operate within for normal network transmissions. Department of Defense (1994) lists that the propagation frequency the software will accept has to be between 1 and 20,000 MHz which is equivalent to 0.001 to 20 GigaHertz (GHz). The common propagation frequencies for LTE as listed in Sauter (2013) are: 791-960 MHz, 1710-1880 MHz, and 2500-2690 MHz. For both initial testing and the full model, we use 2000 MHz because it is in the center of the ranges and where LTE is likely to broadcast because higher frequencies can have higher bandwidth but span a shorter distance.

Input 4: Path Points Between Tower and Client. This determines how fine of a mesh TIREM looks at for the elevation profile between the tower and the client. The number of points needs to be a minimum of 3 but there is no upper limit other than whatever amount the computer can handle (Department of Defense 1994). For relatively flat ground, this could be a coarse path (e.g., with 10 points between the tower and the client) because there aren't any significant hills to cause disruptions so total path loss \approx free space path loss. For more complex terrain, total path loss \gg free space path loss, and few path points will not provide accurate path loss calculations. Here, a larger sample size (e.g., 500 points) would be more appropriate to accurately account for changes in elevation and surface conditions. The general rule is more elevation change and higher population requires a finer path while little elevation change and low population requires a coarser path.

For our analysis, we use a number of path points related to the distance from the transmitter to the receiver. In particular, we assume a sample rate of 40 m between path points to capture changes in elevation. This approach results in TIREM calculations with few path points (near the transmitter) and many path points (far from the transmitter).

Input 5: Forward Path Profile Elevation at Path Points. This is the surface elevation data for each intermediate path point used to calculate path loss. This is input into TIREM as an array of elevations above mean sea level and each elevation must be between -450 and 9,000 meters (Department of Defense 1994). The elevations are sampled using a dynamic elevation model with 3m by 3m accuracy of the USVI Territory provided by the U.S.

Geological Survey (USGS) The National Oceanic and Atmospheric Administration (NOAA) Office of Coastal Management (2014). Elevation is sampled for each path point along the azimuth between transmitter and receiver. The resulting forward path profile array is input into TIREM.

Input 6: TIREM Distances Between Path Points. The distances between path points are an array representing the total distance from transmitter to the path point along the azimuth from the cellular transmitter to receiver. Each distance within the array must be greater than or equal to zero (Department of Defense 1994). For our analysis, we assumed a distance of 40 m between all path points. However, distances between path points can vary.

Input 7: Extension. This parameter is a Boolean parameter where True means the profile is an extension of the last path along a radial and False means it's a new profile (Department of Defense 1994).

Input 8: Refractivity. The surface refractivity of the Earth influences radio wave propagation. For TIREM, this input must be between 200 and 450 Newton-units (Department of Defense 1994) state. For refractivity, we assume 300 Newton-units, according to Nicholas (2009).

Input 9: Conductivity. This parameter is the conductivity of the Earth's surface which must be entered between 0.00001 and 100 Siemens per meter (Department of Defense 1994). For conductivity, we assume 50 Siemens per meter (Nicholas 2009).

Input 10: Permittivity. The permittivity is how reactive an environment is to the application of an electromagnetic field, such as a propagating radio wave. Department of Defense (1994) lists this parameter as relative permittivity, putting it on a scale of 1 to 100. We assume the permittivity of the USVI to be 25 (Nicholas 2009).

Input 11: Humidity. This parameter is the surface humidity at the transmitter site and must be between 0 and 50 grams per cubic meter (Department of Defense 1994). The surface humidity in the USVI varies but for simplicity, we assume a uniform humidity of 75% which equates to approximately 18 grams per cubic meter.

Input 12: Polarization. Polarization of radio antennas can either be vertical or horizontal. In TIREM, this parameter is simply “V” or “H”, respectively, to denote which polarization is used by the transmitting antenna (Department of Defense 1994). Given the varied elevation profiles (vertical has best propagation for antenna heights lower than 100 meters), the urban areas with other broadcast types (television and broadcast radio are usually horizontal polarization), and for model simplicity, we are assuming vertical polarization for all antennas. However, in practice, each tower could be configured differently or, as mentioned in Sauter (2013) and in Cox (2014), each tower could have two antennas one vertical and one horizontal. The two separate polarization types will not interfere with each other as cell phones are omnidirectional transmitters and receivers because the user is frequently changing position.

Input 13: TIREM Version. This is the version of TIREM being used and is input using a version() function. We use version “b” for this model which corresponds to TIREM 3.18.

Input 14: Mode of Propagation. This is the mode of propagation and refers to either a rough earth model where terrain is taken into account or a smooth spherical earth model such as is used for calculating losses over bodies of water or at sea level (Department of Defense 1994).

Input 15: Total Path Loss. When calculating path loss by Extension, this value is an input to TIREM for current losses at the initial transmission point. For calculations originating from the transmitter, this input is assumed to be 0.0 Decibel-milliwatt (dBm).

Input 16: Free Space Loss. When calculating path loss by Extension, this value is an input to TIREM for current free space losses at the initial transmission point. For calculations originating from the transmitter, this input is assumed to be 0.0 dBm.

Additional Parameters There are a few additional parameters that are used in the calculation but are not explicitly listed in the inputs in the Department of Defense (1994) and these include the transmitter power in dBm, the fade margin in dBm, and the antenna gain in dBm. Typical transmitter power for cell towers is between 10-20 Watts (W) according to Sauter (2013) which equals 40-80 dBm so, initially, we assumed full power or 80 dBm but then we scaled it back after looking at the coverage maps because 60 dBm was more realistic when compared with the coverage maps from 2014. The antenna gain is the ratio of

radiation intensity in a particular direction to the radiation intensity in that direction using an isotropic radiation pattern and for this model we assume the gain is 2 dBm (Nicholas 2009). The fade margin is used to account for huge propagation uncertainties and is used to compensate for the cumulative effects of all signal losses that aren't estimated with TIREM so for this model we assume that the fade margin is 0 dBm (Nicholas 2009).

Output 1: Total Path Loss. The initial value input as total path loss is replaced by the calculated value when running TIREM. This is the primary output, combining free space loss, ground diffraction loss, and multiple losses into one overall loss value in dBm. This value can be used to calculate received signal strength when subtracted from the sum of the antenna gain and the transmitter power.

Output 2: Free Space Loss. The initial value input as free space path loss is replaced by the calculated value when running TIREM. This is the secondary output, and is the loss from wave propagating through the air over the total distance from transmitter to client.

Output 3: Multiple Losses. These are the losses from all means other than free space loss and are included within the total path loss value. For this thesis, the focus is on the total path loss rather than the various types of losses.

3.2 Data Processing, Input, and Computation

The primary output from TIREM is a point-to-point path loss. Several data processing, input, and computational challenges were overcome prior to producing outputs from TIREM for the USVI.

3.2.1 Model Assumptions and Input parameters

Data for analyses was determined using a combination of publicly available data sets and on-site observation.

Tower Locations and Antenna Heights

First, tower location and height data were acquired from the FCC database of registered antennas for the entire U.S. (Federal Communications Commission 2014; National Telecommunications and Information Administration 2014). Individual data sets were acquired for

each of the islands in the USVI. The data was originally condensed into a Comma Separated Values (CSV) file and was then input into QGIS as a GeoJSON file to view the locations on a map.

Tower locations were verified in person utilizing geo-tagged photographs taken from cell phones and a paper copy of a map with grid squares during a visit to the USVI from February 2-8, 2020. All towers were mapped across all three islands. The site visit helped put the importance of coverage in perspective and gave a better sense of the terrain that coverage had to be able to traverse, especially in STT and STJ where service could be degraded from one hill to the next. In addition, locations without service were identified on the north western coasts of STX and STT and from multiple locations in STJ. Examples of some of the towers that were located while visiting the USVI are in Figure 3.2, note that some were stand-alone structures, while others were just mounted on top of buildings depending on the location, also the number of actual antennas per tower varied greatly.

Together, the locations of towers determined using online and in-person verification for STX are presented in Figure 3.3 and for STT and STJ in Figure 3.4. These locations are used as transmitter locations for TIREM calculation. The tower numbers presented in Figures 3.3 and 3.4 are provided by the FCC and used to describe towers for the remainder of this thesis.

Territorial Topography and Surface Elevation

We processed and analyzed a Dynamic Elevation Model (DEM) for each island in the USVI to generate path profiles and determine obstructions between cellular transmitters and receivers. We acquired a USGS DEM data set from the UVI. The data set was provided in a Tagged Image File Format (TIFF) file type and was input into Python using the `rasterio` Python package (MapBox 2016). The underlying data was originally developed in the EPSG32620 Coordinate Reference System (CRS), and needed to be converted to WGS84 for analysis. We used the C-library and associated Python package Geospatial Data Abstraction Library (GDAL) for DEM conversion (Warmerdam et al. 1998). The resulting elevation models used for analysis are presented in Figures 3.5, 3.6, and 3.7.



Figure 3.2. Examples of Cell Towers in the USVI.

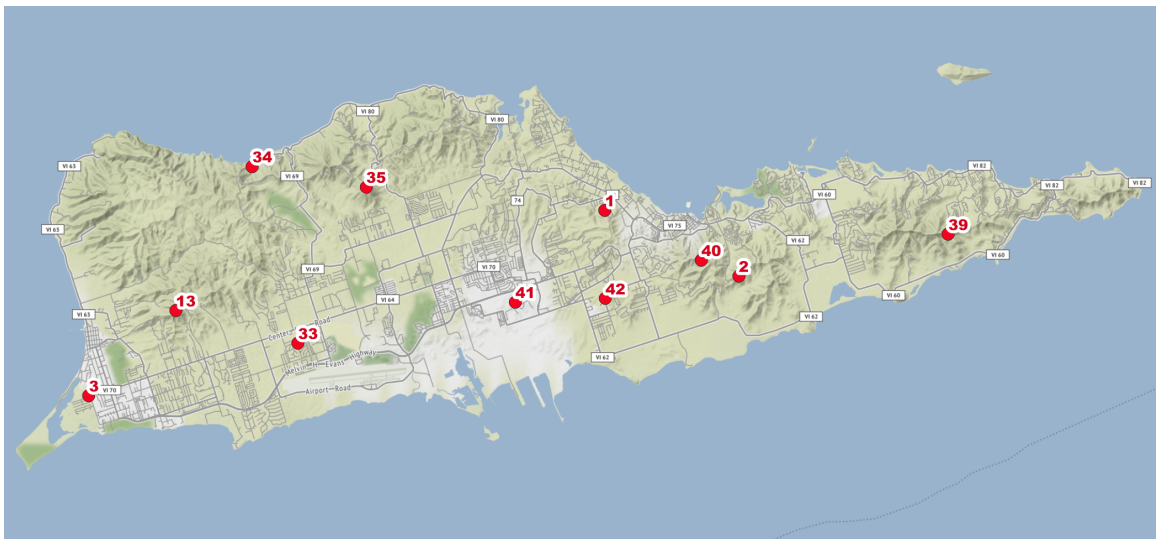


Figure 3.3. Cell Phone Tower Locations on STX.

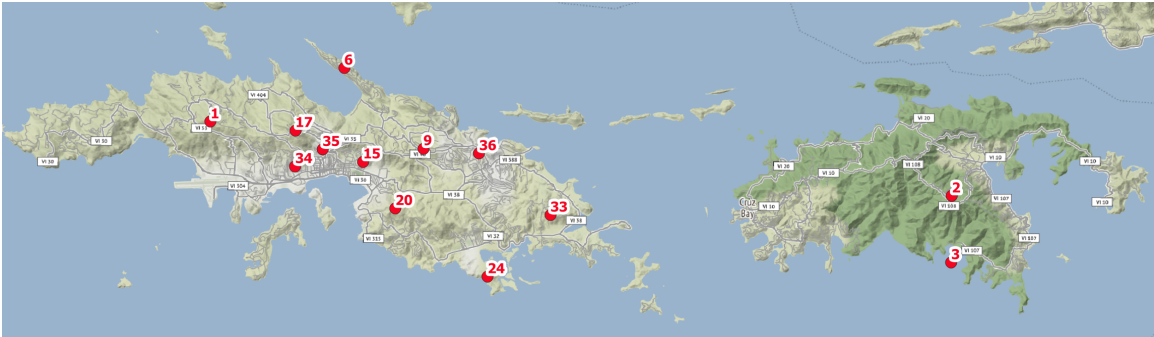
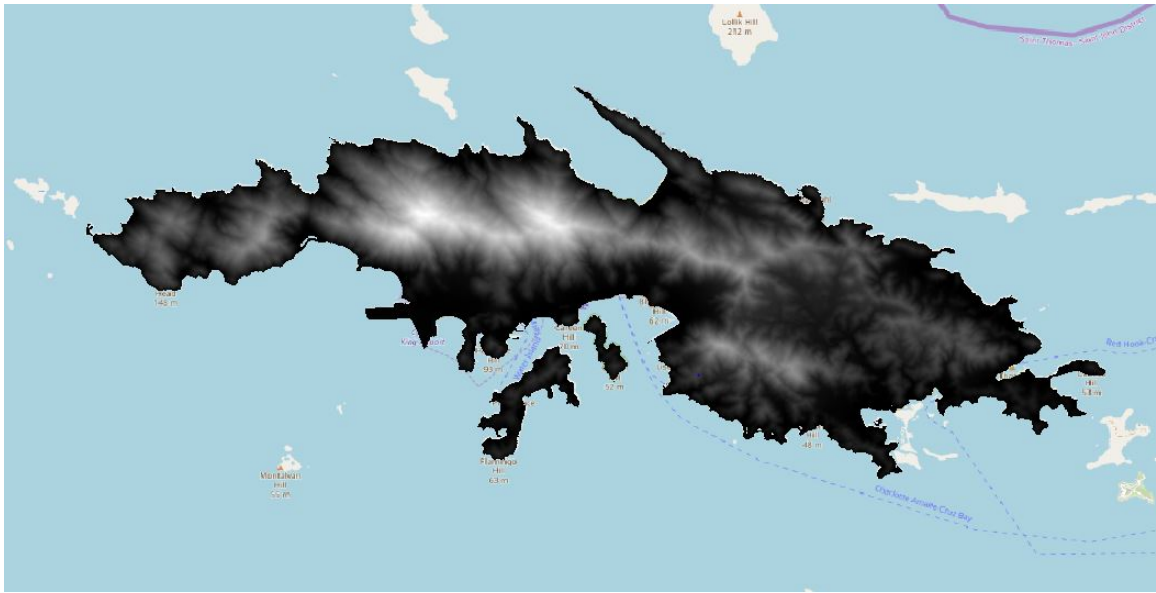


Figure 3.4. Cell Phone Tower Locations on St. Thomas and St. John.

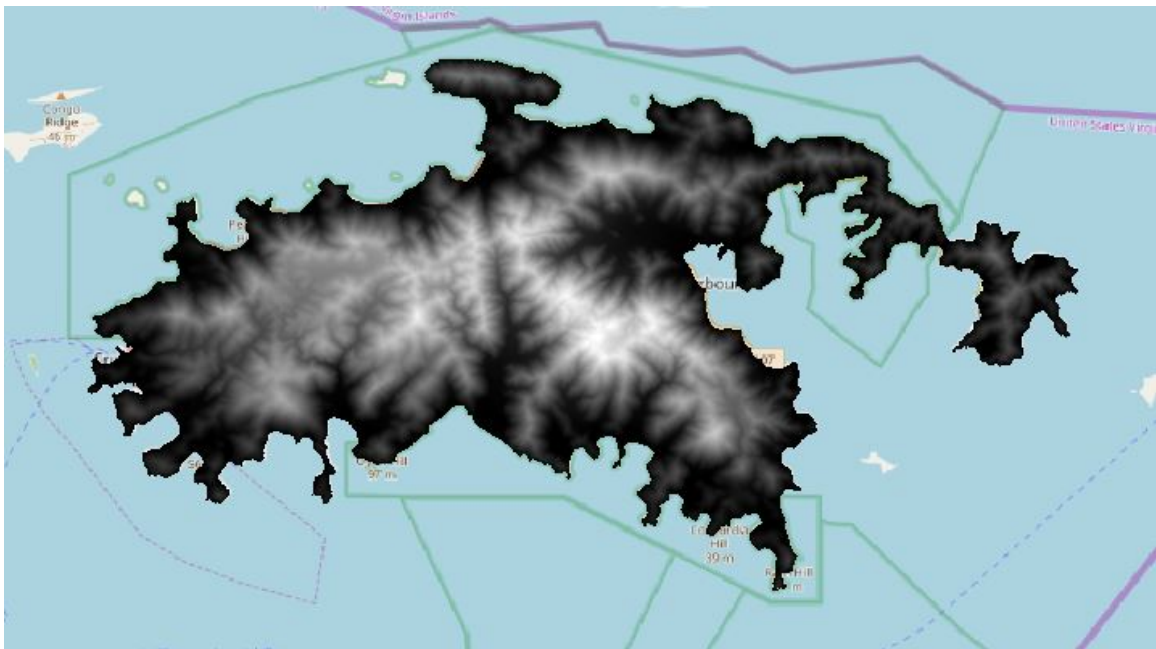


Source: NOAA Office of Coastal Management (2014).

Figure 3.5. USGS 3m Dynamic Elevation Model for St. Croix.



Source: NOAA Office of Coastal Management (2014).
 Figure 3.6. USGS 3m Dynamic Elevation Model for St. Thomas.



Source: NOAA Office of Coastal Management (2014).
 Figure 3.7. USGS 3m Dynamic Elevation Model for St. John.

Additional Data Assumptions and Input Parameters

Additional data from the FCC was read into the Python Programming Language (Python Software Foundation 2001) for cleaning and input to TIREM. All data was imported into Python as a GeoPandas DataFrame for processing and analysis (GeoPandas Developers 2013). Included in the data is the status of each tower, indicating which of them were operational. Each tower with the status flag “Cancelled”, “Dismantled”, or “Terminated” were removed from the data set. Location data was provided as degrees, minutes, seconds, and direction but also in the NAD27 CRS and the WGS84 CRS. In addition, the site elevation, height above ground level, and height above sea level were provided in meters along with the geometry object from GeoPandas. Additional data acquired from the FCC included tower geolocation, the height above ground level (the tower/antenna height), and the geometry object. New columns were added for transmitter frequency, polarization, elevation, total path loss, total free space loss, difference between path and free space, and the received signal strength. The data was then output to a GeoJSON file (Internet Engineering Task Force 2016) for storage and analysis.

We make the following assumptions for each cellular tower within the USVI :

- antenna gain is assumed to be 2 dBm for all towers;
- transmission power is assumed to be uniform but the most common transmission power for cell tower antennas is between 10 and 20 W (i.e., 40-80 dBm) (Sauter 2013);
- the combination of transmission power and gain is assumed to be 62 dBm for all towers; and,
- the receiver antenna (e.g., customer cell phone) is assumed to be 1.7 m, roughly the height of a person standing up.

Table 3.1 summarizes the assumed input parameters.

Table 3.1. Table of Assumed Input Parameters for TIREM Model Computation

Input	Name	Value
Input 1	Antenna Height Transmitter	Varies by Tower
Input 2	Antenna Height Client	1.7 m
Input 3	Propagation Frequency	2000 MHz
Input 4	Path Points Between Tower and Client	Varies by Method
Input 5	Forward Path Profile Elevation at Path Points	From Elevation Data
Input 6	TIREM Distances Between Path Points	20 m
Input 7	Extension	FALSE
Input 8	Refractivity	300 N-units
Input 9	Conductivity	50 S/m
Input 10	Permittivity	25
Input 11	Humidity	18 g/cm ³
Input 12	Polarization	V
Input 13	TIREM Version	Function - version()
Input 14	Mode of Propagation	Function - mode()
Input 15	Total Path Loss	0.0 dBm
Input 16	Free Space Loss	0.0 dBm
Additional 1	Antenna Gain	2 dBm
Additional 2	Fade Margin	0 dBm
Additional 3	Transmission Power	60 dBm

This table summarizes the assumed values for all parameters input into TIREM for analysis in this thesis. The primary outputs are total path loss and the free space loss for each pair of transmitter-client sample points.

3.2.2 Computational Challenges

There were a number of additional computational challenges to overcome. First, our version of TIREM was not a Python package, but instead a Windows Dynamic Link Library (DLL) written for an x86 (32-bit) architecture. All analyses had to be completed on a Windows machine with the appropriate Python version and architecture. This means all computations were run on a personal Windows computer and could not utilize on-campus Linux-based super-computing resources. All associated analyses and computational algorithms were developed with this limitation in mind.

The second challenge was determining the internal functionality of the TIREM DLL and using the appropriate Python conversion packages to access, send input data to, and extract output data from the DLL. The first part of this challenge required the use of Dependency Walker (Microsoft 2015) to determine which additional DLLs TIREM depended on to function. In this process, a second DLL for internal Fortran computations was discovered as a dependency and acquired. The second part of this challenge was identifying the input and output parameter types required by the DLL to calculate total path loss. This was achieved by decompiling and comparing Python code written in Python 2.7.x that accessed the TIREM DLL with C-programs that use TIREM with JetBrains DotPeek (JetBrains 2011). Finally, the third part of this challenge was sending the appropriate datatypes to TIREM from Python. This was achieved using the ctypes Python Package to convert Python objects into C objects and then calling the TIREM DLL with ctypes functions.

3.3 Coverage Map Generation, Validation, and Analysis

The primary outputs for this thesis are coverage maps for each cellular tower in the USVI and composited maps for each island. Coverage maps show the signal strength provided by a tower at a series of locations within a geospatial area. Signal strength is calculated using the total path loss output from TIREM and subtracting transmission power and antenna gain.

3.3.1 Coverage Map Generation

There are many ways to generate sample points for TIREM analysis and associated coverage maps for a region. The elevation raster data could effectively generate a coverage map for

each 3m x 3m grid across all islands (NOAA Office of Coastal Management 2014). While this gives the finest possible mesh and a highly accurate coverage map, this also is very computationally intensive. Instead, we tested two methods to upscale elevation data to a more computationally effective method: (1) a signal “sweep” method that generates sample points radiating around a cellular tower in a circle, and (2) a signal “grid” method that generates sample points from a lower-fidelity rectangular mesh grid overlay of each island. We present the pros and cons of each method for analysis and validate both against publicly available coverage data.

Signal Sweep Method

The signal sweep method generates a 360° circle around a tower then samples equal distance increments along each azimuth away from the tower. We use 1° radial increments to generate 360 azimuths and sample distance increments along each azimuth to a maximum distance of signal propagation based on tower height and the curvature of the Earth. In general, we utilized between 500 to 1,000 intermediate sample points along a single azimuth to accurately account for the distance that the tower can propagate signal and the elevation profile of the region. This approach takes approximately 6-10 minutes per tower to generate a coverage map with a personal laptop depending on the number of sample points along each azimuth.

This method has issues related to model accuracy and reproducibility that make it non-ideal for coverage analysis. This method generates high-fidelity signal results near each antenna and lower fidelity results far from the tower with fast computation. This is generally sufficient for signal tower analysis as model-based coverage maps far from a tower are less accurate than those near the tower. However, due to the curvature of the Earth and increasing separation distance between each azimuth far from the tower, it is computationally and mathematically difficult to compare coverage maps of many overlapping towers.

For these reasons, we use the signal sweep method to validate TIREM input parameters for individual towers, but do not use it to compare coverage for multiple towers simultaneously or analyze coverage results.

Signal Grid Method

Because of the issues with the signal sweep method at greater distances and to help make the model uniform for all towers, we use a signal grid method for analysis. The signal grid method uses a fixed grid of points to generate a signal map that is lower-fidelity overall, but is consistent from tower to tower to enable comparison and analysis. For this method, we generate a mesh grid of polygons of size 0.001 degrees latitude and longitude that covers the entirety of each island and some of the surrounding ocean (set to zero elevation). This grid generates rectangles that are approximately 40m by 40m over the entire Territory. We use the grid centroids as the sample points for input into TIREM. Even though this method is more coarse than signal sweep, it generates a large set of sample points (~40,000 for STX and ~60,000 for the combined grid of STT and STJ). Thus, computation using the grid method is longer than the signal sweep, taking between 30-50 minutes per tower on a personal laptop.

This method has particular benefits useful for analysis. First, we can use the same mesh grid as sample points for every tower on each island, so the coverage maps can be compared on a one-to-one basis. Moreover, the sample points (i.e., grid centroids) are easily related to a geo-located polygon to relate coverage results to other objects in the territory like buildings. This point-to-polygon translation is necessary for analysis.

Coverage Map Visualization

For both the signal sweep and grid method, we define three decibel bands that correspond to good signal, medium signal, and no signal. We use these bands to generate maps that identify regions with and without signal. Specifically, we assume that cellular signal above -65dBm is a “good” signal, where normal cellular phones should have enough signal strength for all wireless communication needs. For all coverage maps, we present this region with the color green. We assume that cellular signal between -85dBm and -65dBm is a “medium” signal, where normal cellphones will likely receive telephone signal, but may not have strong enough connectivity for internet and other services. We present this region as the color yellow. Finally, any signal worse than -85dBm is left uncolored and assumed to be such a bad signal that it is essentially background noise that does not support any telecommunications.

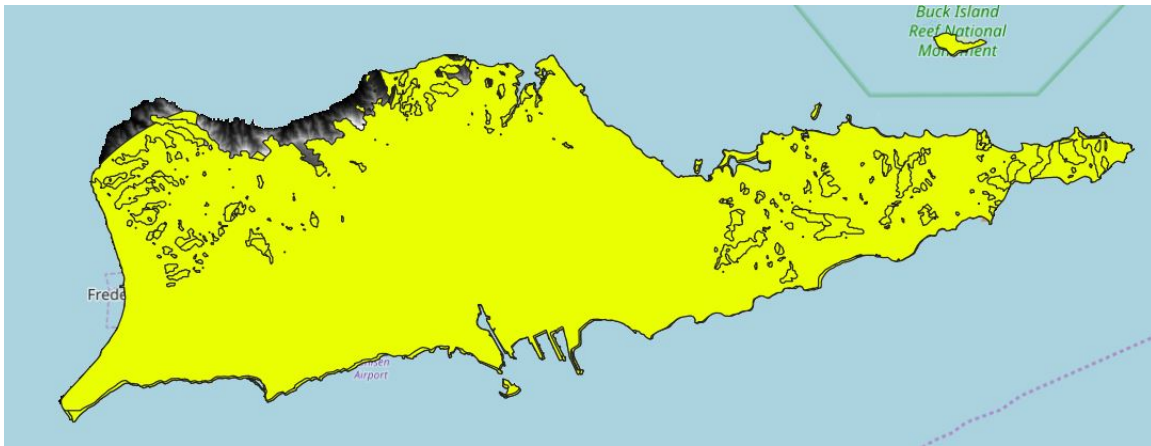
3.3.2 Coverage Map Validation

We compare both sweep and grid methods to National Telecommunications and Information Agency (NTIA) coverage data sets to determine final methods for analysis.

National Telecommunications Infrastructure Agency Coverage Maps

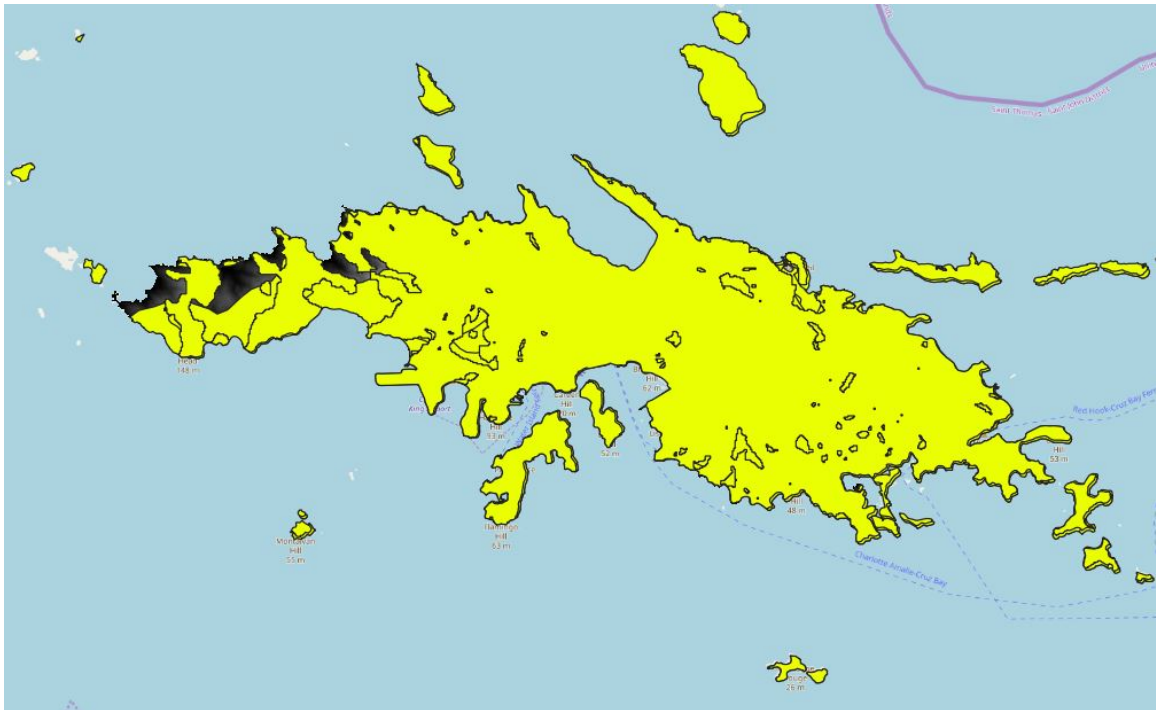
We use cellular coverage maps for 2014 from the NTIA to compare model-based coverage map generation methods. The NTIA data is separated by the cellular service provider. In 2014, AT&T coverage maps showed perfect coverage for all three islands. However, perfect coverage is not actually experienced on any island. During on-site validation with AT&T providers, cellular coverage was lost when traveling to more remote regions on each island. Here, non-AT&T service providers show gaps in coverage on all three islands. For these reasons, we use non-AT&T coverage maps.

Figures 3.8, 3.9, and 3.10 show non-AT&T coverage maps for 2014. Each map shows regions of low to no cellular signal coverage used to test and validate results generated with TIREM. In STX, key coverage gaps exist along the northwestern coast and along the eastern island panhandle. In STT, key coverage gaps exist along the northwestern coast. In STJ, key coverage gaps exist over the northern and southern coastlines. In all cases, coverage gaps exist in these areas due to the small total population making it difficult to economically justify building a cellular tower and significant variations in elevation that block signals.



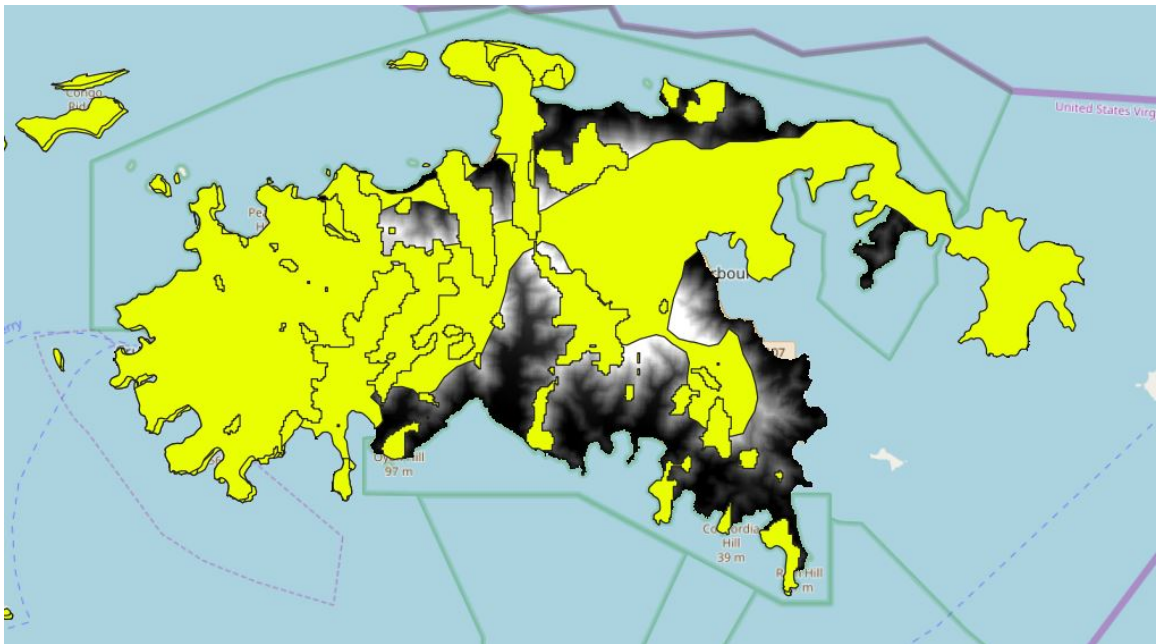
Source: National Telecommunications and Information Administration (2014).

Figure 3.8. Coverage Map of St. Croix from 2014. We superimpose regions identified in publicly available data to have cellular coverage on Figure 3.5 for comparison. White/grayscale/black represents the elevation profile from Figure 3.5, and yellow represents the coverage map from NTIA.



Source: National Telecommunications and Information Administration (2014).

Figure 3.9. Coverage Map of St. Thomas from 2014. We superimpose regions identified in publicly available data to have cellular coverage on Figure 3.6 for comparison. White/grayscale/black represents the elevation profile from Figure 3.6, and yellow represents the coverage map from the NTIA.



Source: National Telecommunications and Information Administration (2014).

Figure 3.10. Coverage Map of St. John from 2014. We superimpose regions identified in publicly available data to have cellular coverage on Figure 3.7 for comparison. White/grayscale/black represents the elevation profile from Figure 3.7, and yellow represents the coverage map from NTIA.

Validation of TIREM Parameters using Signal Sweep Method

We determine the accuracy of assumed parameters for TIREM using the signal sweep method. Specifically, we use NTIA coverage maps for STJ to validate model parameters and outputs because it has the most complex combination of regions with usable and unusable signal regions.

Figure 3.11 shows the coverage from Tower 2 (from Figure 3.4) on STJ with transmission power set to 80 dBm. It appears that coverage is excellent overall with the exception of some minor issues on the northern edge of the island — in-person observation shows this part of the island has limited to no cell phone signal. For this reason, we re-tune parameters to more accurately reproduce NTIA data.

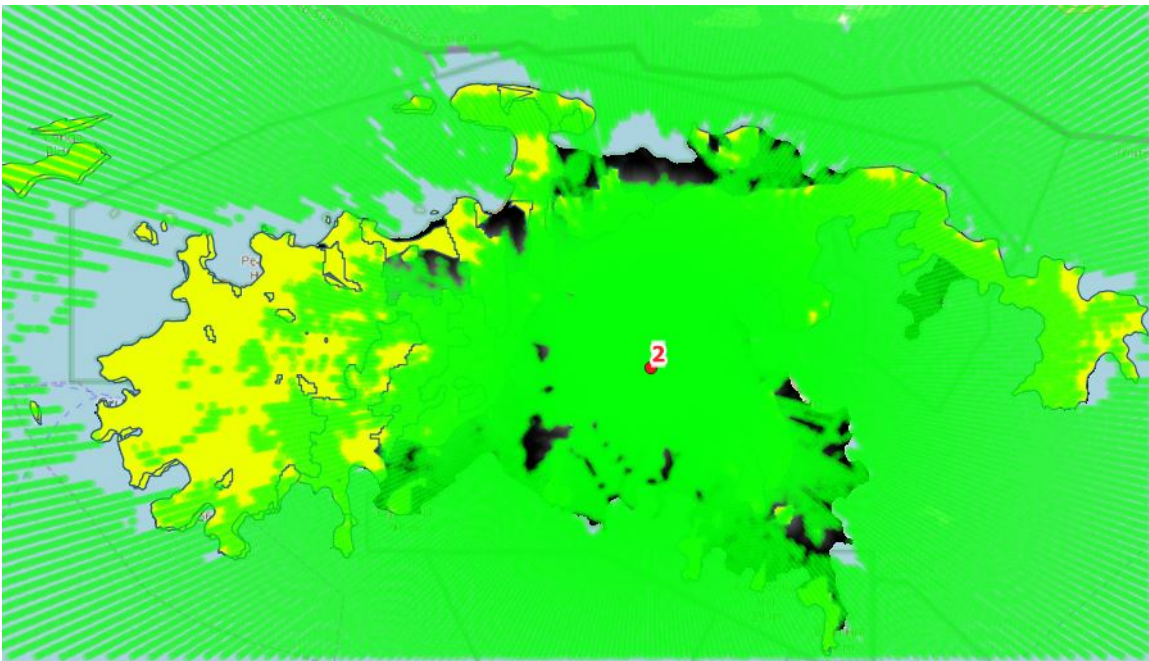


Figure 3.11. Coverage Map of St. John from Tower 2 at 80 dBm Transmission Power. We superimpose signal sweep coverage results on Figure 3.10 for comparison. White/grayscale/black represents elevation, yellow represents NTIA 2014 coverage map, and green represents good coverage from the signal sweep method.

Figure 3.12 depicts coverage from the same tower as 3.11, but with initial transmission power set to 60 dBm. This coverage map more closely resembles the coverage map from 2014 and data from visiting the USVI. This verifies that the model is working as intended

and that the transmission power setting should be approximately 60dBm for all towers (as included in Table 3.1). The gaps on the western edge of the island also point towards coverage coming from either additional towers not available in the existing data, or, more likely, coming from the easternmost towers on STT.

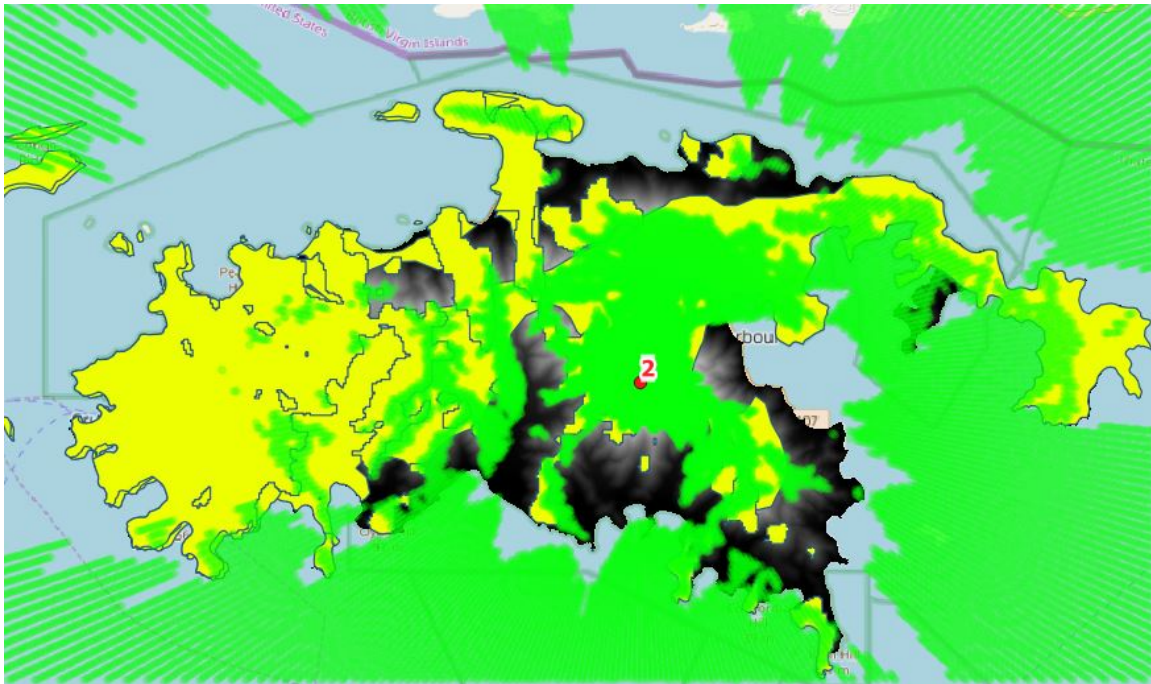


Figure 3.12. Coverage Map of St. John from Tower 2 at 60 dBm Transmission Power. We superimpose signal sweep coverage results on Figure 3.10 for comparison. White/grayscale/black represents elevation, yellow represents NTIA 2014 coverage map, and green represents good coverage from the signal sweep method.

Comparison of Signal Sweep and Grid Methods

We demonstrate the differences in signal sweep and grid methods for Tower 2 on STJ to show differences in final results. Figure 3.13 shows another view of the results of the signal sweep method for tower 2 on STJ at 60 dBm transmission power with the island elevation profile in the background. Actual location for tower 2 is denoted by the red circle. Figure 3.14 shows the coverage from Tower 2 with the grid method at 60 dBm transmission power, and again with the elevation profile in the background. Notice the grid creates a more uniform coverage in areas where there is coverage while there are gaps that form further away from the tower for the sweep method. Another advantage of the grid method is that every tower's

signal strength is calculated at the same set of points in the grid so all the coverage maps align with each other while the sweep method leaves each map off by a few degrees from the others.

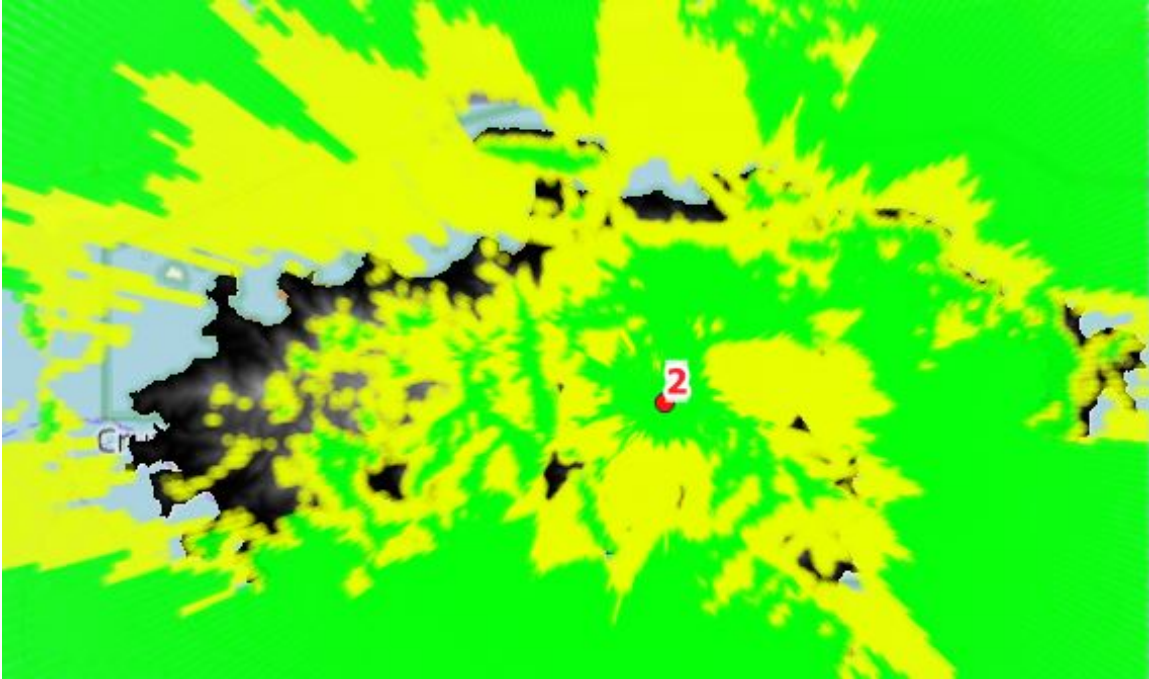


Figure 3.13. Coverage Map of St. John from Tower 2 with Signal Sweep Method. We superimpose signal sweep coverage results on Figure 3.7 for comparison. White/grayscale/black represents elevation, yellow represents medium coverage from the signal sweep method, and green represents good coverage from the signal sweep method.

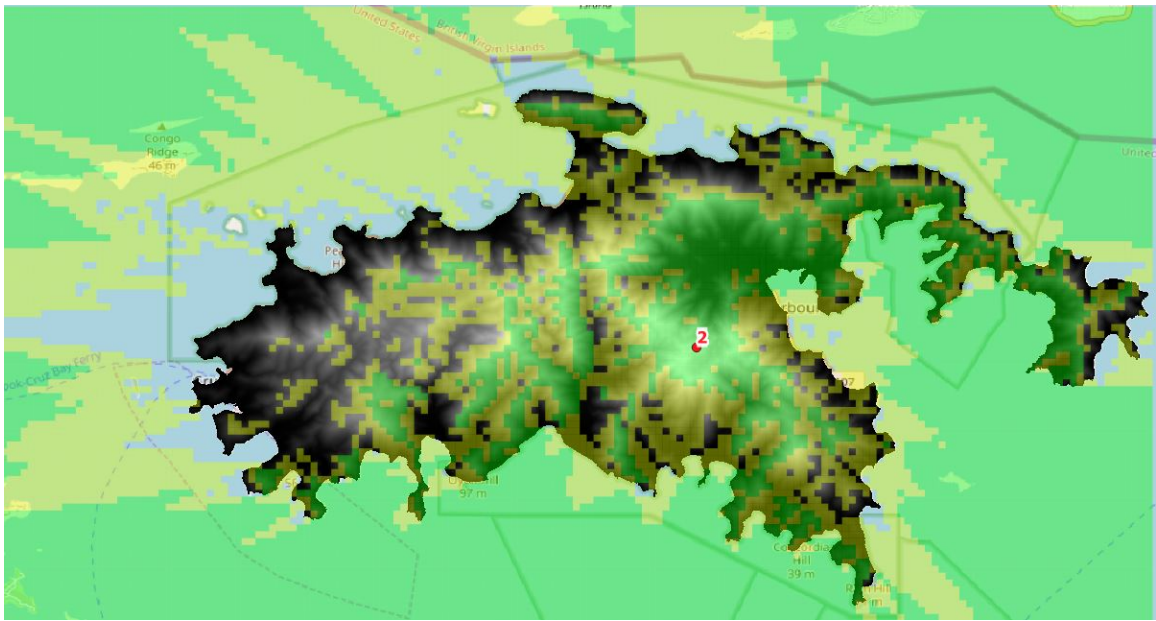


Figure 3.14. Coverage Map of St. John from Tower 2 with the Signal Grid Method. We superimpose signal sweep coverage results on Figure 3.7 for comparison. White/grayscale/black represents elevation, yellow represents medium coverage from the signal grid method, and green represents good coverage from the signal grid method.

3.3.3 Coverage Map Analysis

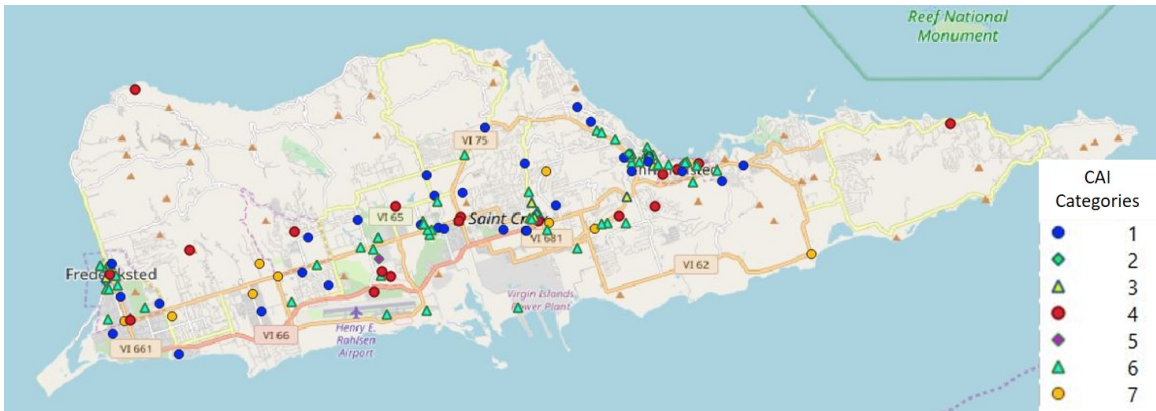
We analyze coverage maps generated with the signal grid method for final results. We compare the composite coverage maps produced using the results from all towers on all islands to determine accuracy of results to NTIA data. We use two additional building data sets to quantify the service provided by each cellular tower to Territorial stakeholders and determine the criticality of individual towers for coverage.

Community Anchor Institutions

The first data set is of Community Anchor Institutions (CAIs), which include schools, hospitals, and other community installments that are critical locations both during normal daily operations and especially during disasters. Each CAI is given an FCC-designated category code defined in the list below (National Telecommunications and Information Administration 2014):

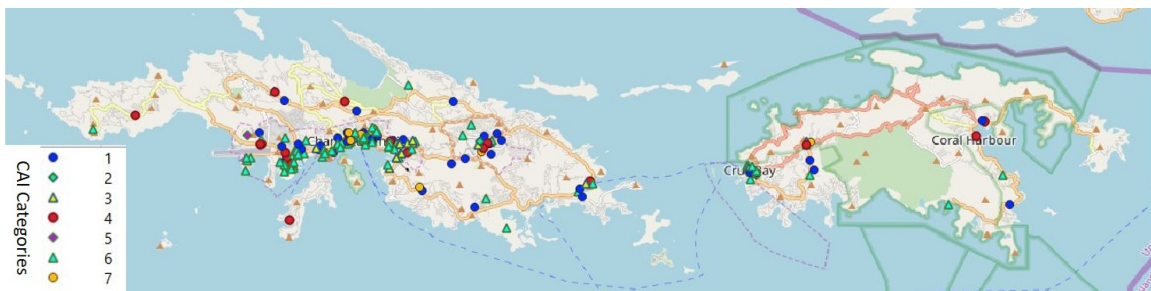
1. School K-12;
2. Library;
3. Medical/healthcare;
4. Public Safety (includes police, fire stations, and first responders);
5. University College or Post-secondary School;
6. Other community support — governmental; and,
7. Other community support — non-governmental (includes Non-Governmental Organizations (NGOs) and support organizations).

The location of CAIs was originally determined by Territorial stakeholders in the 2010-2014 time-frame as key locations requiring telecommunications services. Providing cellular service and Internet to these buildings was one of the main drivers for the construction of the initial wired telecommunications backbone in the USVI Territory. CAI locations were acquired from FCC data sets from 2014. Figures 3.15 and 3.16 show the locations for all CAIs on STX and STT/STJ, respectively. Coverage of these locations based on our model is in the next chapter.



Source: National Telecommunications and Information Administration (2014).

Figure 3.15. Community Anchor Institution Locations on St. Croix. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.



Source: National Telecommunications and Information Administration (2014).

Figure 3.16. Community Anchor Institution Locations on St. Thomas and St. John. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.

Territorial Buildings and Building Segments

In addition to identifying which cellular tower provides coverage for critical locations, we provide statistics on how each tower covers all communities in the territory by comparing coverage maps to building locations. There are thousands of buildings on each island from individual homes to hotels and critical facilities. To relate coverage maps to communities, we acquired data on building locations with associated polygons representing their orientation and size from the Geographic Information Systems (GIS) Program of the Lt. Governor of the USVI (GIS Program of the Office of the Lt. Governor of the U.S. Virgin Islands 2020).

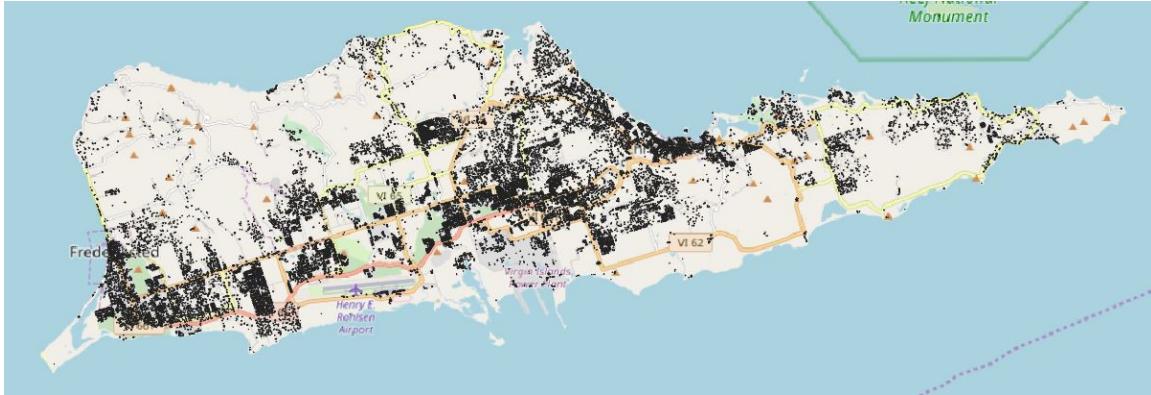
Further processing of the building data was necessary to assess coverage. The mesh grid generated for each island for the signal grid method does not correspond as a 1-to-1 overlay for buildings — i.e., all building polygons do not fit within a single grid square. Instead, numerous buildings fall on the edge of grid squares, meaning their cellular signal is a mixture of results from multiple sample points. Managing these overlapping regions can be done in a number of ways, such as assigning a building the best signal or average signal from multiple sample points.

Instead, we intersect the building data with the signal grid to turn individual buildings into “building segments” that correspond to subsections of each building. We measure coverage for each building segment for each tower and do not combine results into an average. This approach assumes that the signal measured at each sample point is uniform over each signal grid square in a coverage map. It also assumes that individual buildings may have multiple zones with different quality of cellular service.

Figures 3.17 and 3.18 show the locations of all building segments for each island. The total number of building segments on STX is 30,092 and the combined total number of building segments for STT and STJ are 25,332.

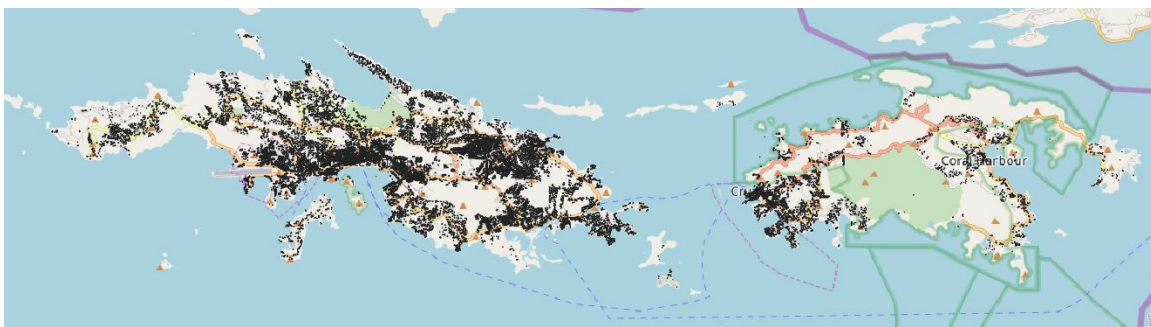
3.4 Discussion

Now that we have shown the model works as intended and we defined the locations to analyze coverage levels for, we use the model for all cellular towers in the territory. The results of these model iterations is the focus of the next chapter to determine how many building segments and CAIs are serviced by each tower and then do some vulnerability analysis to determine what effect losing a certain tower will have for the territory.



Source: GIS Program of the Office of the Lt. Governor of the U.S. Virgin Islands (2020).

Figure 3.17. Building Locations for St. Croix. Each black region is composed of thousands of small polygons representing individual buildings.



Source: GIS Program of the Office of the Lt. Governor of the U.S. Virgin Islands (2020).

Figure 3.18. Building Locations on St. Thomas and St. John. Each black region is composed of thousands of small polygons representing individual buildings.

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CHAPTER 4: Analysis

For each island, we present three key analyses of coverage maps:

1. Comparison of 2014 FCC cellular signal coverage maps to the combined coverage map generated from all towers,
2. The number and type of CAI covered by each tower, and
3. The number of building segments covered by each tower.

As described in Chapter 3, we illustrate all results in terms of “Good” cell coverage (greater than -65dBm) as green, “Medium” cell coverage (between -65 dBm and -85 dBm) as yellow. All results presented in this chapter use the signal grid method for producing coverage maps.

4.1 Wireless Coverage in St. Croix

Figure 4.1 shows the overall cellular coverage for STX for all towers. There are 11 towers that provide cellular service on STX, some of which have antennas from multiple providers while others are only for a single provider. Using the signal grid method, we present the coverage of each tower for all 11 towers simultaneously.

Figure 4.1 shows the majority of towers are centrally located on STX, leading to regions in the center of the island having overlapping coverage from multiple towers. Here, overlapping coverage is most likely the result of relatively flat terrain, such that a single tower can cover a much longer range without signal blockage or shortfalls. We expect this region to have a robust cellular network, where the loss of any single tower due to disaster might lead to no change in coverage.

In contrast, Figure 4.1 also shows regions of weak or nonexistent service on the northwestern and eastern coast of STX. Even with 11 towers spread out across STX, the hilly terrain leads to regions without signal coverage. These regions also do not have many CAIs or large communities, meaning the coverage is not as critical as in the central portions of the island. However, in many cases, the limited coverage may only come from a single tower.

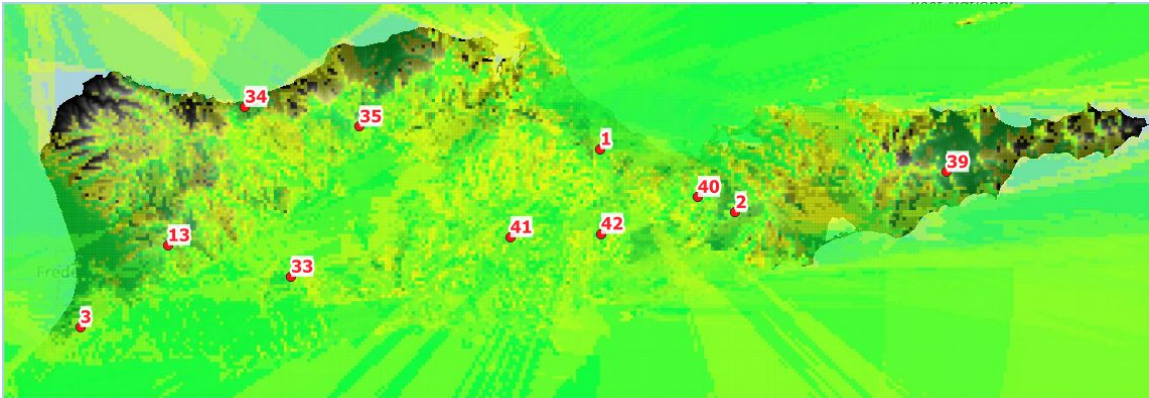


Figure 4.1. Combined Coverage Map of St. Croix for All 11 Towers. Overall coverage for STX is good in central regions with redundant towers. Locations with limited service include the northwest and eastern portions of the island. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

We expect these regions to have less robust cellular networks, where the loss of a single tower may lead to large reductions in coverage.

4.1.1 Comparison of Model-Based Results to 2014 Coverage Maps

We compare the results from TIREM to the 2014 coverage maps from the NTIA to further validate the model. Figures 4.2 and 4.3 show the comparison of the 2014 data for Virgin Islands (VI) PowerNet (currently known as Viya) with the composite coverage from all towers on STX using the signal grid method. Figure 4.2 presents results for the northwestern coast of STX. Here, we find strong correspondence between model-based results and FCC published coverage maps. These losses in signal along that coast were also verified in-person on a visit to the USVI. Figure 4.3 further shows the accuracy of our model-based approach when compared to published data. Here, we present the eastern coast of STX and show that the model aligns with previous data. Again, the lack of signal in this area was verified in-person during the visit to STX.

Taken together, they conclude that the use of TIREM with assumed model parameters provides an appropriate estimate of cellular coverage on STX. This combined view of all 11 towers implies coverage maps for individual towers on STX can be assumed to produce accurate estimates of real coverage. Moreover, we note that there has been limited change

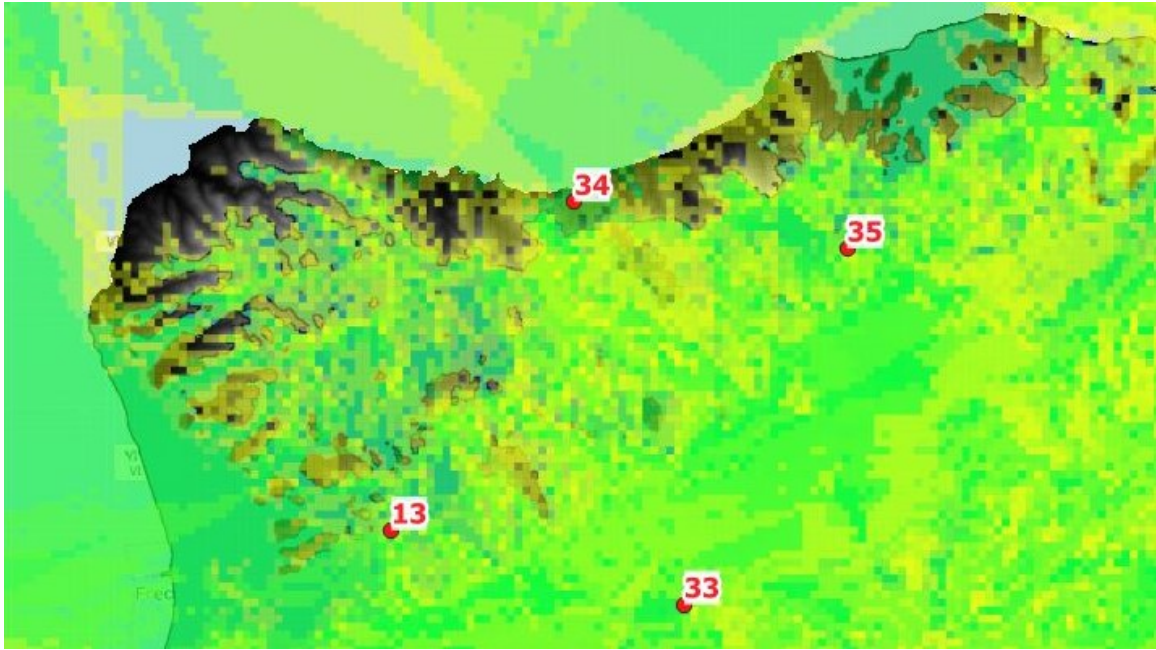


Figure 4.2. Coverage Map of Northwestern St. Croix from the Model Compared to VI PowerNet in 2014. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal represents the 2014 VI PowerNet Coverage.

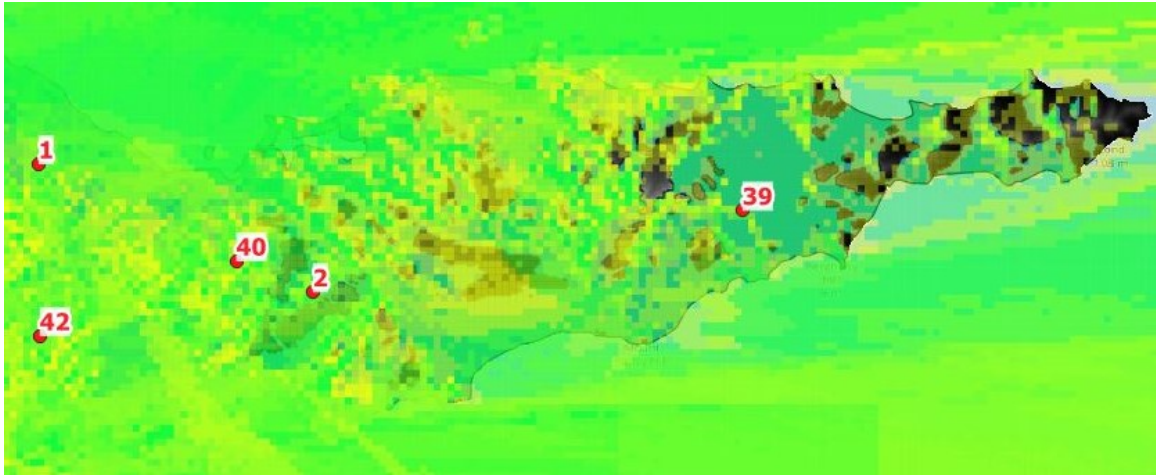


Figure 4.3. Coverage Map of Eastern St. Croix from the Model Compared to VI PowerNet in 2014. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal represents 2014 VI PowerNet Coverage.

in signal or cellular network access since 2014 since the results presented here are using data verified for 2020.

4.1.2 Coverage of Community Anchor Institutions

Tables 4.1 and 4.2 show the total number of each type of CAI that receives Good and Medium coverage from each tower on STX. Results show that most of the towers on STX cover a large number of CAIs across various CAI types. This is likely a result of the flat terrain on the island, as transmission signals can reach further distances with less interference.

The top three towers for good CAI coverage are tower 40 (61.7%), tower 13 (54.1%), and tower 2 (48.1%). Towers 40 and 13 cover the most diverse range of larger proportion of CAI types than other towers. Specifically, tower 40 covers the largest proportion of libraries, medical buildings, public safety buildings, universities, and NGO buildings. Tower 13 covers the largest proportion of grade schools, universities, and NGO buildings.

When considering medium coverage, the top three towers are tower 42 (50.4%), tower 2 (30.1%), and tower 40 (24.1%). Tower 42 is unique for STX as it provides the largest proportion of medium coverage to every CAI type in STX. Moreover, towers 2 and 40 each cover over 75% of the CAIs on STX with good and medium signal. This means that if all towers are lost except tower 40 or 2, 75% of critical facilities on STX will still receive cellular services. Taken together, these four towers (40, 2, 13, and 42) may be the most important for hardening efforts to maintain cellular service at critical facilities. In addition, recovery operations after major disasters may want to prioritize restoration of these towers to provide cellular service to the greatest number of facilities.

Table 4.1. CAIs with Good Service on St. Croix by Tower and CAI Type

Tower	CAI 1	CAI 2	CAI 3	CAI 4	CAI 5	CAI 6	CAI 7	Total
STX-1	7	2	2	4	0	21	0	36 (27.1%)
STX-2	14	2	3	8	0	32	5	64 (48.1%)
STX-3	10	1	1	4	0	24	5	45 (33.8%)
STX-13	19	2	2	8	1	34	6	72 (54.1%)
STX-33	16	0	0	7	1	19	4	47 (35.3%)
STX-34	0	0	0	0	0	0	0	0 (0.0%)
STX-35	19	1	2	8	1	25	5	61 (45.9%)
STX-39	0	0	0	1	0	0	1	2 (1.5%)
STX-40	16	3	5	10	0	43	5	82 (61.7%)
STX-41	11	1	2	5	0	16	4	39 (29.3%)
STX-42	7	1	3	5	0	15	3	34 (25.6%)
All CAIs	31	4	5	19	1	64	9	133

This table summarizes the number of CAIs that receive Good signal on STX by CAI category and includes the total number of percentage of CAIs covered by that tower. The final row gives total counts of each CAI to show duplicate coverage across multiple towers. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.

Table 4.2. CAIs with Medium Service on St. Croix by Tower and CAI Type

Tower	CAI 1	CAI 2	CAI 3	CAI 4	CAI 5	CAI 6	CAI 7	Total
STX-1	8	1	1	3	0	10	1	24 (18.0%)
STX-2	13	1	2	4	0	17	3	40 (30.1%)
STX-3	10	0	1	2	1	7	0	21 (15.8%)
STX-13	3	0	1	3	0	7	1	15 (11.3%)
STX-33	5	1	2	4	0	15	3	30 (22.6%)
STX-34	0	0	0	0	0	0	0	0 (0.0%)
STX-35	5	1	1	5	0	15	2	29 (21.8%)
STX-39	4	1	2	2	0	17	1	27 (20.3%)
STX-40	11	0	0	5	1	11	4	32 (24.1%)
STX-41	7	0	1	6	1	13	3	31 (23.3%)
STX-42	15	2	2	10	1	33	4	67 (50.4%)
All CAIs	31	4	5	19	1	64	9	133

This table summarizes the number of CAIs that receive Medium signal on STX by CAI category and includes the total and percentage of CAIs covered by that tower. The final row gives total counts of each CAI to show duplicate coverage across multiple towers. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.

4.1.3 Coverage of Buildings and Building Segments

Table 4.3 shows the breakdown for how many building segments are covered with Good and Medium coverage by tower. The total number of building segments on STX is 30,092. As shown by the last row, not all building segments receive a signal even when all towers are functioning and only 99.7% of all buildings are covered. Most towers are in more densely populated areas to provide nearby buildings with Good signal. These towers are also at a high elevation and they can serve many more areas with Medium signal. The results show that most towers cover about 30-50% of the buildings on the island with Good service and about another 20-30% of the buildings with Medium service. The remaining towers that cover fewer buildings overall and have a higher percentage with Medium service than Good service are located in more isolated and remote communities.

Table 4.3 also shows how many buildings will lose signal during tower failures. The final column in Table 4.3 shows how many buildings are affected by the removal of that tower from the network (due to disaster or otherwise). For most towers, only about 0.5% of the building segments on the island will have no service if the tower is lost. This is because most population-dense areas, receive coverage from multiple towers. Towers 34 and 39 have the largest percentages of building segments that will lose cellular signal if the tower is removed from the network. This is largely due to those towers covering more remote communities that lack redundant cellular networks. These remote communities receive service from this single tower and will be unable to communicate in the event the tower is disabled or destroyed.

We present coverage maps for towers 35, 42, 34, and 39 to demonstrate the effect of topography and location on individual tower coverage. Figure 4.4 presents the coverage map for tower 35. Tower 35 covers the most building segments on the island with Good service (61.1%). This is possible because of the elevation at which the tower is located and lack of significant elevation change over the central portion of the island near the base of the tower. This topographic feature of STX also helps the overall cellular network because most towers can act as redundant links to tower 35 and cover many of the same areas.

Figure 4.5 presents the coverage map for tower 42. Unlike the majority of towers that are located in population centers, which leads to more building segments with Good coverage vs. Medium coverage, Tower 42 has the opposite coverage profile, where there are more

Table 4.3. Coverage of Building Segments on St. Croix by Tower

Tower	Building Segments with Good signal from This Tower	Building Segments with Medium signal from This Tower	Building Segments with no signal if Tower Lost
STX-1	3,953 (13.1%)	5,743 (19.1%)	4 (0.01%)
STX-2	15,201 (50.5%)	9,442 (31.4%)	6 (0.01%)
STX-3	8,482 (28.2%)	5,763 (19.2%)	9 (0.02%)
STX-13	15,193 (50.5%)	5,828 (19.4%)	50 (0.17%)
STX-33	13,382 (44.5%)	7,085 (23.5%)	0 (0.0%)
STX-34	47 (0.2%)	110 (0.4%)	4 (0.01%)
STX-35	18,389 (61.1%)	6,319 (21.0%)	150 (0.5%)
STX-39	878 (2.9%)	3,966 (13.2%)	312 (1.04%)
STX-40	17,281 (57.4%)	8,301 (27.6%)	5 (0.01%)
STX-41	10,525 (35.0%)	9,634 (32.0%)	2 (0.01%)
STX-42	9,989 (33.2%)	11,639 (38.7%)	0 (0.0%)
All Towers	28,426 (94.5%)	1,557 (5.2%)	109 (0.4%)

This table summarizes the number of building segments that receive Good or Medium service for STX and includes the percentage of building segments covered out of the total number of building segments on the island. The final column presents the number of building segments that will have no signal if the tower is unavailable. The final row, second and third columns present combined results for all towers. The final row last column presents the total building segments currently without coverage.

building segments with Medium coverage than with Good coverage. This occurs because tower 42 is not centrally located and is most likely filling gaps in the overall coverage map. It also means tower 42 is a redundant connection for many customers, rather than the primary connection.

Figure 4.6 presents the coverage map for tower 34. Tower 34 is located in an isolated northeastern community blocked by hills south of the tower. This placement results in the tower only servicing a small area of clients in this isolated region. Despite the key placement of this tower for certain communities, TIREM results indicate that the loss of tower 34 does not lead to significant increases of building segments with no service. This means, even though tower 34 is critical for these isolated communities to have good, strong service, the tower can fail and communities in this region can still use cellular networks for

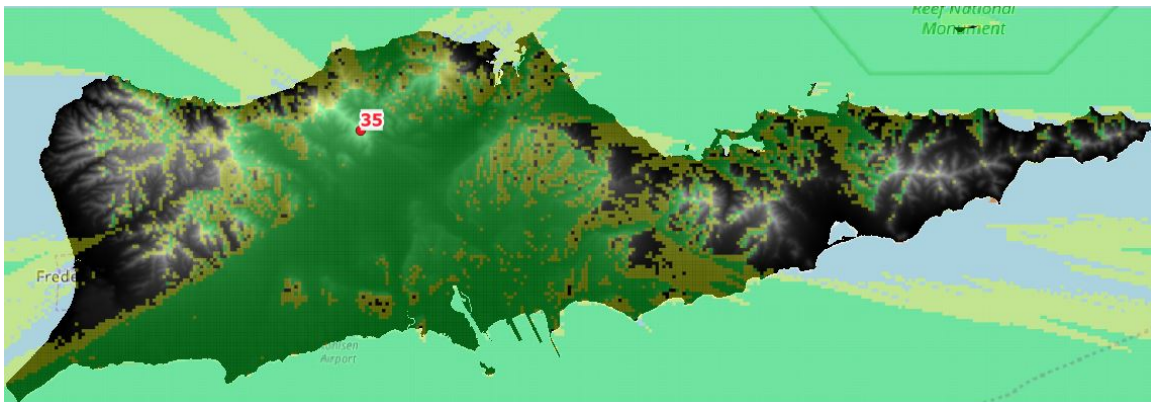


Figure 4.4. Coverage Map of Tower 35 on St. Croix. Tower 35 provides coverage for a large portion of STX due to its location of high elevation with nearby flat terrain and large populations. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

basic services.



Figure 4.5. Coverage Map of Tower 42 on St. Croix. While tower 42 appears centrally located, nearby topography leads to high losses. Thus, the tower provides only medium coverage for nearby populated areas. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

Figure 4.7 presents the coverage for tower 39. Tower 39 is similar to tower 34 in that it serves a more remote community and only provides Good coverage to 2.9% of the building segments on the island. However, unlike tower 34, if tower 39 is lost, a large number of the building segments will lose service completely. This is because the eastern coastline of

STX has limited redundant towers and a varied topography. There are even small regions without any signal near tower 39 despite its prominent location on a high elevation point.

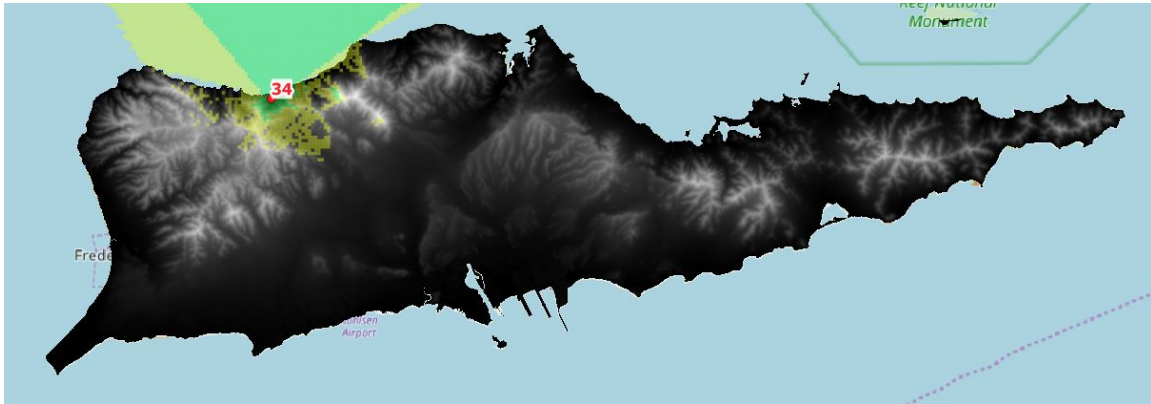


Figure 4.6. Coverage Map of Tower 34 on St. Croix. Tower 34 is unique because it is in a very remote location to provide service to isolated communities. However, loss of tower 34 does not lead to significant reductions in total building coverage. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

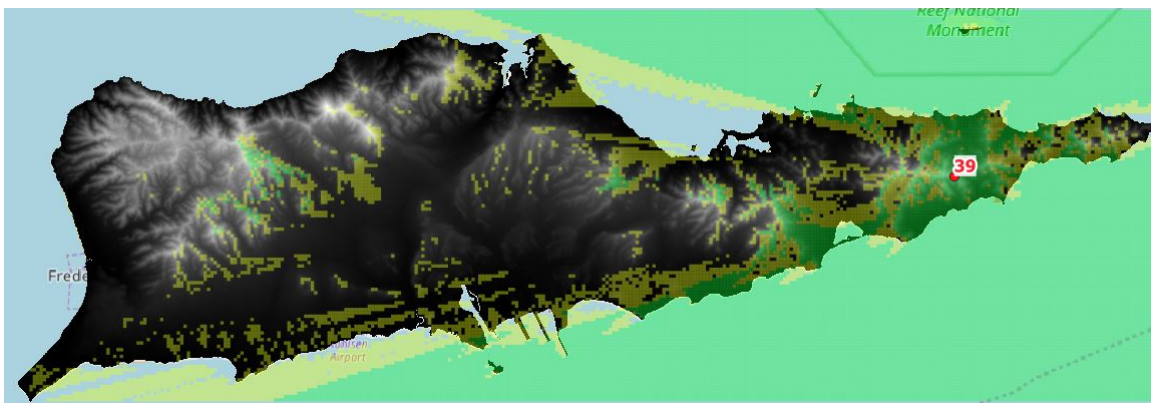


Figure 4.7. Coverage Map of Tower 39 on St. Croix. Tower 39 is also in a remote location, and specifically provides service to parts of eastern STX. Loss of tower 39 leads to the greatest number of building segments losing cellular signals on STX. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

4.2 Wireless Coverage in St. Thomas and St. John

Figure 4.8 presents the model-based coverage map for STT and STJ. Both islands are close enough that towers on each island provide cellular coverage for the other. For this reason, coverage of both islands must be considered together. In total, there are 11 towers on STT and 2 towers on STJ that provide cell phone service, and similarly to STX, some towers carry multiple providers' antennas while other towers are solely one provider. Figure 4.8 presents the results from all 13 towers simultaneously.

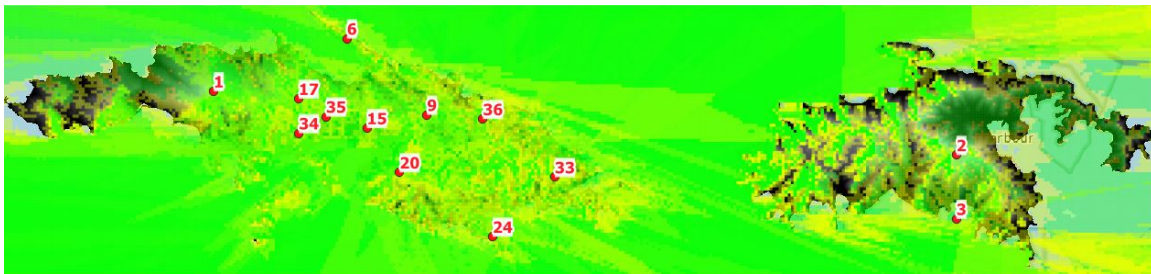


Figure 4.8. Combined Coverage Map for St. Thomas and St. John for All 13 Towers. Overall coverage for STT is good with the exception of the western region. Overall coverage on STJ is sporadic because of the significant elevation changes. Towers on each island provide some level of service to the other island. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

Figure 4.8 shows the majority of towers are located in central and eastern STT, leading to regions in the center of STT and western STJ having overlapping coverage from multiple towers. Unlike in STX, the terrain on both STT and STJ is mountainous, and the proximity of towers leads to less overlap.

Also similar to STX, Figure 4.8 shows regions of weak or nonexistent service on north-western STT and across STJ even when all 13 towers are active. Due to the mountainous terrain, several regions of strong, redundant signal are nearby regions of weak to no signal. Since the topography drives the formation of these regions without cellular service, even with more power and antenna on towers, it will be difficult to fill these coverage gaps. For greater coverage of the STT and STJ land mass, more towers will be required that maintain LOS in regions with coverage shortfalls.

4.2.1 Comparison of Model-Based Results to 2014 Coverage Maps

We also compare the composite coverage of all 13 towers to coverage maps for STT and STJ from the NTIA 2014 data set to test the accuracy of TIREM parameters and model-based estimates. Figure 4.11 shows the coverage for STT that comes from Tower 1 aligned with the data for VI PowerNet from 2014, specifically in the region on the far western coast where the Good coverage lines up right on top of the VI PowerNet coverage.

Figure 4.9 presents composite coverage for the western side of STT for all towers. Figure 4.9 shows that coverage very closely lines up with VI PowerNet data from 2014 for that section of the island. However, it is not exact alignment. This may be an artifact of assuming that all towers in the model are from a single provider (VI PowerNet), where knowing exactly which tower contributed to their network would provide more accurate coverage mapping.



Figure 4.9. Coverage Map of Western STT Compared with VI Coverage PowerNet from 2014. Coverage in western STT aligns to the VI PowerNet data. Notice coverage gaps directly west of Tower 1. In this area, cellular service only seems to exist on the hilltops, while service is lost in the valleys and on the coast. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal is VI PowerNet coverage from 2014.

Figure 4.10 presents composite coverage across all towers for STJ. Note the denser coverage regions for Cruz Bay in western STJ and immediately around tower 2 are right on top of

the coverage maps from VI PowerNet. As mentioned above, this seems to be a result of the number of towers on the east coast of STT that all have the power to provide coverage to the west coast of STJ. For this reason, western STJ has significant redundant coverage.

To demonstrate the importance of the proximity of each island, we further validate coverage maps for tower 33 located on the East Coast of STT. Figure 4.12 presents the coverage map tower 33 on. Tower 33 covers both the eastern side of STT along with the western side of STJ. This means towers on both islands influence both coverage maps. This is important to note because we assumed STJ received half or more of its service from towers on STT after the initial test of the tower in Chapter 3. Moreover, in-person observation of cellular signal regions on STJ shows that certain parts of the island receive a signal from the nearby British Virgin Islands. This is an issue as emergency phone calls can be routed across the water and to another country.

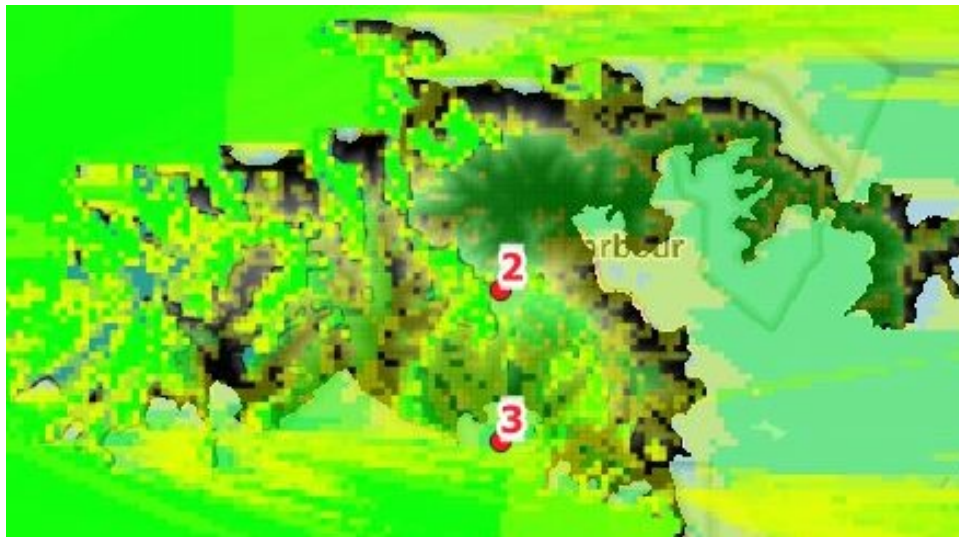


Figure 4.10. Coverage Map of St. John Compared with VI PowerNet Coverage from 2014. Signals from many towers on STT cross the water and overlap to cover the west coast of STJ over the VI PowerNet coverage map. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal is the VI PowerNet coverage from 2014.

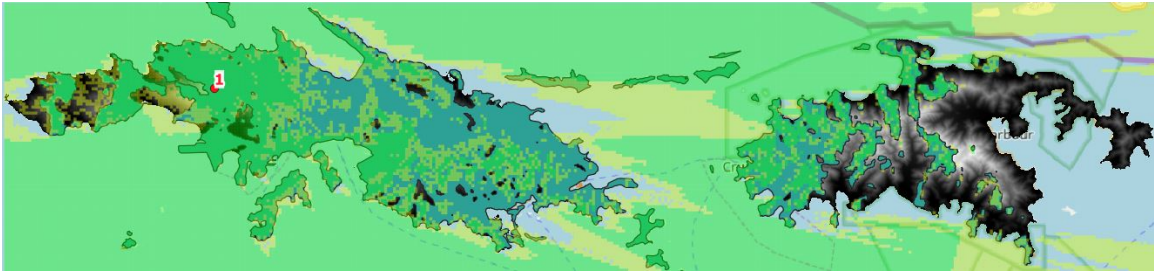


Figure 4.11. Coverage Map of Tower 1 on St. Thomas Compared with VI PowerNet Coverage from 2014. Coverage from Tower 1 aligns with both the western regions of coverage from VI PowerNet on STT and the coverage regions on St. John. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal represents the VI PowerNet coverage from 2014.

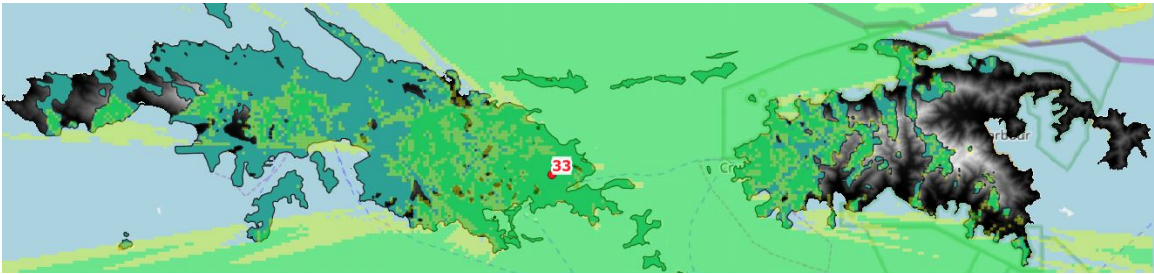


Figure 4.12. Coverage Map of Tower 33 on St. Thomas Compared to VI PowerNet Coverage from 2014. Tower 33 covers a majority of the east coast of STT and the west coast of STJ. Its coverage aligns with VI PowerNet coverage in some of the same regions as Tower 1. White/grayscale/black represents elevation, yellow represents medium coverage, green represents good coverage, and teal represents VI PowerNet coverage from 2014.

4.2.2 Coverage of Community Anchor Institutions

We measure which towers provide Good and Medium coverage to CAIs on STT and STJ. Tables 4.4 and 4.5 show that some towers provide Good service to over 75% of CAIs, even with the more extreme terrain on STT and STJ. This is due to the strong clustering of CAI locations in the center of STT in the USVI capital city of Charlotte Amalie.

The top three towers providing Good coverage to CAIs across STT and STJ are tower 20 (76.5%), tower 17 (76.0%), and tower 35 (52.5%). Towers 17 and 20 provide the largest proportions of Good coverage to each type of CAI as well with tower 17 covering the most grade schools, universities, and government buildings. Tower 20 covers the most libraries,

medical buildings, public safety buildings, universities, and NGO buildings.

When we look at Medium coverage, the percentages are much lower than the Good coverage. However, the ratio of Good to Medium coverage for any given tower is much more even for the towers on STX. The top three towers providing Medium coverage for CAIs on STT and STJ are tower 9 (45.9%), tower 1 (25.7%), and tower 34 (24.6%).

A unique feature of the STT and STJ cellular network is that there are many towers that provide either Good or Medium coverage. There is limited overlap between towers with high levels of Good and Medium service — towers either provide significantly more of one or the other service level. For example, tower 9 provides Medium service to 45.9% of CAIs and Good service to only 24.6% of CAIs. This is opposite of tower 15, which provides Good service to 50.3% of CAIs and Medium service to 19.7% of CAIs.

4.2.3 Coverage of Buildings and Building Segments

Table 4.6 shows the number of building segments with Good and Medium coverage by tower. The total number of building segments for STT and STJ is 25,332 and the overall coverage per tower is significantly lower than towers on STX. The towers for STT mostly provide 20-30% of building segments with Good coverage while towers on STJ only provide 16% or less with Good coverage. The number of building segments serviced with both Good and Medium coverage for each island is much more evenly distributed with relatively equal numbers of building segments serviced for each level by each tower. The towers for these two islands are also interesting because most of them service both islands, especially the easternmost towers on STT covering Cruz Bay on STJ. The lower total percentages of building segments covered per tower also show how much terrain and elevation factors into the calculation because the elevation changes are much more extreme on these two islands in comparison to the relatively flat terrain of STX.

Similar to Table 4.3 for STX, the final column in Table 4.6 shows the number of building segments that will have no signal if that tower fails due to natural disasters or otherwise. STT and STJ have worse overall coverage with 620 (2.4%) building segments having no coverage during normal operations. Similar to STX, there is redundancy in coverage and the majority to towers can fail with limited increases in total building segments losing cellular service. In contrast, the most critical towers on STT and STJ can lead to much larger losses

Table 4.4. CAIs with Good Service on St. Thomas and St. John by Tower and CAI Type

Tower	CAI 1	CAI 2	CAI 3	CAI 4	CAI 5	CAI 6	CAI 7	Total
STT-1	14	0	11	12	1	50	2	90 (49.2%)
STT-6	3	0	1	3	0	8	0	15 (8.2%)
STT-9	11	1	2	6	0	24	1	45 (24.6%)
STT-15	12	2	9	5	0	60	4	92 (50.3%)
STT-17	27	2	11	12	1	80	6	139 (76.0%)
STT-20	24	3	13	14	1	77	8	140 (76.5%)
STT-24	5	0	1	0	0	10	0	16 (8.7%)
STT-33	9	0	3	3	0	18	0	33 (18.0%)
STT-34	12	2	8	4	0	50	3	79 (43.2%)
STT-35	16	2	9	4	0	59	6	96 (52.5%)
STT-36	11	1	2	5	0	14	1	34 (18.6%)
STJ-2	5	0	2	4	0	3	0	14 (7.7%)
STJ-3	0	0	0	0	0	1	0	1 (0.5%)
All CAIs	39	3	14	23	1	93	10	183

This table summarizes the number of CAIs that receive Good signal on STT and STJ by CAI category and includes the total number and percent of CAIs covered by that tower. The final row gives total counts of each CAI to show duplicate coverage across multiple towers and coverage shortfalls. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.

than any single tower on STX. In particular, loss of tower 1 for STT leads to 372 building segments losing service and loss of tower 2 on STJ leads to 1,039 building segments losing service. This shows that the overall cellular network on STT and STJ is more vulnerable to individual tower failures than the network on STX.

We present coverage maps for towers 9, 15, and 17 on STT and tower 3 on STJ to demonstrate the effect of terrain and tower placement. Figure 4.13 presents the coverage map for tower 9 on STT. Tower 9 is important because it has a roughly 1:1 ratio of Good to Medium coverage for building segments. This is due to its northwestern placement on STT, which enables it to cover the north and eastern portions of STT and cover the western portions of STJ. In particular, tower 9 fills in some coverage gaps on the eastern coast and provides the

Table 4.5. CAIs with Medium Service on St. Thomas and St. John by Tower and CAI Type

Tower	CAI 1	CAI 2	CAI 3	CAI 4	CAI 5	CAI 6	CAI 7	Total
STT-1	10	3	1	5	0	26	2	47 (25.7%)
STT-6	4	1	3	2	0	6	1	15 (8.2%)
STT-9	15	3	10	7	0	44	5	84 (45.9%)
STT-15	11	1	1	6	1	13	3	36 (19.7%)
STT-17	7	2	1	6	0	10	2	28 (15.3%)
STT-20	13	1	0	5	0	14	2	35 (19.1%)
STT-24	10	2	3	5	0	12	3	35 (19.1%)
STT-33	9	2	1	4	0	19	4	39 (21.3%)
STT-34	9	0	2	8	1	21	4	45 (24.6%)
STT-35	7	1	1	7	1	13	0	30 (16.4%)
STT-36	4	1	4	3	0	16	3	31 (16.7%)
STJ-2	3	1	0	2	0	10	1	17 (9.3%)
STJ-3	1	0	0	0	0	1	0	2 (1.1%)
All CAIs	39	3	14	23	1	93	10	183

This table summarizes the number of CAIs that receive Medium signal on STT and STJ by CAI category and includes the total number and percent of CAIs covered by that tower. The final row gives total counts of each CAI to show duplicate coverage across multiple towers and coverage shortfalls. CAI categories include: (1) School K-12, (2) Library, (3) Medical/healthcare, (4) Public Safety, (5) University College or Post-secondary School, (6) Other community support — governmental, and, (7) Other community support — non-governmental.

best coverage to some communities in Magen’s Bay on the northern side of STT.

Figure 4.14 presents the coverage map for tower 15 on STT. Tower 15 has a very limited area of coverage compared to other towers. This is due to its placement inside the valley surrounding Charlotte Amalie. Despite the limited physical area of coverage, it provides significant coverage to CAIs (70.0% combining Good and Medium coverage). It is also one of the few towers that provides more Medium coverage than Good coverage, meaning it may serve primary as a redundant tower that fills coverage gaps unlike other towers located in population centers

Figure 4.15 presents the coverage map for tower 17 on STT. Tower 17 provides Good

Table 4.6. Coverage of Building Segments on St. Thomas and St. John by Tower

Tower	Building Segments with “Good” signal from This Tower	Building Segments with “Medium” signal from This Tower	Building Segments with no signal if Tower Lost
STT-1	8,446 (33.3%)	5,655 (22.3%)	372 (1.5%)
STT-6	3,299 (13.0%)	2,742 (10.8%)	13 (0.05%)
STT-9	7,785 (30.7%)	8,025 (31.7%)	2 (0.01%)
STT-15	4,578 (18.1%)	5,804 (22.9%)	0 (0.0%)
STT-17	11,780 (46.5%)	6,280 (24.8%)	5 (0.02%)
STT-20	11,556 (45.6%)	7,042 (27.8%)	13 (0.05%)
STT-24	4,994 (19.7%)	5,947 (23.5%)	29 (0.11%)
STT-33	7,222 (28.5%)	6,583 (26.0%)	78 (0.31%)
STT-34	4,797 (18.9%)	4,334 (17.1%)	0 (0.0%)
STT-35	5,380 (21.2%)	4,892 (19.3%)	0 (0.0%)
STT-36	6,811 (26.9%)	5,692 (22.5%)	6 (0.02%)
STJ-2	4,121 (16.6%)	4,051 (16.0%)	1,039 (4.1%)
STJ-3	380 (1.5%)	1,015 (4.0%)	37 (0.15%)
All Towers	22,702 (89.6%)	2,010 (7.9%)	620 (2.4%)

This table summarizes the number of building segments that receive Good or Medium service for STT and STJ and includes the percentage of total building segments covered out of all building segments on both islands. The final column presents the number of building segments that will have no signal if the tower is unavailable. The final row, second and third columns present combined results for all towers. The final row last column presents the total building segments currently without coverage.

coverage for the most building segments across all towers on STT and STJ. Where most towers across STT and STJ have signals blocked by terrain, the high elevation and central location of tower 17 on STT means coverage can extend towards both ends of STT. Its location also means it is able to provide service to the east coast of STT and the west coast of STJ.

Figure 4.16 presents the coverage map for tower 3 on STJ. Tower 3 is another tower meant to serve a particular community on STJ and only provides Good service to 380 building segments. Specifically, it provides service to the southern coast of STJ. Due to

the topography of STJ north of the tower, the tower cannot provide coverage to other parts of the territory except very particular locations on STT at the precise elevation that affords LOS.



Figure 4.13. Coverage Map of Tower 9 on St. Thomas. Tower 9 is located on a high elevation point in northwestern STT. From here, it provides equal amounts of good and medium coverage across both STT and STJ. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

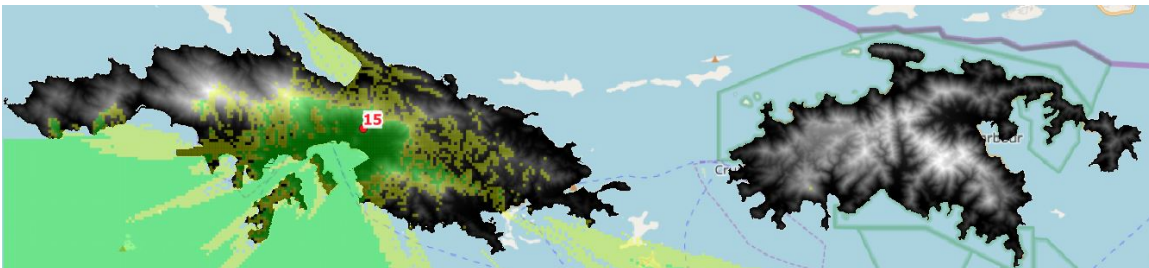


Figure 4.14. Coverage Map of Tower 15 on St. Thomas. Tower 15 does not provide coverage over a large geographic area, but does cover a number CAIs due to its placement in the valley around Charlotte Amalie. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

4.3 Discussion

Overall, most of the critical locations and buildings in the USVI appear to receive Good cellular service. Few building segments receive Medium or no service. However, this assumes that all towers have antenna on the same network, which is not the case. If all towers were on the same network, or telecommunications companies collaborated for coverage, then this network would only need a few improvements to cover all facilities on

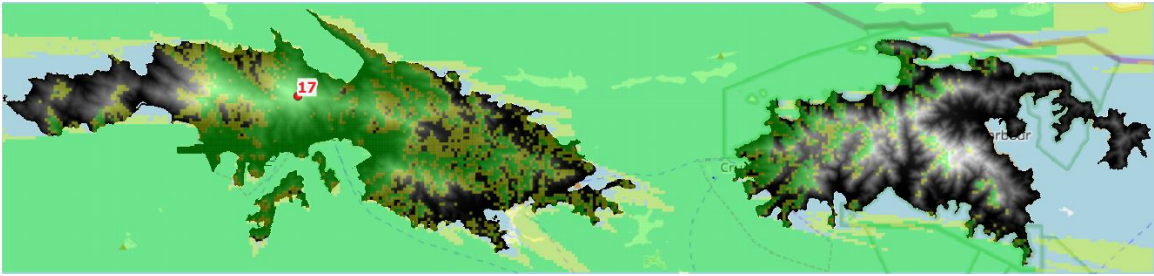


Figure 4.15. Coverage Map of Tower 17 on St. Thomas. Tower 17 is situated in the middle of STT with a decent elevation. From here, it provides good service to the central and populated regions of STT while also providing coverage to the west coast of STJ. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

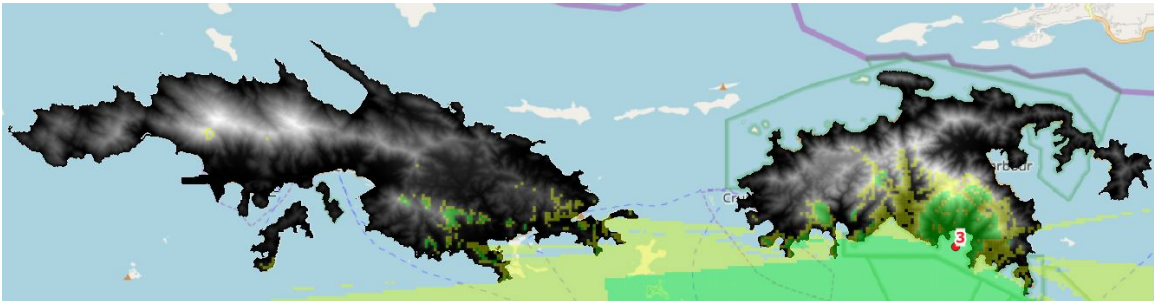


Figure 4.16. Coverage Map of Tower 3 on St. John. Tower 3 on STJ is in a remote location to serve the southern part of the island. Because of its location in the valley, it cannot provide additional service to the rest of STJ or to STT. White/grayscale/black represents elevation, yellow represents medium coverage, and green represents good coverage.

the Territory. In practice, individual providers will have service at least as good or worse than the coverage maps presented herein.

We also identify which regions of the Territory have significant redundancy in its cellular network and which regions are vulnerable to tower failures. The topography of STX, STT, and STJ play a key role in the redundancy of the network. Flat regions of STX share redundant towers, but remote regions with limited service have few towers and varied topography for good coverage. In contrast, all of STT and STJ are mountainous, so coverage is more evenly spread across towers with regions of redundant coverage occurring near population centers with many towers. In general, this leads to more redundancy where the

network exists on STT and STJ, but a greater number of building segments with coverage and a large number of regions with Good coverage nearby regions with no coverage.

The next chapter discusses solutions for hardening this network against future storms. We also list ways to refine the model and make it a more valuable a decision tool.

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CHAPTER 5: Conclusion

The purpose of this work is to help USVI Territorial partners understand how wireless communications networks work throughout the territory, what gaps exist during normal operations, and what new gaps might be created in the event of another natural disaster. The model presented in this paper is meant to be used as a decision tool to quickly identify which towers are more critical to harden or where additional towers may be needed. Results presented in Ch. 4 provide critical information for knowing where total cellular coverage, which critical facilities are served by each tower, and what communities are served by each tower on each island. Thus, the output of this thesis will assist FEMA, Virgin Islands Territorial Emergency Management Agency (VITEMA), and UVI in further research and decision making about wireless communications networks to lessen the impacts of a future storm on communications. This will reduce disaster impacts by allowing first responders to more rapidly and effectively communicate and reduce the need for communities to leave their homes seeking a cellular signal.

5.1 Hardening the Cell Phone Network in the USVI

We consider implications for each island.

5.1.1 St. Croix

From this analysis, towers 13, 35, 40, and 42 should be hardened to better withstand hurricane force winds, flooding, and other adverse conditions. These towers cover the most buildings on STX with the combination of Good and Medium coverage per tower totaling between 70 and 85% of all building segments on the island. These towers could potentially cover more building segments if transmission power was increased to handle additional requirements during a disaster. Each of these towers also services a significant number of CAIs throughout the island. These locations are particularly critical during disasters as they tend to be the locations where medical aid stations are set up and emergency supplies are distributed.

Decision-makers may also consider additional permanent towers to add to the network. In particular, a tower to act as a redundant connection for tower 34 on the northwest coast and/or additional towers fill in coverage gaps in that region would be useful. If the right location and antenna height are chosen, that tower could also act as a redundant link for tower 13 and cover most of the west side of STX. Another additional tower in the east to act as a redundant link for tower 39 would also be helpful and fill in the rest of the gaps on the east coast. Again, if the right location and antenna height are chosen, this tower could both cover the gaps on that side of the island and also act as a redundant link for tower 40.

Finally, decision-makers may want to consider WMNs that utilize emergency response towers set up immediately after a disaster. For example, a short term solution to disabled towers or areas without service during a disaster could also be a portable tower that can fill coverage gaps. Assuming emergency responders only have access to existing tower locations, choosing to set up the ad hoc networks at tower locations 13, 35, and 39 may provide coverage to the vast majority of the STX population.

5.1.2 St. Thomas and St. John

Towers 1, 9, 17, 20, and 33 on STT and tower 2 on STJ should be hardened to better withstand future disasters. Because of the increased communications isolation from terrain on STT and STJ, more towers need to be hardened to maintain the same portion of the network as STX. On STT, towers 1, 9, 20, and 33 each handle between 50 and 70% of the buildings between both islands. For STJ, tower 2 is the primary wireless communications tower, where tower 3 only serves a single remote community. Moreover, STJ tower 2 is the most critical during normal operations, where any other tower can fail with limited impact on coverage. These towers also service a number of CAI locations that would critically require communications following another disaster.

Decision-makers may consider the several locations for additional permanent towers. The first would be the west coast of STT to both act as a redundant link for tower 1 and fill the gaps along that coast. The second would be in STJ along the ridge north of tower 2 because it would provide a redundant link for tower 2 and also would help support tower 2 in overall bandwidth. The terrain of both STT and STJ presents a variety of problems because trying to set up a fully redundant network would require more towers than the same concept would

on STX.

Similarly, portable towers and WMNs could be a short term solution in a disaster to provide service where it is needed. However, an effective WMN on STT and STJ will require more planning and more towers to provide coverage in the hilly terrain.

5.2 Complementary Results

In addition to the explicit output of this thesis, we highlight additional work as part of the larger project supporting critical infrastructure resilience in the USVI.

5.2.1 Previous Research

There have been three masters thesis research projects completed for the USVI in support of FEMA rebuilding efforts.

- **Water and Energy:** Electric power and water distribution (Bunn 2018). The first master's thesis completed for the USVI was by Brenden Bunn who made a model of the interdependent operation of potable water distribution and electric power distribution infrastructure systems. The model links engineering models for water and power and focuses on a small scale network such as a small island territory or a military base.
- **Transportation:** STX Surface roads and supply chain (Good 2019). The next thesis was by Jeffrey Good who modeled surface road transportation and supply chain infrastructure in the USVI, specifically STX, and conducted analysis to inform efficacy and prioritization of proposed infrastructure modifications and investment for community mobility and hurricane relief.
- **Water and Energy:** Electric Power and Water distribution (Wille 2019). The third thesis was by Dominik Wille and it assessed the operational resilience of electric power and water distribution systems on STX by simulating hurricane scenarios, measuring the impacts from the scenarios and the benefits of hurricane hardening, and using the results to recommend hurricane mitigation via system hardening and redesign.

5.2.2 Concurrent Research

There are other masters thesis research projects currently being worked on for the overall FEMA project in the USVI that cover various critical infrastructure areas.

- **Telecommunications:** Wired / fiber optic networks (Moeller 2020). The other telecommunications thesis is being written by Brian Moeller who is working on a representative model of the fiber optic network to identify vulnerabilities, critical points, potential improvements, and possible prioritization of certain efforts. The goal is to provide analysis and results that can help guide future investment in telecommunications infrastructure.
- **Water:** Water Demand (Borgdorff 2020). Another thesis is being worked on by Andrew Borgdorff who is creating a water demand model to look at interactions between customer demand, water infrastructure, and weather. The goal is to utilize the model to create snapshots of water demand to offer realistic estimates for water use and demand across the territory and to study community vulnerability and determine which communities might be most vulnerable to water shortages after a disaster.

5.3 Future Work

The results of this thesis suggest many opportunities for additional research.

5.3.1 For the USVI

It is important to emphasize that the results produced in this thesis are *model-based* using TIREM. For this reason, the results in this thesis are assumed to be correct, but are not as accurate as cellular signal measurement in-person in the USVI. Moreover, the outputs of TIREM can be improved by working with the communications companies in the USVI to get more accurate data for model input.

The model can be used by researchers at UVI to inform FEMA and VITEMA when making decisions cellular coverage during disasters. Moreover, this work provides recommendations for which towers could be hardened now to mitigate loss of communications during a future disaster. In addition, if UVI can work with the USVI telecommunications companies, the model can be refined further with more accurate data for a variety of the inputs, specifically propagation frequency, antenna height, antenna polarization, transmission power, and

the data could be separated out by carrier so that each individual carrier network could be mapped by itself. Another piece that could be added is merging the model calculations with experimental coverage measurements taken around the island to further increase the accuracy of the model.

As this model only shows the vulnerability analysis for the loss of any one tower, future work could look at losing two or more towers to see how the network is affected. This type of “What-if” analysis is why the model is useful as a decision making tool because it does not just show the current status of the network, but how the network can change under different circumstances and scenarios.

5.3.2 For Other Regions

Now that this model/method has been created and tested in a small setting of the USVI, there is the potential to take it and expand it for other islands or other regions of the U.S. or to other areas of the world. To start, this could be used to look at cellular coverage for other U.S. island states and territories like Puerto Rico, Hawaii, or Guam. One could also take the model and look at larger states like Alaska, which may not experience tropical storms, but blizzards could leave more remote locations in need of coverage for emergencies. An alternative outside the U.S. would be to look at coverage on an island like Okinawa, Japan that sees typhoons on a yearly basis and has a significant number of U.S. service members who need communications during times of crisis.

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