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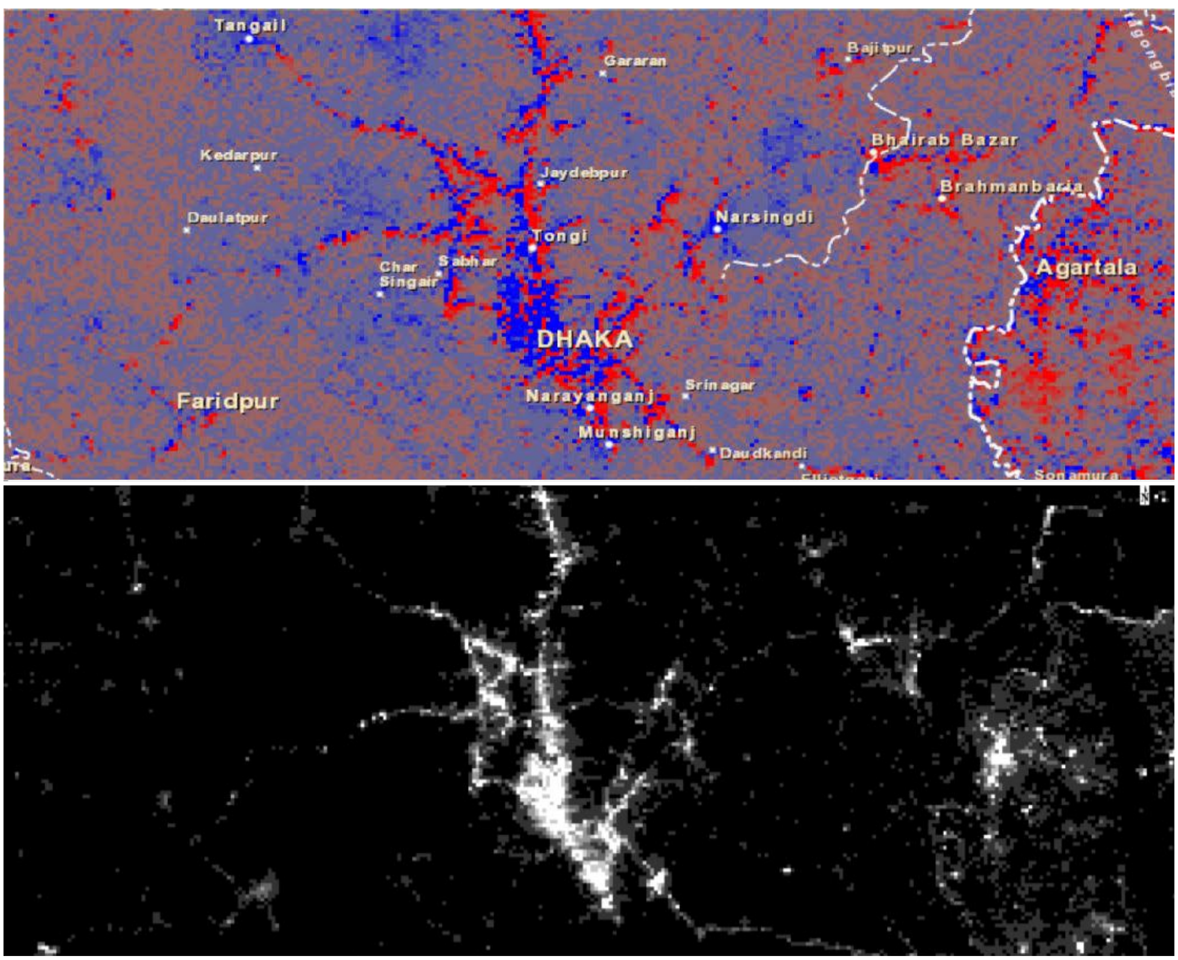
Army Study Program

Analysis of Operational Data

A Proof of Concept for Assessing Electrical Infrastructure Impact

Rosa T. Affleck, Jeanne M. Roningen, Jennifer S. Macpherson, Brian Tracy, and Demetra E. Voyadgis

November 2015



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Abstract

Infrastructure variables required for a community or society to function include basic facilities, services, and installations; and these variables can impact many aspects of daily life. The structure and functionality of the electrical grid in an operating area can affect multiple operational variables. Other infrastructure sectors that rely on the electrical grid can fail when electricity is disrupted. Thus, the impact of electricity in a society is vital for prosperity and security and expands the broad impact on economic and social well-being.

This study used remote-sensing data to examine the electrical system and power-grid functionality for Dhaka, Bangladesh. We focused on the transmission and distribution networks, the network patterns, and the electrical capacity. In addition, we used the pattern of a power outage (i.e., the 1 November 2014 blackout) and the duration of the outage to assess the affected neighborhood and the power-production disruptions at other major power stations within the country. When we combined the Visible Infrared Imaging Radiometer Suite (VIIRS) data with the panchromatic sharpening of WorldView-2 imagery, we were able to focus on the affected areas, thereby narrowing the search for electrical-grid components. This study is an example for understanding the dynamic physical environment relevant to military operations.

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Preface

This study was conducted for the Army Study Program under Project Number 30, “Analysis of Operational Data for Tactical Situational Understanding.”

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COL Bryan S. Green was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

ACOKA	Observation and Fields of Fire, Cover and Concealment, Obstacles, Key or Decisive Terrain, Avenues of Approach
ASCOPE	Areas, Structure, Capabilities, Organizations, People, and Events
BPDB	Bangladesh Power Development Board
CACD	Commander's Appreciation and Campaign Design
CCIR	Commander's Critical Information Requirements
CRREL	Cold Regions Research and Engineering Laboratory
DESCO	Dhaka Electric Supply Company
DIME	Diplomatic, Information, Military, and Economic
DMSP	Defense Meteorological Satellite Program
DNB	Day/Night Band
DPDC	Dhaka Power Distribution Company Limited
EDR	Environmental Data Record
EEFI	Essential Elements of Friendly Information
ERDC	U.S. Army Engineer Research and Development Center
ERSI	Environmental Systems Research Institute
ENVI	Environment for Visualizing Images
FM	Field Manuals
GIS	Geographic Information System
GRL	Geospatial Research Laboratory
HDIAC	Homeland Defense and Security Information Analysis Center
IPB	Intelligence Preparation of the Battlefield
MDMP	Military Decision-Making Process

METT-TC	Mission, Enemy, Terrain and Weather, Troops and Support Available, Time Available, and Civil Considerations
MODIS	Moderate Resolution Imaging Spectroradiometer
NAICS	North American Industry Classification System
NCC	Near-Constant Contrast
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
OE	Operational Environment
OLS	Operational Linescan System
PMESII-PT	Political, Military, Economic, Social, Information, Infrastructure, Physical Environment, and Time
SDR	Sensor Data Record
TRADOC	U.S. Army Training and Doctrine Command
UTC	Coordinated Universal Time
VCM	VIIRS Cloud Mask
VIIRS	Visible Infrared Imaging Radiometer Suite
WV2	WorldView-2

Executive Summary

Whether the Army is called to deal with problems under combat or non-combat operations, the operational process requires a new way of thinking: *design*. This *design* is one method for applying critical and creative thinking to understand, visualize, and describe complex problems and then to develop approaches to solve them. The design emphasizes developing a holistic understanding of the operational environment and framing the problem. Working from the problem framework for the military decision-making process (MDMP), a design is used to develop a broad approach for problem resolution (campaign design). The MDMP is a tool to help solve *a problem* while design is a tool to help ensure you are solving the *right problem* without introducing collateral problems.

Situational understanding is the product of applying analysis and judgment to relevant information to determine the relationships among the mission variables and to facilitate decision making. Mission variables describe not only the military aspects of the operational environment but also the civilian populations' influences on it. Commanders and their staff analyze and describe an operational environment in terms of eight interrelated variables: political, military, economic, social, information, infrastructure, physical environment, and time (PMESII-PT). In terms of the civilian variables of the operational environment, the key features and data requirements include areas, structure, capabilities, organizations, people, and events (ASCOPE). A PMESII-PT/ASCOPE matrix shows the interrelationships of factors with both spatial and non-spatial attributes and provides requirements for creating mission-relevant technologies to aid operators in understanding the military–civilian operating environments.

In military operational environment contexts, infrastructure variables include the basic facilities, services, and installations required for a community to function. The infrastructure variables' roles are interrelated: factors impact an area, the people, organizations and businesses, and social and economic capabilities that are included within its structures. For example, electricity in a community is vital for prosperity and security and expands the broad impact on economic and social well-being. Specifically, this impacts the functioning of government centers, financial institutions, essential facilities (schools, water, sewer, hospitals, etc.), transportation, and communication networks.

In this modern era, every aspect of daily life depends on electricity. The structure and functionality of the electrical grid in an operating area can affect multiple operational variables, and other infrastructure sectors that rely on the electrical grid can fail when electricity is disrupted. The infrastructure for transmission of electricity through interconnected networks forms the bridge between electrical suppliers and consumers.

This study examines the electrical system network and power-grid functionality of a region by using remote-sensing data through reasoning processes and illustrates the relevance of this methodology in an operational environment. We focus our assessment on the electrical transmission and distribution networks, the network patterns, and the network power capacity. Additionally, we assess the system capacity by using the pattern of power outage (i.e., blackout) and the duration of outage to assess the affected neighborhoods. Our remote-sensing method of using high-resolution WorldView-2 (WV2) satellite imagery greatly aided feature detection through visual inspection. By combining WV2 with low-resolution Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data, we were able to focus on affected areas, thereby narrowing the search for electrical-grid components.

Our study area was Dhaka, the capital of the People's Republic of Bangladesh. The generation and distribution of electricity for Dhaka is provided by Dhaka Power Distribution Company Limited (DPDC), a private sector firm, and is managed by Dhaka Electric Supply Company (DESCO) as a government executing agency. The population in Dhaka continues to struggle with an insufficient supply of electricity. In fact, a major unplanned power outage occurred on 1 November 2014 that affected Dhaka and the entire national grid along a transmission line that brought power from Baharampur in West Bengal, India, to Bangladesh's Bheramara. This disruption caused power production to cease at other major power stations within the country. This study used this blackout event as a baseline scenario.

The latest type of commercial- and government-launched satellites opens new possibilities of using unclassified high-resolution imagery for military operational assessment to extract infrastructure conditions. One of the most common applications of remote-sensing imagery is for extracting land-cover information by means of classification techniques for feature extraction and light detection. Our analysis used 11 high-resolution WV2 images, collected on 28 January 2012, 22 February 2013, and 27 April 2014, to create the Dhaka dataset. The high-resolution satellite imagery was geo-processed and combined to create a single, seamless dataset of the Dhaka region.

The VIIRS Day/Night Band (DNB) provides temporal imaging of nighttime visible light. Other studies have applied VIIRS image data to assess community-scale power outages following storms, energy service demand during holidays when outdoors lights are displayed, and tracking traditional holidays through light patterns. In our study, we used the VIIRS-DNB imagery to detect night lights and to infer electrical-grid usage and outage. Using the example of the 1 November 2014 blackout, we obtained VIIRS imagery that temporally bracketed the power outage. As a result, we could assess both the extent and duration of the blackout and the potential to gather information on local power issues.

Our preliminary analysis using the VIIRS-DNB data detected patterns during the 1 November 2014 blackout. This blackout affected large swaths of central metropolitan Dhaka; and the VIIRS-DNB imagery showed a decrease in standardized radiance values, indicative of a massive power outage. This blackout impacted critical infrastructure, such as hospitals, roads, the airport, and government buildings. Power was restored in central Dhaka by the second day (3 November 2014), about 48 hours into the blackout, and was detected by VIIRS-DNB imagery.

Our approach in this study identified the blackout areas by using VIIRS-DNB imagery. Additionally, when combining imagery with geospatial electrical and infrastructure information, our study could evaluate indications of the operating status for this electrical distribution. Reestablishing the electrical power grid in a data scarce area necessitates the identification of the infrastructure’s components from imagery. This study provides an example of integrating these datasets for understanding the dynamic physical environment relevant to the interdependencies of factors in the PMESII-PT/ASCOPE matrix for military operations.

1 Introduction

The Army may not currently be engaged in insurgency and counterinsurgency operations (U.S. Army 2009), but the requirement still exists for the Army to engage in non-combat responses, such as *Defense Support to Civil Authorities* (Joint Chiefs of Staff 2013; U.S. Army 2010) and *Foreign Humanitarian Assistance* (Joint Chiefs of Staff 2014) operations. Whether combat or non-combat operations, the Army deals with wicked problems* in complex, dynamic, and adaptive environments† (U.S. Army 2008a). The ability to address wicked problems in complex environments requires a new way of thinking. *Commander's Appreciation and Campaign Design* (CACD) (U.S. Army 2008a) introduces *design* as a methodology for applying critical and creative thinking to understand, visualize, and describe complex problems and to develop approaches to solve them. The design methodology in CACD allows commanders to develop a shared understanding of complex operational problems within their commands (commander's appreciation). Critical to design are the cognitive aspects—the need to understand and visualize the space in which complexities exist. Design emphasizes developing a holistic understanding of the operational environment (OE) and framing the problem. Working from the problem frame, design is used to develop a broad approach for problem resolution (campaign design).

1.1 Understanding the Military Decision-Making Process

In the military decision-making process (MDMP), the concept of understanding entails situational understanding, operational and mission variables, and cultural understanding. *Understanding* is more than awareness of information or the immediate surroundings. In the context of the cognitive hierarchy, understanding is knowledge that has been synthesized and

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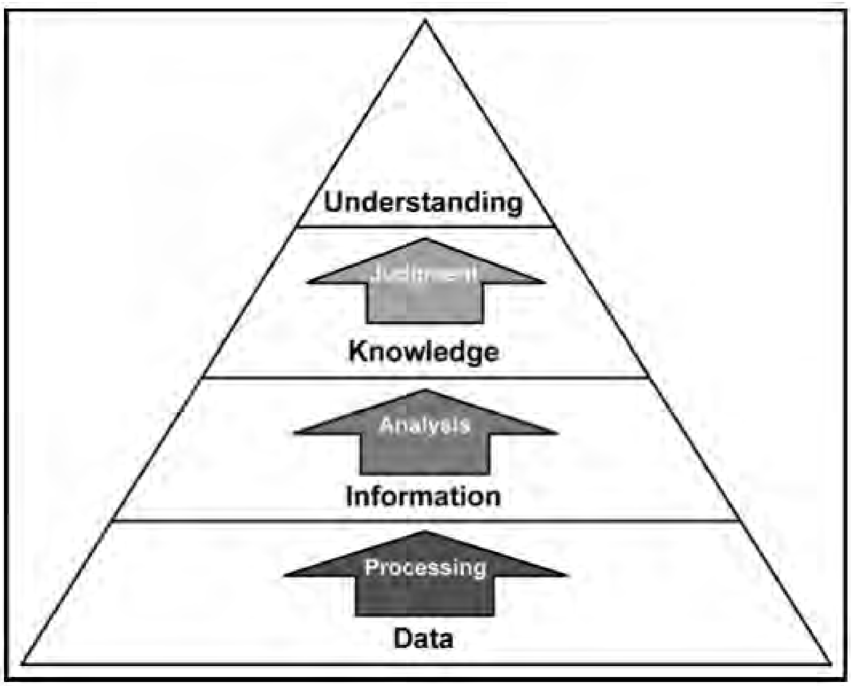
* Wicked problems are characterized by (a) being unique, (b) having a unique solution that is neither right nor wrong, (c) having no stopping rule (the solution has no definitive end), (d) being difficult to define and better understood after formulating a solution, and (e) being the symptom of another problem.

† Complex adaptive environments or systems are characterized by (a) the number (and types) of parts in the system and the non-trivial number of relationships between the parts, (b) a memory or feedback and the ability to adapt according to the memory or feedback, (c) non-trivial (non-linear) relations between the system and its environment, and (d) being highly sensitive to initial conditions (similar systems can have dissimilar futures due to slight differences at the outset).

had judgment applied to it in a specific situation to comprehend the situation's inner relationships (U.S. Army 2012c).

The term *design* is used to understand complex environments (Figure 1). In the MDMP, design, if warranted by the mission, is a key input to mission analysis. The key outputs of mission analysis include commander's critical information requirements (CCIR), essential elements of friendly information (EEFI), and an updated intelligence preparation of the battlefield (IPB). This is central to understanding this study's relevance to commanders and staff. IPB necessitates relevant information. Information is the second level of the cognitive hierarchy, as defined in *The Operations Process* (U.S. Army 2012c). Information comes from the processing of data; and in our study, information is obtained from our prescribed methodology for feature extraction on electrical or power infrastructure, including distribution.

Figure 1. The cognitive hierarchy in the military decision-making process.



"Design is not a process, but a set of 'thinking tools' that complement and reinforce [the] operations process with a rational, logical approach to an increasing complex and dynamic operational environment" (Kem 2009). The operations process is dominated by the MDMP, which focuses on analysis to develop a course of action. "MDMP is a tool to help solve 'a problem' while design is a tool to help ensure you are solving the 'right problem' without creating collateral problems" (Battle Command Training Program, n.d.) In complex OEs, a design concept is developed as an input to mission analysis (step 2 of the MDMP), which subsequently informs and updates the IPB.

Getting to the level of knowledge in the cognitive hierarchy requires context. Context results from the analysis of relevant ancillary data, but determining relevancy is non-trivial. The design procedure is iterative so that context being developed and understood should be revisited for consideration of additional information and parameters. In the final step of the cognitive hierarchy, commanders and staff apply judgment to transform knowledge into understanding (Figure 1).

1.2 Reasoning approach

The design procedure should use deductive, inductive, and abductive logic to arrive at understanding (Waltz 1998). These three forms of reasoning provide stages of inquiry, including hypothesis generation, prediction, and evaluation (Flach and Kakas 2000) (Table 1). Deductive logic is the process of reasoning from a premises to reach a logical and certain conclusion. The conclusion is reached by reductively applying general rules that apply to a closed domain of knowledge. This means that deductive reasoning results in a true answer, but the answer is constrained to the known body of knowledge. This is referred to as a closed world assumption. Inductive logic is where premises seek to supply strong evidence for the conclusion, hence the conclusion is uncertain but likely. Induction has open world assumptions, which posit that there are things unknown but true and that, in general, no single agent or observer has complete knowledge. Abductive logic is a form of logical inference that goes from an observation directly to a theory that accounts for the observation. Fundamentally, it is inference to the best explanation. Ideally, it seeks to find the simplest and most likely explanation for the observation. Sometimes, it involves developing multiple working hypotheses that are simultaneously evaluated until one proves more likely than the others. In the context of operational design, framing the problem is achieved through abductive reasoning.

Table 1. Framework for reasoning processes (after Waltz 1998).

<table>
<tr><th>Logic</th><th>Process</th><th>Implementation</th></tr>
<tr><td>Abduction</td><td>Create hypotheses for specific sets of data; discovery processes detect the presence of “interesting” patterns or relationships in data sets that may be general models or signatures that characterize events or objects of interest.</td><td rowspan="2">Data mining—the discovery of complex relationships. (This is described in Sections 4 and 5.)</td></tr>
<tr><td>Induction</td><td>Extend model hypotheses for representative sets of data to make a general assertion or explanation; validate by human analysis.</td></tr>
<tr><td>Deduction</td><td>Apply models to create hypotheses to detect and classify (explain) the presence of the target or the subject of interest</td><td>Data fusion—detection and classification. (The integration of mining and fusion techniques is described in Section 6)</td></tr>
</table>

1.3 Study objective

Data is crucial for developing the context needed for problem framing and IPB and for developing a course of action. Data mining and data fusion are complementary processes that contribute abductive-inductive (learning and discovery) and deductive (detection) capabilities (Waltz 1998). Our study proposes a methodology to learn, discover, and detect to evaluate the status of critical infrastructure, such as electrical power networks, from remote-sensing imagery. We used two sets of remote-sensing data to identify discrete objects and to develop the spatial and temporal relationship and patterns on electrical infrastructure of a region. Electrical infrastructure is integral to the complex, adaptive, urban environment. Problem framing and developing a course of action require an understanding of electrical infrastructure and its relationships to other parts of the urban system.

In this modern era, every aspect of daily life depends on electricity. The structure and functionality of the electrical grid in an operating area can affect multiple operational variables. Other infrastructure sectors that rely on the electrical grid can fail when electricity is disrupted. Thus, the role of electricity in a society is vital for its prosperity and security and enhances the economic and social well-being of an urban community.

The emphasis of this assessment is on the importance of potential data on man-made and physical infrastructure. In particular, this study examines the spatio-temporal distribution of an electrical system and power-grid functionality on a neighborhood scale in an urban area by using remote-sensing data. We focus our assessment on the transmission and distribution networks, the network patterns, and the electrical capacity based on media reports on a massive power outage in Dhaka in November 2014. In particular, this study assesses the capacity by using the pattern of power outage (i.e., blackout) and the duration of outage to evaluate the affected or impacted neighborhood.

2 Background

The U.S. Army Training and Doctrine Command's *Operational Environments to 2028* (U.S. Army 2012a) describes strategic environments as intricate and complex, containing multiple potential OEs where U.S. forces operate. Dynamic complexities require commanders to continually assess and reassess the changing factors influencing the OE, which affect not only the U.S. forces but other actors as well (U.S. Army 2012b). At various echelons, Army commanders and planners use diverse tools to assess an OE in support of the operations process (U.S. Army 2012b). Table 2 shows the entities, processes, and tools that are used.

Table 2. The hierarchy of processes and tools for exercising mission command.

Entity	Process	Tools
Combatant Commands, Joint Task Force, Joint Force Land Component Commander	Joint Operations Planning Process	DIME (Diplomatic, Information, Military, and Economic) PMESII-PT (Political, Military, Economic, Social, Informational, and Infrastructure, Physical Environment and Time)
Division, Brigade, Battalion	Military Decision Making Process (MDMP)	PMESII-PT ASCOPE (Areas, Structures, Capabilities, Organizations, People, and Events) METT-TC (Mission, Enemy, Terrain and Weather, Troops and Support Available, Time Available, Civil Considerations) ACOKA (Observation and Fields of Fire, Cover and Concealment, Obstacles, Key or Decisive Terrain, Avenues of Approach)
Company, Platoon	Troop Leading Procedures[a]	PMESII-PT ASCOPE METT-TC ACOKA

[a] This is used by units with no staff.

Contributing to the commander's understanding of the complexities of the OE and to operational success are the activities of geospatial engineers. Geospatial engineering is the art and science of applying geospatial information to enable an understanding of the physical environment as it affects terrain for military operations. The art is to understand mission variables and to apply the relevant geospatial information. The science is to produce spatially accurate products for measurements, mapping, visualization, and modeling (U.S. Army 2014a). The products being developed under this Army Study Program contribute to the art and science of Geospatial Engineering.

Military analysts have recognized that data gaps render the tactical decision-making tools used by small units (see Table 2) less effective, specifically gaps pertaining to salient features and data fidelity. During operations and because of the dynamic nature of operations, gaps in existing data are discovered. Specifically, these involve data acquisition needs or data obsolescence. Additionally, existing data may lack sufficient details, such as attributes or relationships to other features, that are likely needed for decision making. Data gaps are prone to occur in the area of civil considerations.

2.1 Situational understanding and PMESII-PT/ASCOPE

Situational understanding is the product of applying analysis and judgment to relevant information to determine the relationships among the mission variables to facilitate decision making (U.S. Army 2008b). As part of the IPB process, commanders and staff use operational variables and mission variables to help build their situational understanding (Table 3). These variables describe not only the military aspects of the environment but also the population's influences on it (U.S. Army 2008b). Military commanders and staff analyze and describe an operational environment in terms of eight interrelated variables: political, military, economic, social, information, infrastructure, physical environment, and time (PMESII-PT). The mission is examined through analysis of the mission variables: mission, enemy, terrain and weather, troops and support available, time available, and civil considerations (METT-TC) (U.S. Army 2012c). The mnemonic device of ASCOPE (areas, structure, capabilities, organizations, people, and events) was developed to guide analysis of civil considerations. Examining operational PMESII-PT variables in terms of the civil consideration, the ASCOPE device identifies key features and data requirements. If data gaps exist with regard to key features, they can be filled through CCIRs or EFFIs. The IPB process builds a database for each potential area in which a unit may be required to operate. The database is then analyzed in detail to determine the impact of the enemy, terrain, weather, and civil considerations on operations.

2.2 PMESII-PT/ASCOPE

The OE variables and their interrelationships with the environment and mission provide keen insight for decision makers and operators. These interrelationships of factors identify the contexts, both spatial and non-spatial, that provide requirements for creating mission-relevant technologies to aid operators in understanding the civil-military space (Table 3). Organizing and defining information within the doctrinal standards of PMESII-PT and ASCOPE can inform data collection objectives and examine the OE conditions.

A detailed PMESII-PT/ASCOPE matrix was created for use in IPB (Appendix A). As highlighted in the previous section, the PMESII-PT/ASCOPE paradigm is a data organization tool that is useful in determining OE relevance. The matrix tries to be comprehensive without being onerous to use. The difficulty in attaining a balance between thoroughness and usefulness lies in the wide range of locations in which the Army may deploy. As part of an iterative design process, the matrix should be revisited to consider additional entities to have the cognitive hierarchy for the course-of-action development required for commanders and staff.

Table 3. Example factors in the PMESII-PT/ASCOPE matrix for mission-planning analysis in defining the conditions of an operational environment.

	Political, P	Military, M	Economic, E	Social, S	Infrastructure, I	Information, I
Areas, A	District boundary, Party affiliation areas	Area of interest, Influence and operations, Safe havens	Sectors, Formal/informal economies, Natural resources, Trade routes, Movement of goods and services	Diaspora, Camps, Enclaves, Migration pattern, Neighborhood, Boundaries of influence	Commercial, Industrial, Residential, Rural, Urban	Coverage of different media types
Structures, S	Government centers	Bases, Headquarters	Banking, Fuel, Manufacturing, Warehousing, Markets, Stockyards	Penal facilities, Historical structures and facilities, Libraries, Schools and universities, Stadiums	Emergency shelters, Energy (distribution, natural gas, power plants), Medical (hospitals), Public buildings, Transportation (airfields, bridges, ports and harbors, railroads, roadways and subways), Waste treatment and storage, Water treatment and storage	Communication (lines, towers), Command and control systems, Internet services, Cellular and mobile services, Postal service, Print shops, Telephone
Capabilities, C	Administration, Framework (legislative, judicial, etc.)	Doctrine, Training, Materials, Manpower, Facilities, Equipment, etc.	Fiscal (currency, monetary policy)	Medical, Language and dialects, Social networks, Property records and control	Clean water, Clothing, Communication system, Law enforcement, Firefighting, Medical capacity, Sanitation	Indigenous communications networks, communication links to other areas, Internet access, Printed materials, Propaganda mechanisms, Radio, Television, Messaging, etc.
Organization, O	International partners, Political parties, etc.	Border guards, Corrections, Insurgents, Terrorists, Tribal militias, etc.	Business organizations, Guilds, Labor unions, Volunteer groups	Clan, Community, Criminal, Familial, Patriotic and service organizations, Religions, Tribes, etc.	Government ministries, Business communities	Media groups, Influential groups, Foreign governments, International organization groups, etc.
People, P	Leaders, Partnerships	Key leaders	Labor occupations, Business leaders, Consumption patterns, Avg. daily wage, Income distribution	Education, Ethnicity, Key figures, Racial structure, Vulnerable populations, Gender roles, etc.	Officials, Local people, Business communities, Facility managers, Workers, etc.	Decision makers, Leaders, Newspaper publishers, Journalists, Media
Event, E	Elections, Meetings, Speeches,	Historical, Non-combat	Agricultural and market schedules, Harvesting periods, Market days, Paydays, Planting schedule	Celebrations, Census, Civil disturbance, Criminal, National holidays, Religious holidays	Maintenance activities, Construction of projects	News cycles, Press conferences, Group meetings

2.3 Infrastructure in the PMESII-PT/ASCOPE matrix

Within the OE, infrastructure variables include the basic facilities, services, and installations that are needed for a community or society to function (U.S. Army 2009). The conditions of the infrastructure can affect specific localities within an area of operation and determine the resources required for reconstruction. Typical key infrastructures include sewers, water, energy and electrical, academic, trash, medical facilities, safety, and other considerations. Each of these key services has its own infrastructure to deliver basic needs. The degradation or destruction of these infrastructures will negatively affect both the host nation and its population.

Infrastructure can be a prerequisite and an enabler for the economic, governing, and social components of long-term state stability (Roningen and Affleck 2014). Protecting critical infrastructure and, when necessary, restoring economic foundations are a necessary part of operational planning. Long-term state stability for a society could likely be achieved through rebuilding key infrastructure. Restoring public services is a viable infrastructure development project where infrastructure is vulnerable or weak. A country's level of economic development has a substantial impact on the key features that are dependent on their existing infrastructure. In electrical infrastructure, for example, advanced economies rely on microprocessors embedded in control systems. Having these provides available, reliable, measurable, controllable, and stable power supply.

In most cases, the impact of infrastructure is interrelated: factors impact an area, the people, organizations and businesses, and social and economic capabilities, including within its structures (**Error! Not a valid bookmark self-reference.**). For example, the role of electricity in a society is vital for prosperity and security and expands the broad impact on economic and social well-being; this impact extends to the government centers, financial institutions, essential facilities (schools, water, sewer, hospitals, etc.), and communications (**Error! Not a valid bookmark self-reference.**).

In **Error! Not a valid bookmark self-reference.**, the PMESII-PT/ASCOPE matrix identifies key features that are related to or dependent on the electrical infrastructure. The entities in the PMESII-PT/ASCOPE matrix are compiled from various taxonomies. These include the Homeland Security and Federal Emergency Management Agency taxonomies of critical infrastructure (Figure 3). Also, we used the North American Industry Classification System (NAICS) to identify types of economic activity that could be affected by electrical outages. This study provides a PMESII-PT/ASCOPE matrix for analysis and development of context and lists necessary and relevant entities for understanding the electric infrastructure. This matrix contains explicit and implicit requirements that were stated in 2009 versions of these U.S. Army Field Manuals (FM):

- FM 2-0 Intelligence Operations (2014b)
- FM 2-91.4 Intel Support to Urban Operations (2008d)
- FM 3-0 Operations (2008b)
- FM 3-05.401 Civil Affairs Tactics Techniques, and Procedures (2007)
- FM 3-06 Urban Operations (2006)
- FM 3-07 Stability Operations (2008c)
- FM 3-13 Inform and Influence Activities (2013)
- FM 3-24.2 Tactics in Counterinsurgency (2009)
- FM 6-0 Commander and Staff Organization and Operations (2014c)

Figure 2. The interrelationships of factors in ASCOPE affecting infrastructure with respect to civil considerations for operational environments.

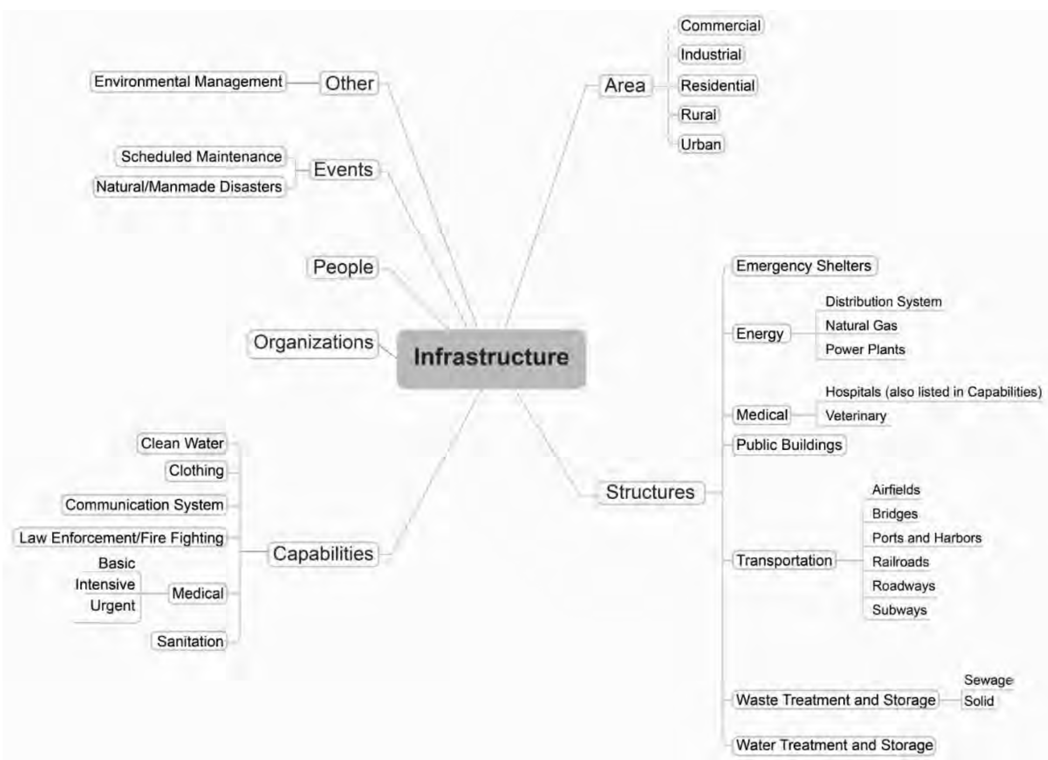
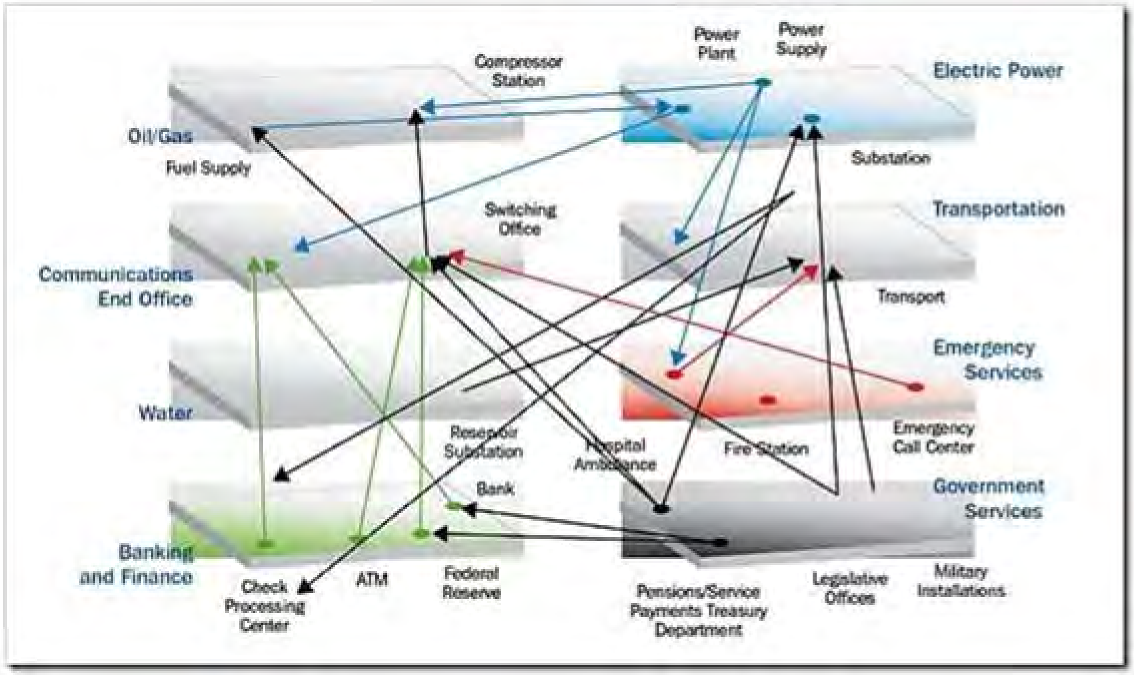


Figure 3. Interdependencies across the economy (HDIAC 2015).



2.4 Electricity generation and distribution

Electricity is a geographically focused utility constrained to a service area in a local region. Electric utilities include generation, trading, transmission, and distribution. Electricity in itself is neither renewable nor nonrenewable; yet, electricity is generated from renewable and nonrenewable sources. Simply, electricity is the flow of electrical power or charge (Vadari 2013). Electricity is generated from the conversion of other sources of energy, such as coal, natural gas, oil, nuclear power, and other natural sources (water or wind). The generating facilities or power plants can run by fuel (e.g., fossil fuel, hydroelectric, nuclear, cogeneration, solar, wind, geothermal, etc.) or by prime mover (i.e., steam turbine, water turbine, gas turbine, etc.). Power plants are typically located where resources are available to generate the electricity. The power grid forms a bridge between electrical suppliers and consumers through interconnected networks. Described by Vadari (2013), the electric-utility delivery chain is as follows:

1. Electricity is generated in the power plant.
2. A substation near the generation plant increases the voltage.
3. Electricity enters the transmission system, carrying high voltage over long distances.

4. A distribution substation near the final destination decreases the voltage.
5. Distribution lines carry electricity on smaller cables.
6. Electricity is delivered to the end user.

The electricity transmission transports bulk quantities of electricity via electric conductors (composed of substations) from the power plant to the electrical distribution system. Substations are where much of an electrical system comes together and consists of components such as transformers, circuit breakers, protective relays, etc. Generation substations handle from supply to consumption levels; thus, voltages are either stepped up or down. Distribution substations distribute lower voltage capacities; thus, they are smaller than the generation substations, delivering electricity to the end users.

2.5 Operational scenario for blackout

Using the example of the blackout, we will illustrate how a commander can use in an operational environment the methodology created by this study. Let us assume that restoring power is part of a stabilization operation. Electrical power is vital in reconstruction activities because it supports many essential functions for daily life. The destabilizing effects of a lack of electricity are why the electrical power system has always been a high priority target in warfare (Lewis 2010). Stabilization efforts are led by the Department of State and use a whole-of-government approach to include a range of U.S. Government agencies and departments. Within this approach, the responsibility of the military is to protect the population and to enable their security, thereby creating an environment for political, economic, and human security (U.S. Army 2008c). A commander's concern is to shore up essential services while reestablishing the electrical power grid. These efforts must occur simultaneously. The essential services for restoration are identified through use of the taxonomy matrix. The remote-sensing methods are used for locating electrical system components and for determining areas affected by the blackout.

Commanders and operators consult the ASCOPE variables of the taxonomy matrix (Appendix A) to identify mission-essential elements of the electric infrastructure. The *Structures* column identifies the key features that are impacted by electricity. The *Capabilities* column identifies the functions that are provided by those features listed under *Structures*. The

Areas column identifies the areas that affect or are affected by the features. The *Organizations* column identifies the organizations typically associated with the features, and the *People* column identifies the categories of people who occupy positions of responsibility or people who are affected. The *Events* column provides examples of significant occasions, and the *Other* column lists other things to consider.

To shore up essential services in this example, we would look for structures whose capabilities are needed for stabilization. These would include centers for public health and safety (i.e., hospitals, clinics, morgues, police, fire, military, jails, and prisons) and for food storage and distribution. Once these features have been identified, their location and status must be determined. In data-scarce areas, the open-source geospatial data available through Google Earth can be a starting point. Determining the status of these features can be difficult, depending on the nature of the crisis. Our approach is to use the method detailed in this study to identify the blackout areas by using Visible Infrared Imaging Radiometer Suite (VIIRS) imagery. A simple overlay analysis of blackout areas and key features can give an indication of the operating status.

Reestablishing the electrical power grid in a data-scarce area necessitates identifying from imagery the infrastructure's components. The use of high resolution WorldView-2 (WV2) satellite imagery aids in feature detection through visual interpretation. When combining WV2-derived products (features) with the VIIRS methodology to delineate impacted areas of the blackout, it is possible to focus on affected areas, thereby narrowing the search for electrical-grid components or providing an independent assessment of how a local government is managing and prioritizing electrical distribution in an area of interest. This integrated multi-sensor approach may also prove useful for monitoring the long-term health of the system.

3 Study Region

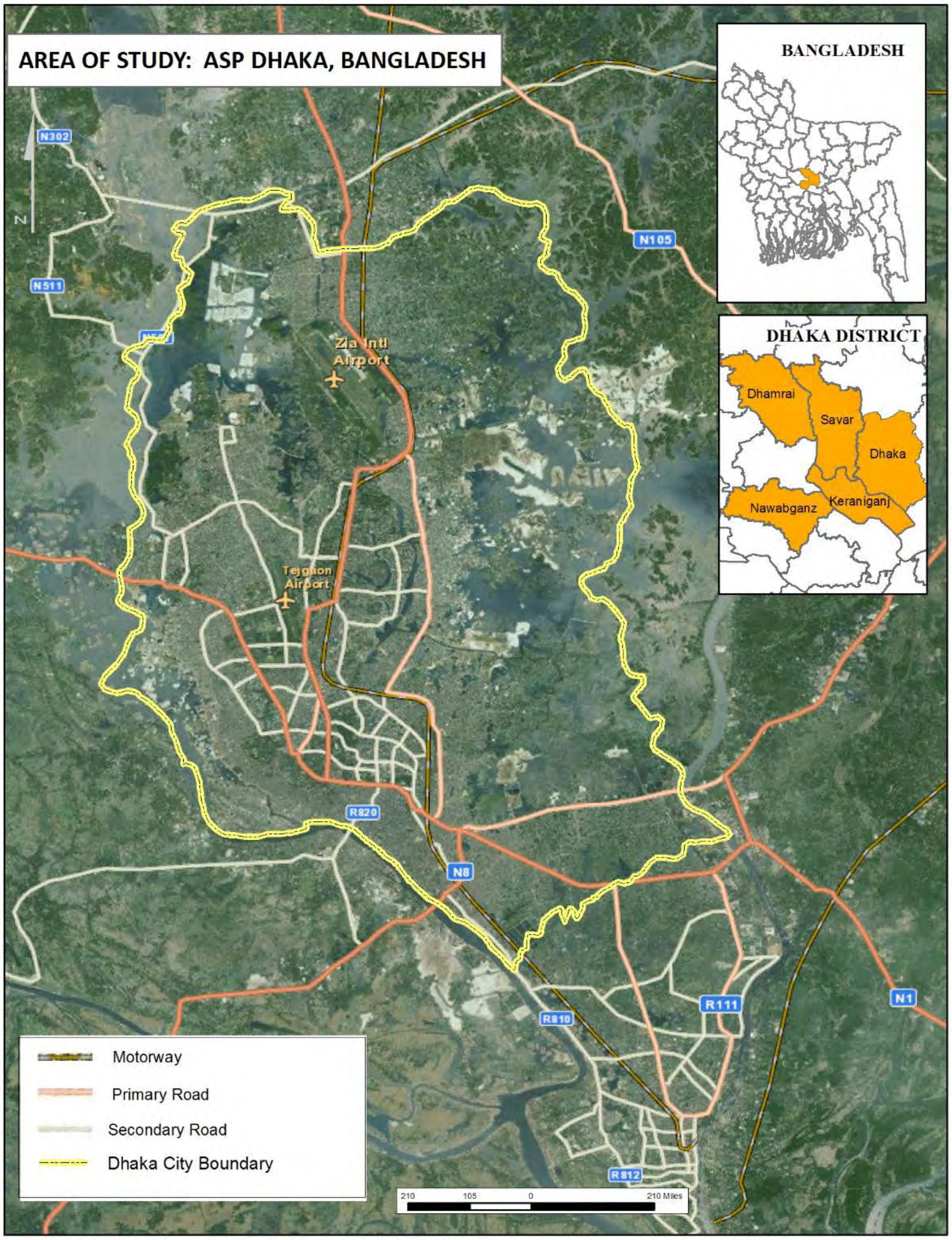
3.1 Environmental setting

Our study region for this assessment was Dhaka, the capital of the People's Republic of Bangladesh (23.810332° N, 90.412518° E; Figure 4). Historically, Dhaka became the capital city of East Pakistan after the partition of the Indian subcontinent in 1947 into India and Pakistan (Dewan and Corner 2014). Bangladesh became an independent state in 1971, and Dhaka remained as a capital of the country. Dewan and Corner (2014) provide the historical background and detailed environmental and socioeconomic settings of Dhaka.

Dhaka is composed of several municipalities and unions or urban areas. The spatial extent or boundary of Dhaka varies from 930 to 1528 km^2 in area, depending on the data sources (Dewan and Corner 2014). This low-lying city borders the eastern banks of the Buriganga River at an elevation of 4 m above sea level. The population of Dhaka is more than 16 million inhabitants (CIA 2015) and currently is considered one of the most populated megacities in the world (Dewan and Corner 2014).

The climate of Dhaka is considered to be tropical monsoon with three distinct seasons, including monsoon (June–October), summer (March–May), and winter (November–February). Approximately 80%of the precipitation occurs during the monsoon season with an average annual rainfall of about 2 m. In the summer months, the temperature ranges between 28°C and 34°C, while in the winter months, temperature ranges between 10°C and 21°C.

Figure 4. The project study area.



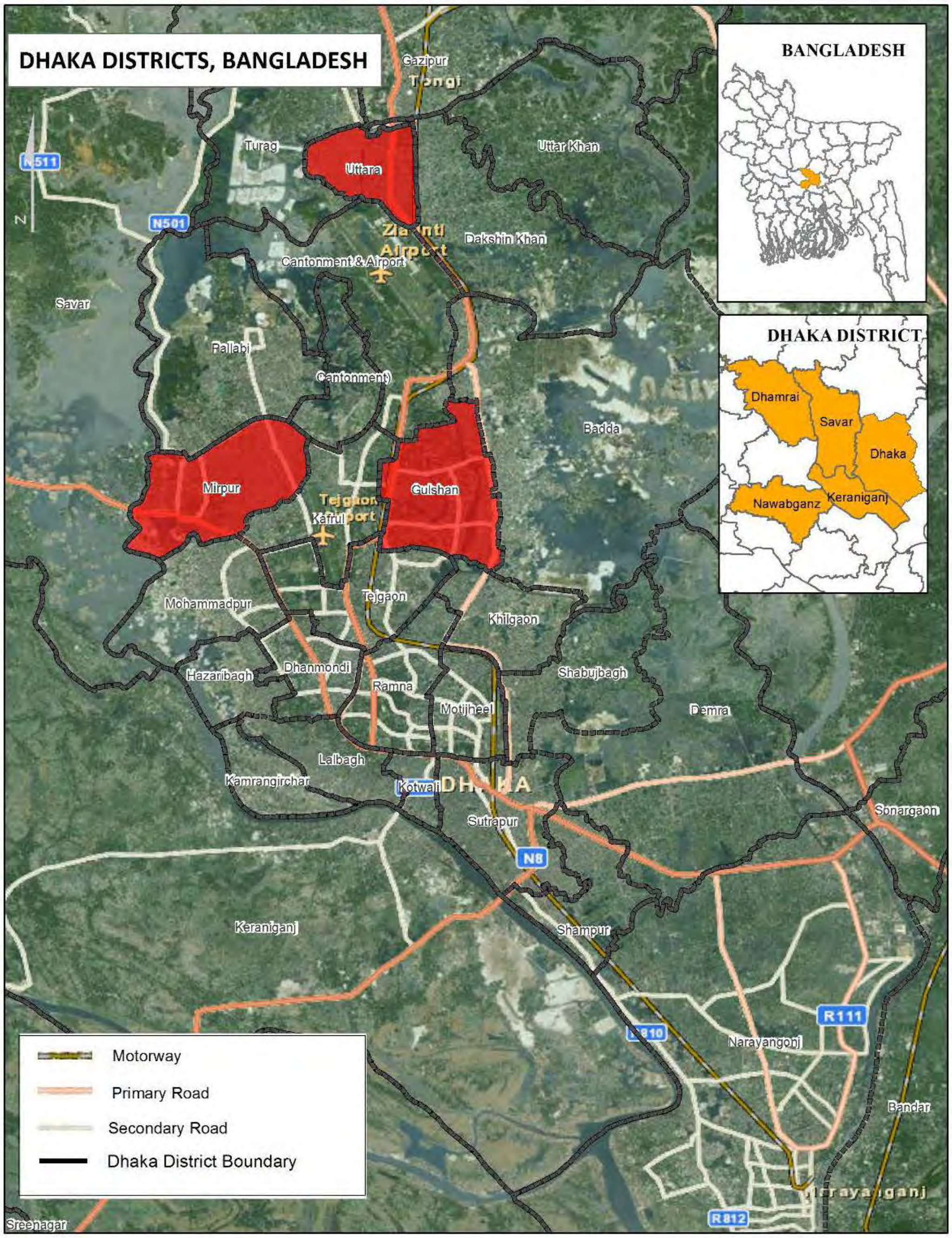
3.2 Electrical infrastructure

The Bangladesh Power Development Board (BPDB) was established in 1972 soon after Bangladesh became an independent country (BPDB 2015). In the early ’90s with the country’s economy performing well, the electricity demand grew; and the government had gone through several reforms to privatize the power sector (DESCO 2015a). Based on 2011 figures, electricity in the country was generated with conventional fuel sources, including 82% natural gas, 9% imported oil, 5% coal, and 4% hydropower (Kabir and Endlicher 2014). BPDB currently provides the majority of generation and distribution of electricity for the western part of the country and other urban areas, but not for Dhaka.

The generation and distribution of electricity for Dhaka is provided by Dhaka Power Distribution Company Limited (DPDC), a private sector firm, and managed by Dhaka Electric Supply Company (DESCO), a government executing agency (DESCO 2015a). The population in Dhaka continues to struggle with an insufficient supply of electricity (Kabir and Endlicher 2014) although the current report by DESCO highlighted expansion and upgrade of the electrical systems to meet the increasing electricity demand for the area (DESCO 2014). As of 2014, DESCO reported having 30 (33 kV and 11 kV) substations; and transmission consisted of both overhead and underground lines (DESCO 2014) with more than 5000 distribution transformers. In 2013–14, the generating demand capacity provided for Dhaka could handle up to 960 MW, and the maximum demand was reported as 786 MW.

However, scheduled load shedding occurred in various places, which was likely to avoid excessive load on the generating plant (DESCO 2014). This load-shedding schedule could potentially be a routine procedure for which DPDC has an online link for publishing the power outage in various locations (DPDC 2015; DESCO 2015b). These rolling power outages have continued to occur in 30 min blocks or an hour in some places, and the schedules are staggered within the affected zones. The zones affected in the load shedding are mostly in the Gulshan, Mirpur, and Uttara districts (Figure 5). The 2014 load-shedding posts were occurring at least twice a day, while the 2015 schedules are taking place at least three times a day. Thus, we can assume that the city continues to struggle to provide an adequate supply of electricity as the service area continues to grow and demand continues to increase.

Figure 5. The districts (in *red polygons*) affected by the load-shedding schedule.



3.3 1 November 2014 blackout

We used media reports on a massive power outage in Dhaka in November 2014 to provide context and serve as a type of ground truth for testing the potential applicability of remote sensing datasets for understanding the dynamic characteristics of electrical infrastructure and the power restoration responses on the part of the local government in the area. A major unplanned power outage occurred that affected Dhaka and the entire national grid when a failure occurred on 1 November 2014 between 11:00 a.m. and 12:00 noon local time along a transmission line that brought power from Baharampur in West Bengal, India, to Bangladesh's Bheramara. This disruption caused power production to cease at other major power stations within the country (The Daily Star 2014a). Some areas had power temporarily restored by the afternoon but had power cut off again as the components of the system were being brought back online. On Saturday afternoon, Dhaka was reported to be mostly dark with backup power provided preferentially to major government hospitals, the president's house, the prime minister's residence, and the airport (International Business Times 2014; Alam 2014). The power company reported that by 9:30 p.m. local time, half of the coverage area had been restored, that most residents had power by 1:00 a.m. on Sunday, and that they expected the system to return to normal by Sunday afternoon. Some locales were able to continue partial operations during part or all of the blackout as frequent outages have induced many larger buildings to make use of generators as backup systems (Figure 6), and newspaper reports indicated that residents and employees rushed to buy fuel to power their generators (Manik and Najar 2014; The Daily Star 2014b). However, backup generators are both expensive to run and require periodic shutdowns to prevent overheating. Many hospitals reduced operations to serve intensive care wards (Figure 7) while diagnostic equipment sat idle and routine procedures that rely on water, such as patient preparation and dialysis, could not be performed due to electricity-related problems with the water supply (The Daily Star 2014b). Five days after the outage, a seven-member fact-finding committee reported that they were unable to identify the cause behind the malfunction (The Daily Star 2014a).

Figure 6. During the blackout, light shone from car headlights and from select buildings with access to generators (The Daily Star 2014a).

Figure 7. The flashlight setting of a mobile phone serves to check on a patient at the High Dependency Unit of Dhaka Medical College Hospital (The Daily Star 2014b).

4 Data

Current commercial satellites provide high-resolution imagery to extract infrastructure conditions for military operational assessment. One of the most common applications of remote-sensing imagery is the delineation of vegetative land-cover characteristics. Similar methodologies can be applied to extract urban features, infrastructure, and night lights. The National Oceanic and Atmospheric Administration (NOAA) VIIRS satellite provides image data on night lights, and the Digital Globe constellation of WorldView satellites provides high-resolution imagery to interpret infrastructure and electric power-grid networks.

4.1 WorldView-2

WV2 is a commercial earth observation satellite owned by Digital Globe, providing commercially available panchromatic imagery of 0.46 m resolution and eight-band multispectral imagery with 1.84 m resolution. This eight-band multispectral imagery is well suited for a variety of urban planning applications, mapping of land surfaces, coastal and geological mapping, oil and gas mapping, and many others applications (Navulur 2006).

The Digital Globe image archive was researched for available WV2 image scenes of the Dhaka area of interest. Search parameters included date range (2012–14), cloud cover (<5%), and time of year (January–May: dry season). A total of 11 WV2 images were acquired on 28 January 2012, 22 February 2013, and 27 April 2014 and were used as a high-resolution baseline of the area of interest. Interpretation of this WV image dataset provided neighborhood-level information on the electricity distribution network, including transmission towers, power poles, and substations.

4.2 VIIRS

The NOAA VIIRS sensor onboard the Suomi National Polar-orbiting Partnership (NPP) satellite provides global day–night light composite data. More generally, VIIRS collects visible and infrared imagery and radiometric measurements of the land, atmosphere, cryosphere, and oceans. VIIRS data are designed to be used for a variety of purposes similar to those of the Moderate Resolution imaging Spectroradiometer (MODIS) data to which it is a follow-on satellite for measuring Earth’s albedo, cloud and aerosol properties, ocean color, sea and land surface temperature, ice motion, and fires. The addition of data streams that allow for analysis of nighttime lights provides a significant improvement in resolution and onboard calibration capacity over the existing satellite data stream designed for night light analysis, that of the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) (Shi et al. 2014).

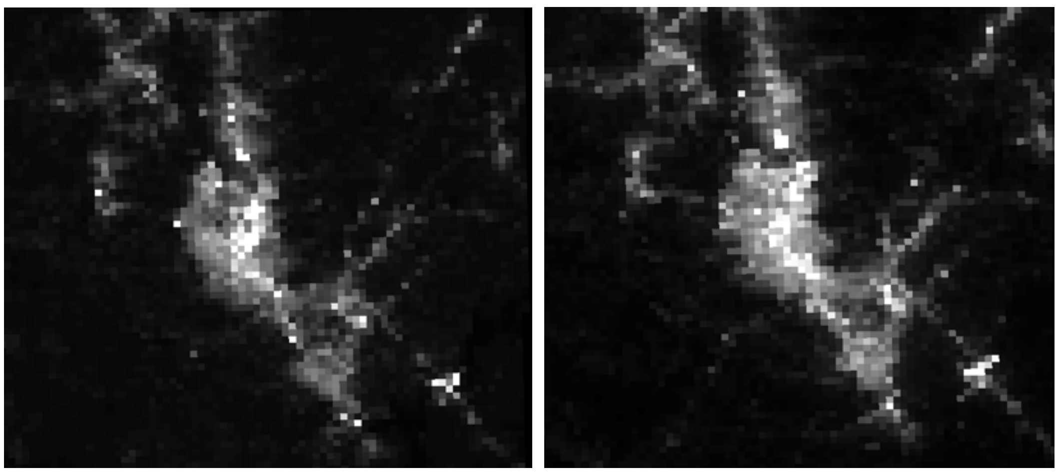
The use of VIIRS Day/Night Band (DNB) data has been primarily focused on the role of technology, economics, and individual behavior in the attenuation of global energy demand (Lijesen 2007; Wilson and Dowlatabadi 2007; Gillingham et al. 2009; Popp et al. 2009; Stern 2014). Additional studies using VIIRS-DNB have linked power generation, power consumption, and power plant CO_2 emissions (Letu et al. 2014); identified statistical relationships between light emission and city-scale gross domestic product (Shi et al. 2014); analyzed community-scale power outages following large storms (Cao et al. 2013); and inferred variations of energy demand patterns during holiday timeframes at community-level scales in the United States and elsewhere (Román and Stokes 2015).

In this study, we used the VIIRS-DNB imagery to detect night lights and to infer electrical-grid usage and outage. The DNB is sensitive to visible and near-infrared wavelengths ranging from daylight down to the low levels of radiation observed at night. The low spatial resolution of DNB data (750 m) and the large swath width (120 km north–south by 3000 km east–west) (NOAA 2014) allowed us to assess and monitor the electrical-grid network of megacities, such as Dhaka.

The VIIRS provides complete coverage of Earth twice a day in ascending and descending overpass modes. The ascending overpass is in the early afternoon, and the descending overpass is in the early morning (NOAA 2014). We used the VIIRS-DNB early morning, descending overpass mode, between 1:00 a.m. and 4:00 a.m. local time. This time of day captured the illumination of electrical lighting at night in Dhaka. The variations of illumination can be the result of socioeconomic regions of the city, electrical power failure due to weather events, or selective-intermittent electric power supply.

Accessing the NOAA Comprehensive Large Array-Data Stewardship System (NOAA 2014), our study conducted a data search for VIIRS-DNB of the Dhaka area and then downloaded and processed it into geospatial coordinates. Because a single VIIRS image frame comes in a large swath covering a large aerial extent, we extracted a defined subset of the Dhaka area. Figure 8 shows examples of extracted VIIRS-DNB of Dhaka for 1 and 23 March 2013.

Figure 8. VIIRS-DNB collected for the Dhaka area: *left* image was on 1 March 2013 and *right* image was on 23 March 2013.



The point sources of light and the stability of these sources over periods of time are affected by atmospheric effects (clouds and aerosols), surface reflectance, and geometric factors. The type of light source and where it is located contributes to the strength of brightness reflected by the surface and detected by the VIIRS-DNB sensor. Section 5.2 discusses corrections for these factors for this study

Inspection of the DNB images of Dhaka indicated that the brightest pixels coincide with a bridge crossing (southeast corner), major road intersections (center), and the international airport and train station (north-central portion of the images). The range of grayscale pixels represents built-up areas with secondary road networks with lower light reflectances (an indication of a reduced number of street lights and point sources of light). The dark, or black, pixels are of rural areas (agricultural) without reflectances of sources of light. There is variation in the bright pixels between these two image dates. However, the variation of the grayscale range of pixels may be an indicator of the impact to the socioeconomics of the built-up areas. As a possibility, the variation of grayscale to darker pixels in the built-up areas may indicate local power outages and reduced usage.

5 Methods

5.1 WorldView-2 panchromatic sharpening

To achieve the highest level of resolution, we applied panchromatic sharpening to each image. This process uses a higher-resolution panchromatic image (raster band) to fuse with a lower-resolution, multiband raster dataset. Panchromatic sharpening increases the spatial resolution and provides better visualization of a multiband image by using the high-resolution, single-band image where the two rasters fully overlap. This process is applied just to the panchromatic (single-band) image, which is assumed to be the base image, and is then colored with the multiband image, thus preserving the resolution of the panchromatic image throughout the panchromatic-sharpening process. To perform the process, this project used the ArcGIS Image Server, which provides a number of image fusion methods to choose from (the Gram-Schmidt transformation, the Brovey transformation, Intensity-Hue-Saturation transformation, ESRI (Environmental Systems Research Institute) pan-sharpening transformation, etc.). Each of these methods uses different models to improve the spatial resolution while maintaining the color, and each is adjusted to include a weighting so that a fourth band can be included (such as the near-infrared band available in many multispectral image sources). By adding the weight and enabling the infrared component, these steps improve the visual quality in the output colors. Our project used the ESRI pan-sharpening transformation, which uses weighted averaging and the additional near-infrared band (optional) to create its pan-sharpened output bands. The weighted average (WA) is calculated with the following formula

$$WA = \frac{R * RW + G * GW + B * BW + I * IW}{RW + GW + IW} \tag{1}$$

where

R = red band,
RW = red with weighted average,
G = green band,
GW = green with weighted average,
B = blue band,
BW = blue with weighted average,

I = infrared, and
IW = infrared with weighted average.

The result of the weighted average (Equation 1) is used to create an adjustment value (ADJ) that is then used in calculating the output values as shown in the following example:

$$ADJ = pan\ image - WA$$

$$Red\ output = R + ADJ$$

$$Green\ output = G + AD$$

$$Blue\ output = B + ADJ$$

$$Near\ Infrared\ output = I + ADJ.$$

Thus, the weight values of 0.95, 0.7, 0.5, 1.05 (R, G, B, I) provided the best results for the WV2 imagery.

Once panchromatic sharpening was complete, we could begin analyzing the imagery. Starting in outlying, rural areas and water crossings and zooming to a scale of approximately 300 m, we could easily identify and follow electrical power lines, power structures (plants, substations, etc.), and towers. As the lines approached the densely populated urban areas of Dhaka, they became more difficult to identify, so we used Google Street View to visually locate towers and their alignment, which helped to identify them on the imagery. The image analysis thus allowed for a new vector dataset to be created that serves to identify power plants (point), power lines (polyline), individual towers (point), and the Dhaka power grid as a whole.

5.2 VIIRS corrections

5.2.1 Cloud cover

One of the primary purposes of the VIIRS-DNB is to allow for better nighttime characterization of cloud cover and cloud structure so as to improve overnight weather prediction capabilities. Therefore, one VIIRS product created from this analysis was the VIIRS cloud mask (VCM). The cloud mask provided probability of contamination, type of cloud, and information about cloud shadow for each pixel at each time step. In an analysis of electrical outages following the 2012 Washington, DC, derecho (a widespread, straight-line wind storm) and the 2013 Hurricane Sandy, we chose dates for the pre- and post-storm analyses that were relatively cloud-free; and then we excluded from the study all cloud-contaminated pixels identified by the VCM (Cao et al. 2013). We note that the VCM was a beta product at the time of this publication. As we developed a methodology for data analysis, we chose relatively cloud-free seasons for the initial data analysis and avoided images that contained visual evidence of cloud structure. Later analysis excluded pixels based on the presence of any cloud contamination indicated by the VCM. However to characterize the frequency, duration, and areal extent of outages, we must factor into the types of metrics developed periods of time for which cloud cover makes the VIIRS data unusable.

5.2.2 Moonlight

For nighttime light products that are not time sensitive, researchers typically use data from periods with low lunar light. However, to map short-duration or small changes in lights over time, the effect of moonlight must be estimated so that data from all phases of the lunar cycle can be made useable. Both the lunar phase (from full to new moon) and the lunar elevation affect the total amount of moonlight. The lunar radiance, L_m, can be calculated after Miller and Turner (2009) by using the MT2009 model and

$$L_m = \frac{E_m}{\pi} \rho cos(\theta_m) \tag{2}$$

where

θ_m = lunar zenith angle,
E_m = downwelling top-of-atmosphere sensor response function-weighted lunar irradiance, and
ρ = band-averaged top-of-atmosphere reflectance (derived from daytime M4, M5, and M7 visible VIIRS channels).

An alternative approach for initial analysis, which we have undertaken in this study, can also focus on relative changes across all pixels in a scene such that any night-to-night differences due to changes in moonlight are subsumed by a normalization and standardization of light levels across the scene.

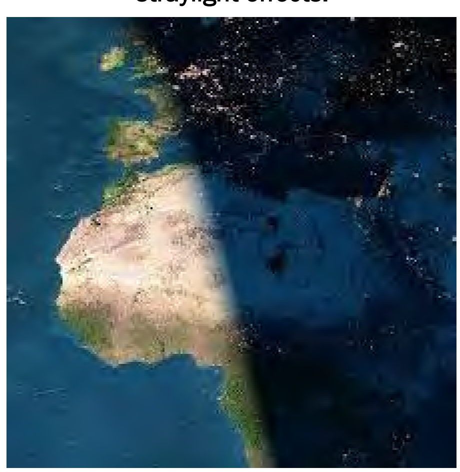
5.2.3 Albedo

Increases in surface albedo can cause increases in the amount of light reflected into space. Snow cover, for example, could cause increases in DNB output that are unrelated to anthropogenic changes in electricity usage. Román and Stokes (2015) used the MODIS snow cover product (MCD12) to exclude snow-contaminated areas from analysis and a MODIS albedo product (MCD43) to further quantify the relative contribution of natural/daytime versus anthropogenic/nighttime changes in DNB output. Our study focused on a location where snow was not present; thus, there was no need for albedo corrections due to snow.

5.2.4 Day/night terminator

A *terminator straylight effect* may occur when the satellite passes through the day-night terminator (Figure 9). The magnitude of this effect can be estimated and may be particularly significant, for example, in much of the northern hemisphere near the summer solstice when overpass times span dawn and dusk (Cao et al. 2013). In our initial research, we selected locations at lower latitudes such that overpass times did not occur at dawn or dusk; and therefore, this effect should be negligible.

Figure 9. Areas near the day/night terminator may require additional processing to estimate and remove straylight effects.



5.2.5 Non-electrical sources of light

Light sources captured by VIIRS can include fires, gas flares, volcanoes, lightning strikes, unspecified background noise, and light output from electricity usage (Shi et al. 2014). In a study conducted in China, Shi used the highest pixel value of the three largest Chinese megacities to threshold DNB data outside of cities to eliminate unusually bright sources of light that might indicate non-electrical sources. Any values located outside of cities above this threshold were replaced by the highest value of that pixel's immediate neighbors. In our study, we do not include this processing step at the outset but suggest that it could be refined further with time-series information that could potentially identify, differentiate, and characterize these other types of light.

5.2.6 Other sources of uncertainty and error

Cao et al. (2015) noted four additional sources of error apart from uncertainty in the above-mentioned effects: aerosol and vapor content, slight daily changes in observation time and viewing geometry, and normal variation in human usage habits. The total estimated uncertainty (10%) from all factors in the DC derecho case study was less than the storm-related light outage percentage (30% to 80%) and, according to Cao et al. (2015), justifies the use of this dataset to examine electrical outages. Other authors include in their calculations of total nighttime light output model-derived atmospheric transmittances on both lunar-ground and ground-sensor paths (Román and Stokes 2015). In our initial analysis, we did not attempt to remove these effects.

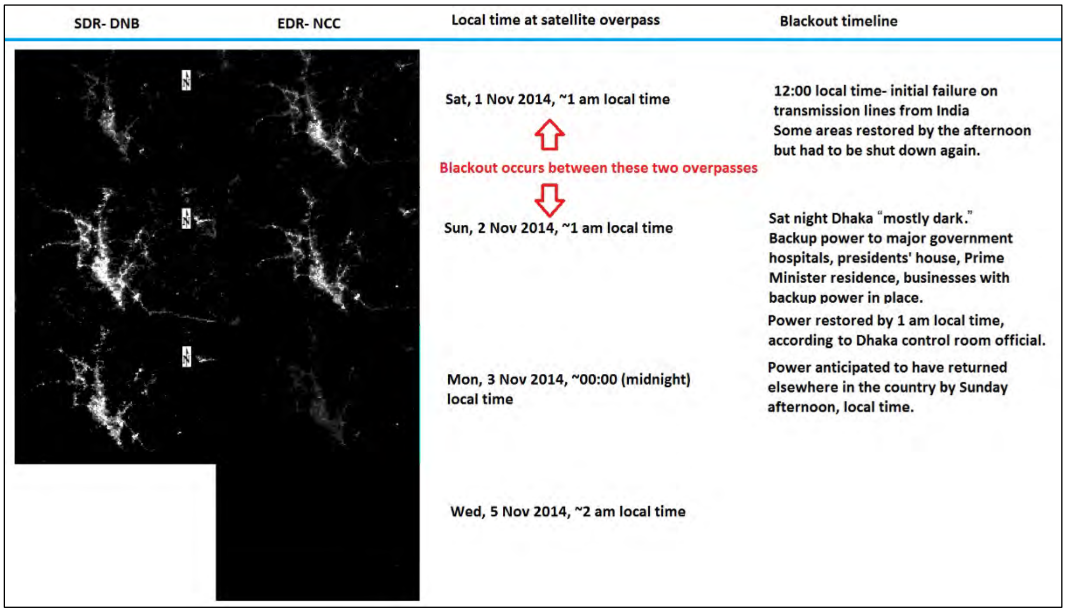
5.3 VIIRS-DNB power outage analysis

To assess both the extent and duration of the blackout and to assess the potential of these data sets to remotely gather intelligence on local power issues, we obtained two types of VIIRS imagery that temporally bracketed the power outage on 1 November 2014.

Figure 10 presents thumbnails of both SDR (sensor data record) DNB radiance and EDR (environmental data record) near-constant-contrast (NCC) pseudo-albedo files along with a timeline of blackout-related events. Note that satellite overpass times are given in local time whereas the satellite files (Appendix B) are named using the UTC (Coordinated

Universal Time) times that bracket the swath. The local time zone in Dhaka is UTC +6, which means that the local time is six hours ahead of the satellite overpass timestamps.

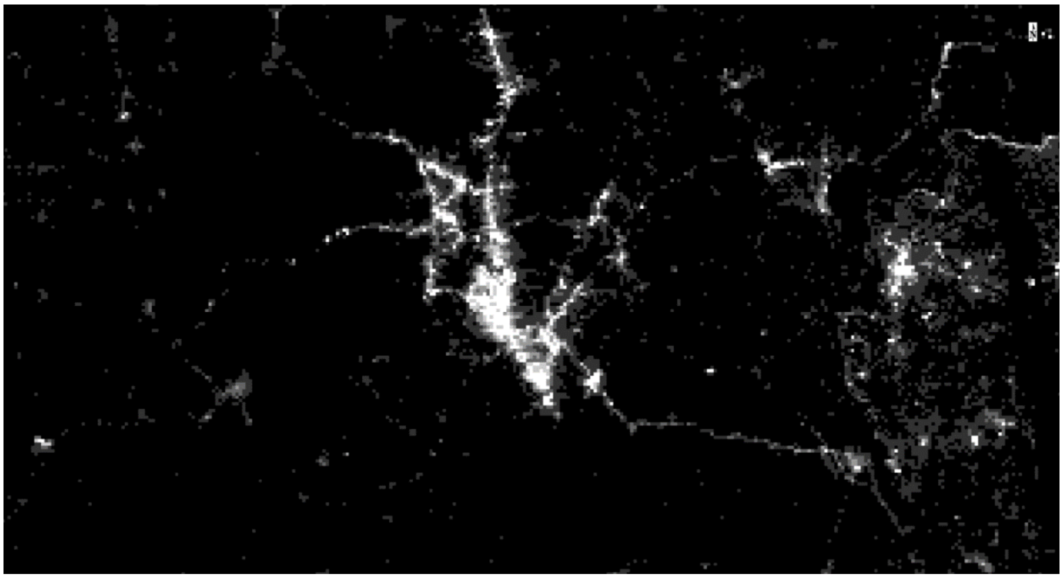
Figure 10. Dhaka and environs as seen by DNB and NCC VIIRS data from the early morning local time on 1, 2, and 3 November 2014. The DNB data has been geocorrected with bowtie mitigation applied via routines internal to ENVI (Environment for Visualizing Images software), and the NCC data is uncorrected.



Because the blackout in question affected a larger area than just the city of Dhaka, we selected a swath of data for analysis that spanned the entire metropolitan area, surrounding towns, and a significant east–west band in the central part of the country by using a spatial subset of the downloaded DNB data from 89.5° to 91.5° E and 23.3° to 24.3° N (Figure 11). The eastern portion of this band extends into the Indian state of Tripura.

The blackout occurred near the beginning of the dry season in Bangladesh, and cloud structure was not visible in the images we analyzed. To reduce the effect of any temporal changes in light levels due to moonlight or other atmospheric effects, we analyzed nightly changes in radiance values where each pixel was subject to a standardization algorithm. To standardize the relative differences in radiance across the scene, we subtracted the image mean from each pixel's radiance value. Subsequently, this value is divided by the standard deviation of radiance values across the scene, giving a standardized radiance value. Changes in this value were compared from one night to the next to indicate pixels that experienced increases or decreases in radiance values as compared to other pixels in the image. Results were then binned for display in one of 11 categories, from an increase in radiance of five standard deviations to a decrease in radiance of five standard deviations.

Figure 11. Nighttime lights from VIIRS-DNB radiance in Dhaka and surrounding regions during Sunday, 2 November, at 1:00 a.m. local time.



6 Results

The following three subsections describe the integration of data-mining techniques applied to assess the spatial and temporal patterns of the electrical infrastructure in the city of Dhaka.

6.1 High-tension overhead transmission lines

Mapping Dhaka's electrical network through the analysis of WV2 imagery began with focusing on the outlying, under-developed areas outside the city limits of Dhaka where we could most easily identify the electrical towers from a distance of 300 m above sea level (Figure 12). We identified a total of 608 transmission towers at regular intervals averaging about 375 m. They were primarily of the steel lattice variety, which has the ability to carry anywhere from single- to four-circuit high-voltage lines (Figure 13a). In some areas, lines were supported by smaller, single-circuit H-Frame towers; and, within the city, we identified wooden, low-voltage lines in addition to the high-voltage steel lattice (Figures 13b and 13c).

This study mapped approximately 215 km of transmission lines in and around Dhaka. They tended to cross open agricultural lands, rivers, and water bodies, continuing for several kilometers around Dhaka or terminating at power plants or stations on the outskirts of the city. The longest continuous lines were located 13 km west of the city center and extended more than 32 km on a north–south alignment.

As the transmissions lines approached the city limits, the distances between them tightened and converged into double, sometimes triple, parallel lines, creating easements half a mile wide before connecting to a power-plant facility. From this point, the lines entered densely packed urban neighborhoods, making it difficult to identify and locate any evidence of towers or overhead lines. Those that we could identify were short in length and terminated at small substations. It therefore seems plausible that, while overhead lines are present throughout the city, just as many have been moved underground.

Figure 12. Power distribution for the city of Dhaka.

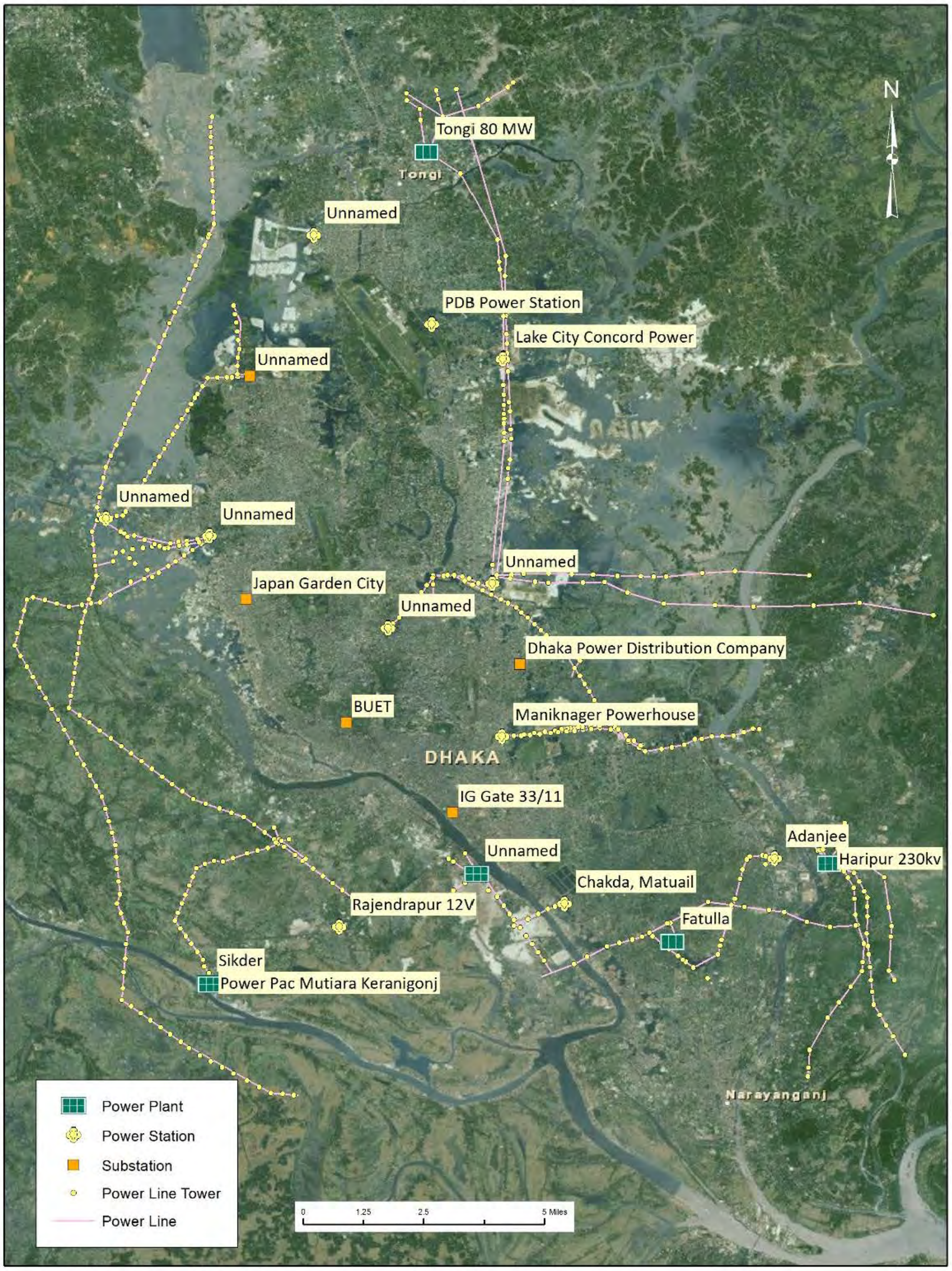


Figure 13. Examples of power transmission lines.

(a) High-voltage transmission lines

(b) Low-voltage power lines

(c) H-frame transmission towers.

6.2 Power plants, station, and substations

We identified a total of 23 electrical power facilities in and around the city of Dhaka: power plants, stations, and substations. The largest ones were located along the outskirts of the city center. Tongi, Haripur, and a third, unnamed power plant west of the Japan Garden area appeared to be handling the highest distribution loads in the north, southeast, and west, respectively. Haripur in particular appeared to be distributing power directly between Dhaka and Naranaganj. Of the four stations located within the city, three of them, Japan City, BUET, and IG Gate 33/11, were each 5 km apart and were situated on the same northwest–southeast alignment. The fourth, Dhaka Power Distribution Company, was located at the airport 6 km northeast of BUET. It is important to note that all four of these were located in the densest parts of the city and did not appear to be connected to any overhead transmission lines.

To the south, Haripur, Fatulla, Rajendrapur, Power Pac Mutiara, Kerani-gon, and Skider were all located at river crossings, which may indicate that these areas were producing hydroelectric power.

6.3 Lighting illumination during the blackout period

Figure 14 shows changes in standardized radiance values between approximately 1:00 a.m. on Saturday, 1 November, prior to the blackout and a similar time on Sunday, 2 November, following the blackout. Bright red pixels indicate that the location registered an increase in radiance over the past 24 hours, and bright blue pixels indicate a decrease in radiance over this period. Overall, we observe that there are areas that registered both increases and decreases in nighttime lights, with many areas appearing to register both types of changes in close proximity. This blue/red “ribbon” effect is likely an indication of pixel shifting due to inaccurate geocorrection, bowtie correction, or resampling during change detection. Until further analysis and correction, this presumed inaccuracy means that the effective area of analysis should not be at the pixel level, as would be ideal, but rather should focus on areas where overall spatial trends are clearer. Figure 15 shows the change detection analysis for the subsequent pair of images; these show the difference in standardized radiance between approximately 1:00 a.m. Sunday, 2 November, and Monday, 3 November, two days following the initial blackout. We highlight several locations in the figures and discuss them below.

Location A in Figure 14 shows where large swaths of central metropolitan Dhaka registered a decrease in standardized radiance values, indicative of a massive power outage. Despite statements in newspaper reports that “most residents” had power by 1:00 a.m. the night following the blackout, central Dhaka appears to have experienced significant outages between 1:10 and 1:16 a.m. during the window of the satellite overpass. Figure 16 overlays this result from Figure 14 on the power distribution infrastructure of the city of Dhaka and shows that this area is heavily urban and is interspersed with pixels indicating both more neutral and positive changes in radiance. Figure 16 shows one such location where an increase in radiance occurred. Here, given some potential pixel shift or offset, it is possible that the areas showing increased relative radiance were those targeted for either significant backup power or for early repairs. The arrangement of these pixels from the coarse resolution VIIRS data combined with the WV2 data depicting the shape of the airport, Presidential Palace, and National Assembly Hall where the Parliament convenes indicated that both data do not perfectly align (Figure 17). (This misalignment of pixels is likely due to the ribbon effect previously discussed and to geoprocessing discussed later in this section). However, showing the results relative to the surrounding areas, these locations registered an increase in power on the night following the blackout (Figure 17).

Figure 14. The change in standardized radiance between the early morning prior to and following the blackout. *Red* areas indicate increase radiance, and *blue* areas indicate decreased radiance. The circles with letters are designated for close-up assessment.

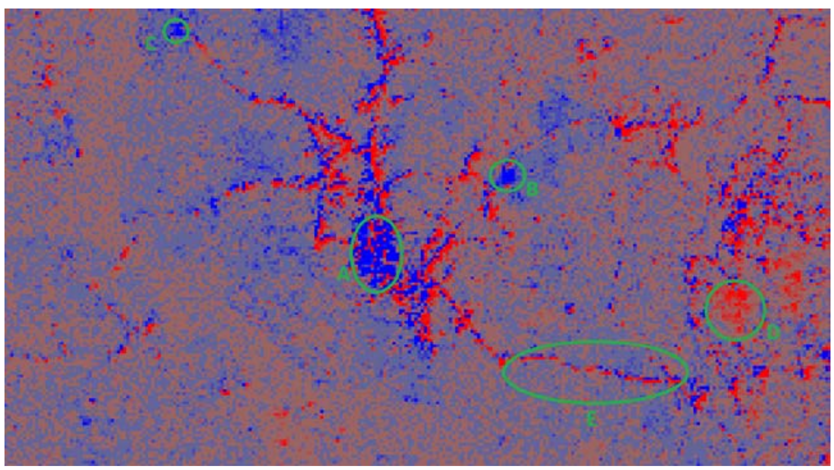


Figure 15. A 24-hours change in standardized radiance between the early mornings two days following the initial blackout. *Red* areas indicate increase radiance, and *blue* areas indicate decreased radiance.

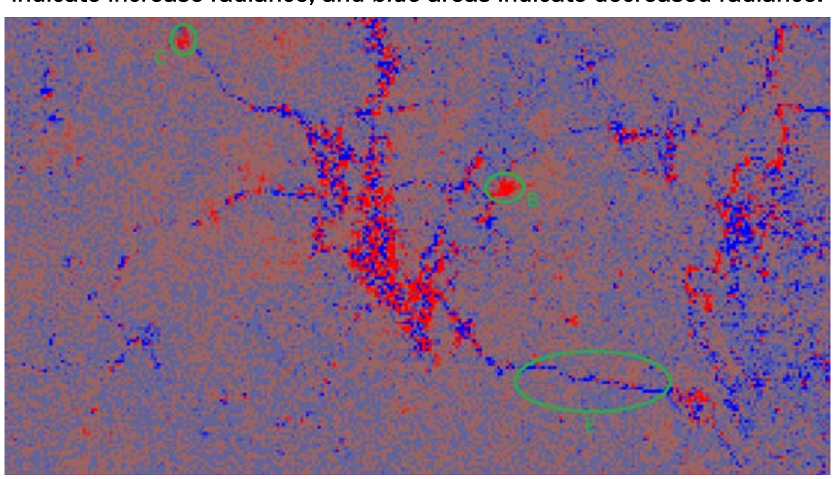


Figure 16. Power distribution in the city of Dhaka based on a 24-hour change in standardized radiance from 1:00 a.m. on Saturday, 1 November (prior to the blackout), to about the same time on Sunday, 2 November (after the blackout). *Red* areas indicate increase radiance, and *blue* areas indicate decreased radiance. The area highlighted in the *green rectangle* corresponds to the airport and government buildings described in Fig. 17.

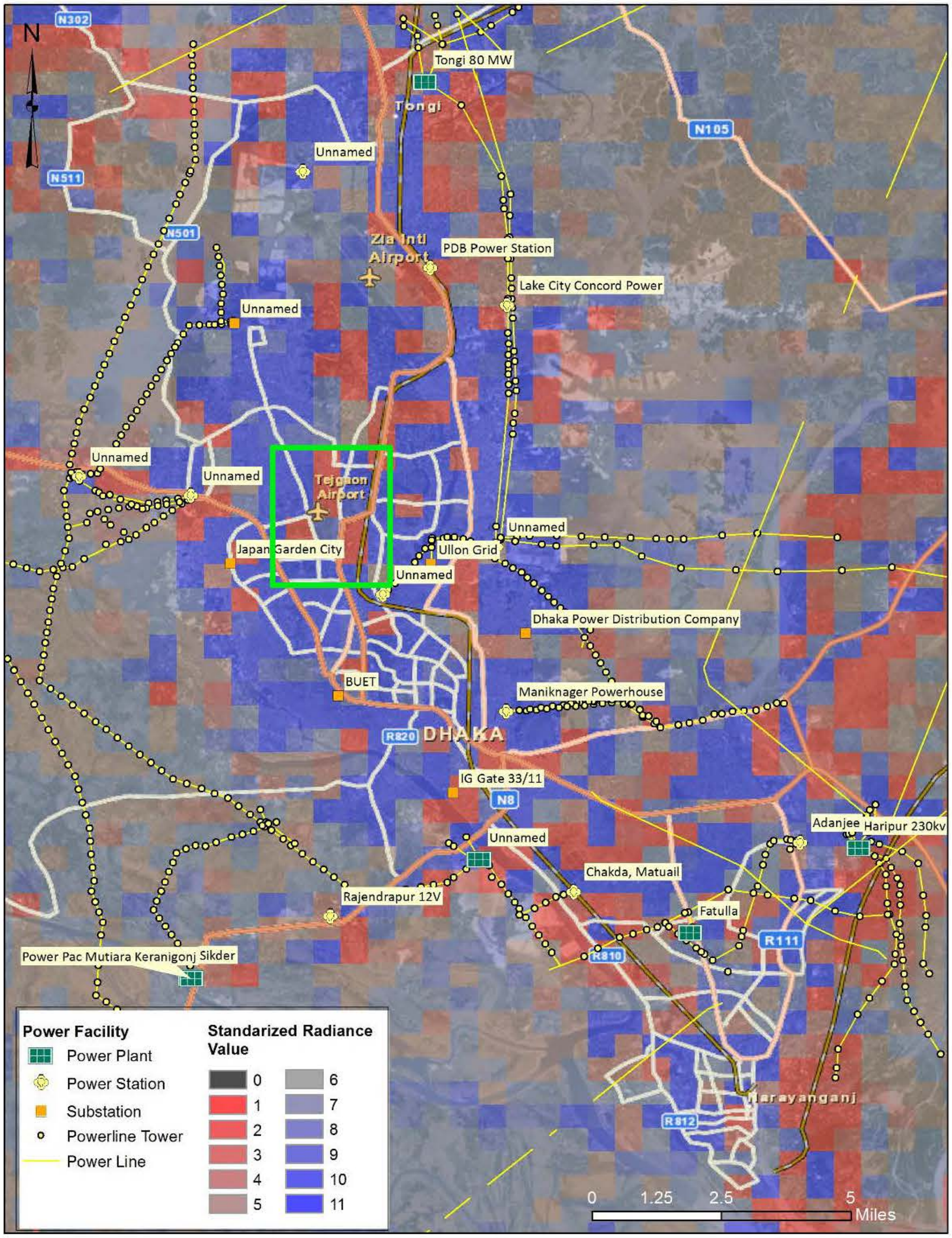


Figure 17. Inset to previous figure showing details of the airport, presidential palace, and parliament house that may reflect both pixel offset and, relative to the surrounding neighborhoods, a relative increase in power to these locations following the blackout.

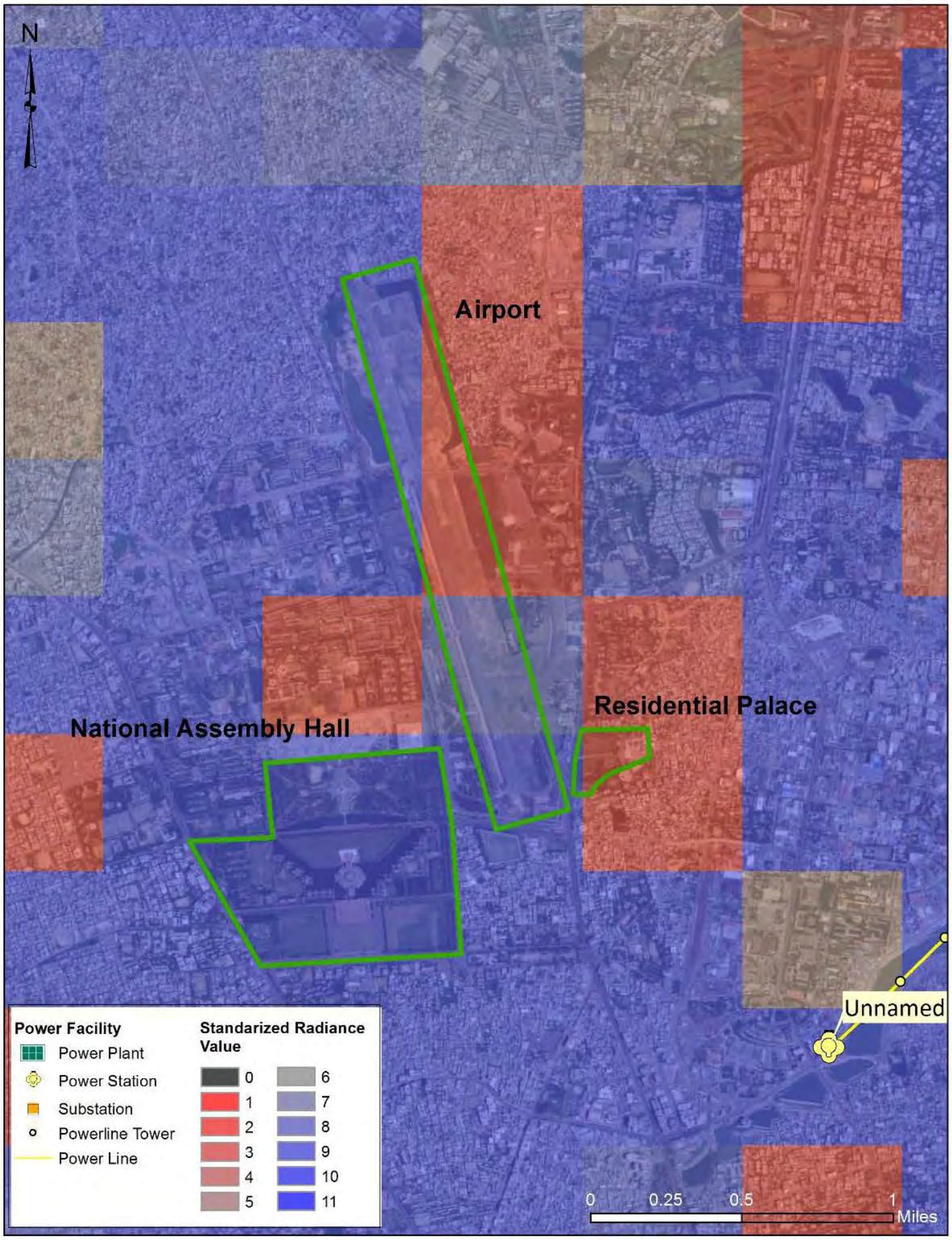
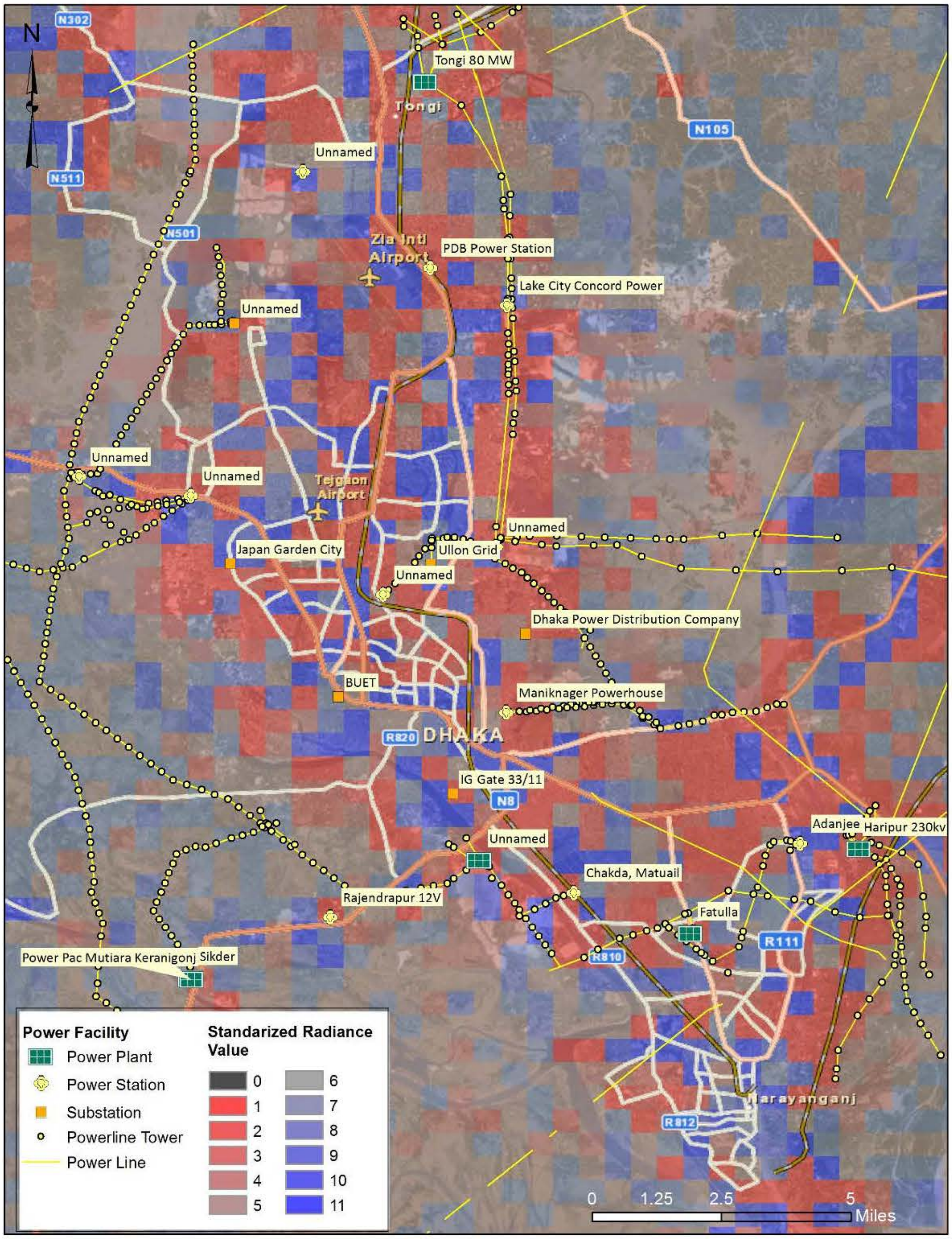


Figure 18 shows that by 1:00 a.m. Monday morning, 3 November, a large percentage of pixels registered an increase in standardized radiance over the previous day, indicating that power may have been largely restored to central Dhaka.

Figure 18. Power distribution on Monday morning, 3 November, indicating that power may have been largely restored to central Dhaka. *Red* areas indicate increase radiance, and *blue* areas indicate decreased radiance.



Other locations, B and C in Figure 14, indicated that power was lost in Narsingdi and Tangail, two smaller towns on the periphery of the Dhaka metropolitan area. Similar to central Dhaka, power appeared to have been restored in these areas by the following day as shown in Figures 15, 19, and

20. Inspection of these areas suggests that the pixel offset at Narsingdi is less pronounced than that at Tangail where the changes in radiance values appear offset to the east of the urban area by one to two pixel widths.

Figure 19. After losing power during the blackout, Narsingdi (location B in Figures 14 and 15) appears to have had power restored by early Monday morning, 3 November.

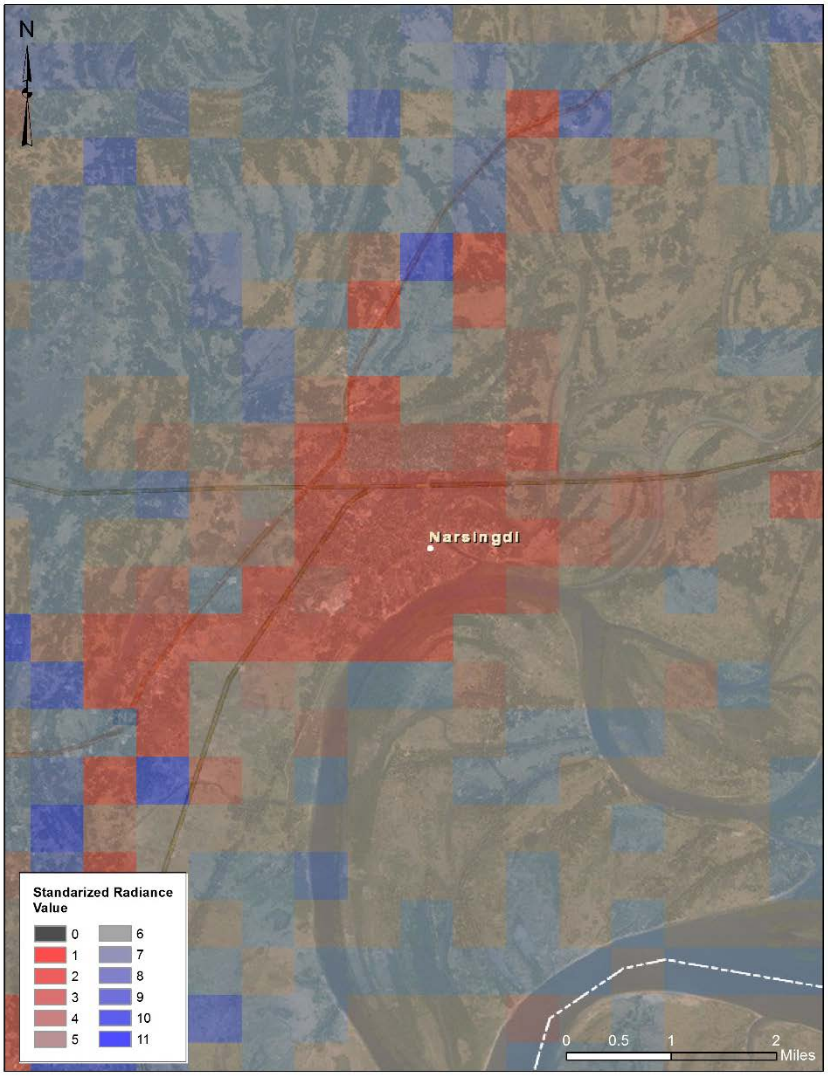
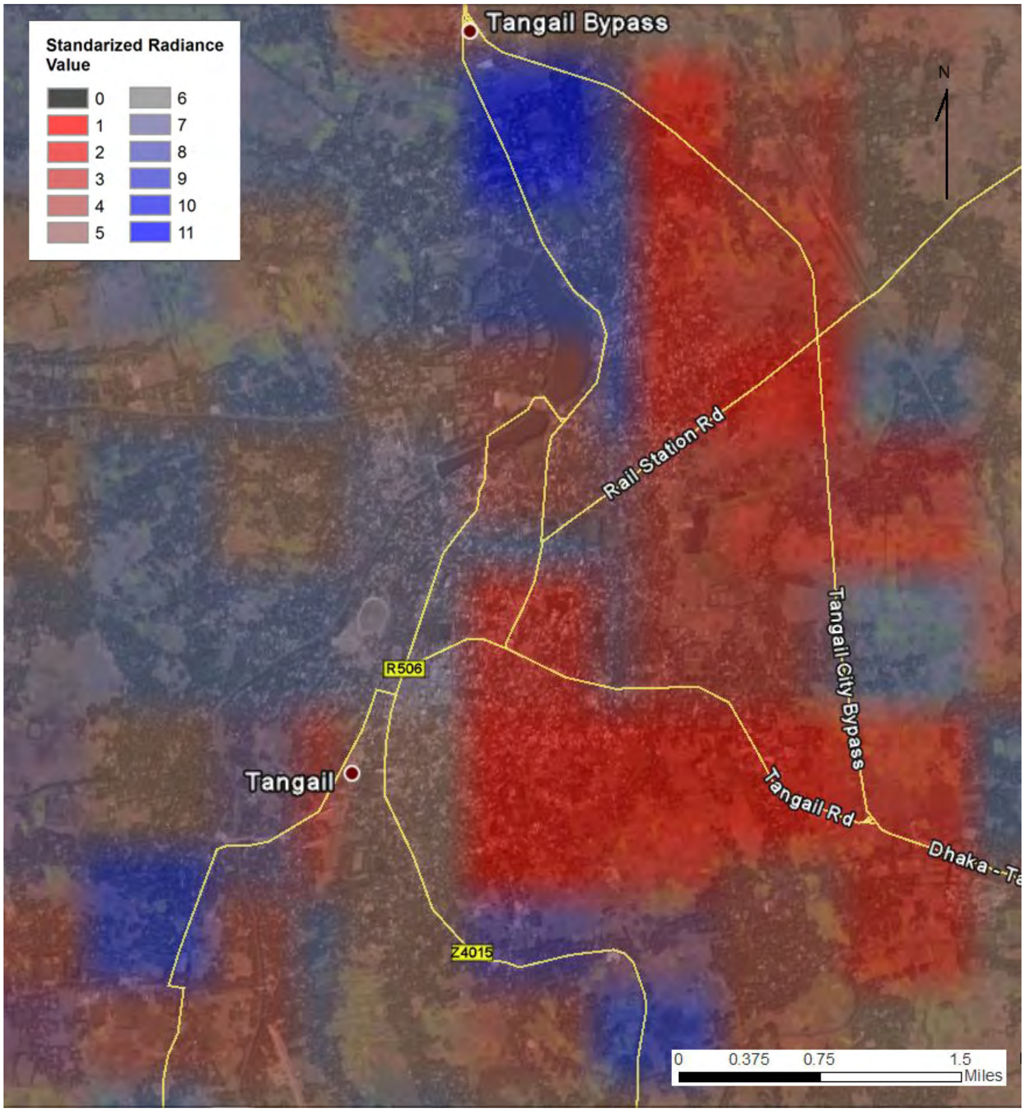


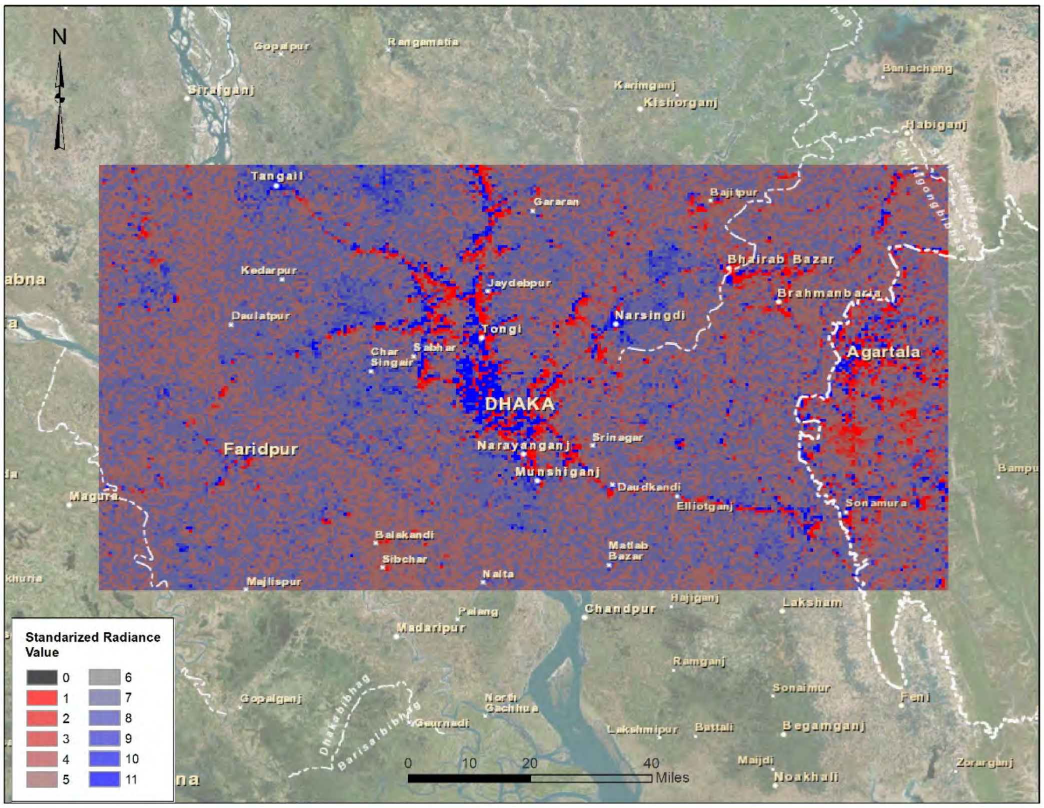
Figure 20. After losing power during the blackout, Tangail (location C in Figures 14 and 15) appears to have had power restored by early Monday morning, 3 November. Some offset is apparent between the radiance change data and the actual urban area.



Location D in Figure 14 shows a large area in which a consistent if subtler increase in standardized radiance occurred in the day following the Dhaka blackout in an area approximately 90 km east of urban Dhaka. In this region, there are a dozen or so smaller towns in areas with both dense and open forest, national parks, plantations, farmland, and waterways. This area, however, lies across the international border with India into Agartala in the state of Tripura (Figure 21); and therefore, its electricity generation facilities and power usage is independent of the Bangladeshi national grid. We note that Tripura was not the state of origin of the power imported to Bangladesh from India; this power came through the Indian state of West

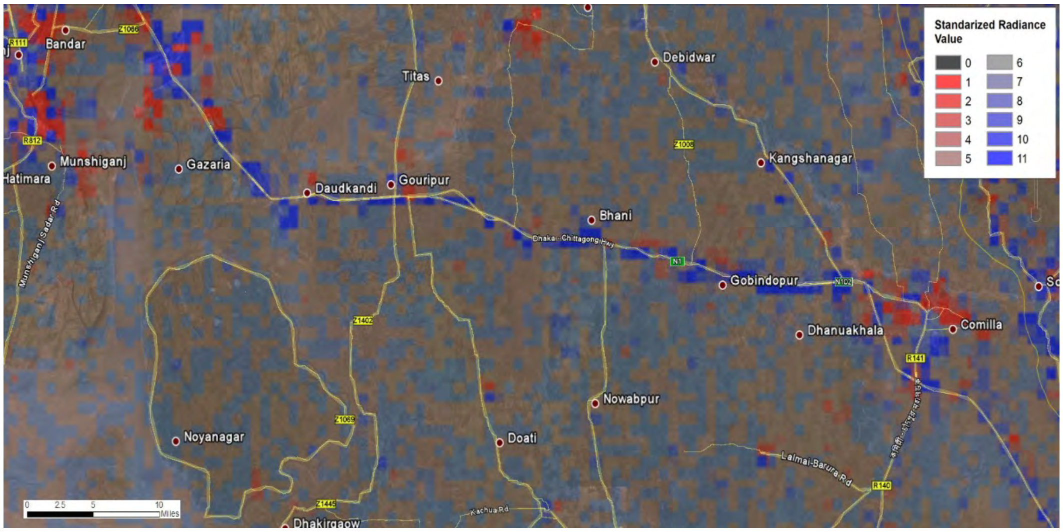
Bengal through the western border of Bangladesh. Therefore, in this case, the increase in standardized radiance in the Agartala area is likely to be an artifact of the relative radiance across the scene under analysis, most of which was under the influence of the Bangladeshi national grid. The fact that power did not fail on the Indian side of the border would cause the standardized radiance value to rise in this area following the blackout.

Figure 21. The imagery analyzed crossed the Indian border into Agartala.



Location E in Figures 14 and 15 highlights radiance changes along the Dhaka-Chittagong highway. This highway passes through a number of towns that appear to be larger or more densely populated closer to the highway, and Figure 22 indicates that there was a decrease in standardized radiance not immediately following the blackout but on the following day. This may be an indication of areas that experienced cascading delays as the national grid was being adjusted; however, we do not have any specific external validation source for the reason for a radiance decrease on this day in this location. However, this location does give us some indication of the magnitude of problems related to the pixel shifts we have observed elsewhere.

Figure 22. Location E from Figs. 14 and 15 shows decreased radiance along the Dhaka-Chittagong highway at approximately 1:00 a.m. on Monday, 3 November, as compared to the previous day.



While the radiance changes in the first night after the blackout (Figure 14) seem to indicate a shift in the location of the source of the radiance (radiance has decreased on the north/blue side of the ribbon and increased on the south/red side of the ribbon), it is likely that the apparent location of the road has changed during the process of geocorrecting and applying bowtie corrections, both of which were done by algorithms internal to the ENVI VIIRS reader, and also during the process of resampling that occurs when one date's imagery is compared to a second date's imagery. In this second case, when pixels do not line up, the final image is resampled to match the grid layout of the initial image. Once again, this misalignment of pixels may be partially correctable but, until corrected, will place a limit on the spatial resolution at which analysis is reasonable. In the examples we have seen here, it appears typical that pixels are displaced by one to two pixel widths. In this case, the satellite swaths downloaded each included Dhaka in opposite corners of the satellite swath, and this suggests that displacements are not likely to be larger than those seen here. The displacements can occur in varying directions within the same scene, so more than a simple registration offset needs to be applied. Given this limitation, we recommend further analysis of administrative districts or following a larger-resolution aggregation of imagery rather than on a purely pixel-by-pixel basis.

7 Summary and Conclusion

The ability to address problems in complex environments requires a new way of thinking. Therefore, we introduce a design to develop a holistic understanding of the operational environment and to frame the problem for the MDMP. This design requires generating key inputs to analyze the complexity of the operational environment for decision makers. These inputs include data that is crucial to developing the context needed for problem framing, information that comes from processing data, and context results of iterative process to transform knowledge into understanding of an operational environment.

Because the design framework is composed of a set of thinking tools, a logical and rational approach should be used that complements and reinforces the operations process. This logical approach includes deductive, inductive, and abductive methods to understand the operational environment. Data mining and data fusion are complementary processes that contribute learning, discovery, and detection capabilities to develop a hypothesis, to locate potential relationships and patterns, and to prove likely events.

The current commercial satellites provide high resolution imagery to extract infrastructure conditions for military operational assessment. One of the most common applications of remote-sensing imagery is the delineation of vegetative land-cover characteristics. Similar methodologies can be applied to extract urban features, infrastructure, and night lights. The NOAA VIIRS satellite provides image data on night lights, and the Digital Globe constellation of WorldView satellites provides high resolution imagery to interpret infrastructure and electric power-grid networks.

The electricity capacity for Dhaka is reported to be higher than the demand. However, scheduled load shedding continues to occur in various places, which is likely to avoid excessive load on the generating plant. There are indeed some times that the rolling and planned blackouts that occurred at nighttime should be visible in some of the VIIRS data. For example, this pattern is found in the VIIRS-DNB from radiance distribution in the Gulshan area, one of the regions where the rolling and planned blackouts typically occur. However, we validated the findings by applying the detected patterns during the 1 November 2014 blackout incident that occurred in Dhaka and its surrounding areas. From this incident, large swaths of central metropolitan Dhaka were affected, having registered a decrease in standardized radiance values, indicative of a massive power outage. This impacted critical infrastructure, such as hospital, roads, the airport, and government buildings. Power was restored in central Dhaka on the second day of the blackout (3 November 2014) as indicated by the change in standardized radiance from 1:00 a.m. on 2 November to about the same time on 3 November.

The techniques used in this study investigate the relative spatial differences based on the combination of static features and temporal changes to understand the power distribution in Dhaka. This study provides an example of integrating datasets for understanding the dynamic physical environment relevant to the factors in the PMESII-PT/ASCOPE matrix for military operations.

8 Discussion

This study suggests that there is a potential application of VIIRS-DNB data to understand static features and temporal variations in power production and usage at operational scales across the globe. The temporal change detection technique used in this study provides enhanced analysis of scenarios when specific dates of interest are known.

Additionally, these results indicate that there is a potential for broad-area analysis of culturally and economically relevant temporal and spatial patterns in the robustness of and changes to infrastructure sectors that produce visible light. Results from this research are relevant to and could provide input data for projects that attempt to characterize infrastructure, infrastructure interdependency, infrastructure optimization, and the structure and capacity of a region or urban area and its populations. To adequately characterize temporal patterns and to move beyond relative changes in light output that assume cross-scene homogeneity, however, the corrections reviewed in Section 5.2 should be applied. This will require significant input from personnel well versed in the technical aspects of processing remotely sensed data.

As addressed elsewhere in this document, further work will need to more fully account for limits on geocorrection and bowtie mitigation of VIIRS imagery. Some improvement may occur as data processing routines are refined both at the level of the data producers and of commercial software readers; it may also be possible to make judicious selections of imagery based on favorable scan angles. Barring these types of improvements, future work must develop a fuller understanding of the limitations of the spatial accuracy of the dataset for a given image and make appropriate accommodations in the analysis to account for them. Detailed information on the methods and limits of VIIRS SDR geocorrection algorithms are available from NOAA (NOAA 2013).

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Appendix A: PMESII-PT/ASCOPE Matrix Created for Use in Intelligence Preparation of the Battlefield (IPB)

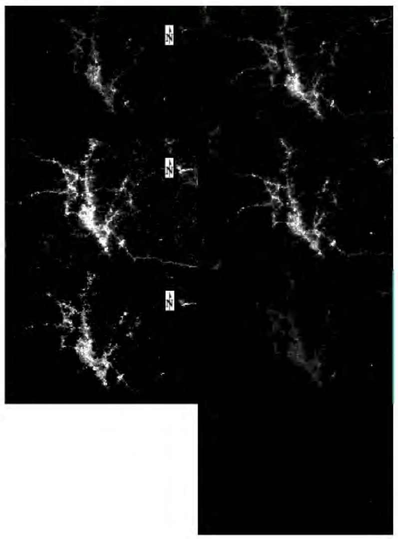
	Areas	Structures	Capabilities	Organizations	People	Events	Other
Political		-Government Buildings -Courts	-Public Administration	-Host Government -Local Government	-Political Leaders	-Elections	
Military	-Lines of Communications	-Bases -Headquarters	-Facility -Equipment	-Border Guards -Corrections -Host Nation -Insurgent Networks -Multinational Forces -Mobile Training Teams -Paramilitary Organization -Police -Terrorists -Tribal Militias	-Key Leaders -Combatants -Political Cadre -Auxiliaries -Mass Base	-Combat -Historical -Non-Combat	
Economics	-Agricultural -Commercial -Fishery -Forestry -Industrial -Mining -Movement of Goods/Services	-Agriculture & Food Processing/Production: -Crop/Animal/Fish -Agriculture & Food Product/Storage -Markets -Bank/Stock Exchange/Investment Firm -Fuel: -Source -Refining -Distribution -Manufacturing/Warehousing -Markets	-Fiscal -Currency -Monetary	-Business Organizations -Guilds -Labor Unions -Volunteer Groups	-Labor Occupations -Business Leaders	-Agricultural/Crop/Livestock & Market Cycles -Planting/Harvesting -Payday	-Black/Illicit Market -Energy -Exports/Imports -External Support/Aid -Jobs -Raw Materials
Society	-Neighborhoods -Displacement Camps -Enclaves	-Penal Facility -Historical -Libraries -Religious -School/Universities -Stadiums	-Medical -Social Network -Property Records & Control	-Clan -Community -Criminal -Familial -Patriotic/Service Organizations -Religions -Tribes	-Key Figures: -Crime/Drug Figures -Religious Leaders -Chiefs/Elders -Educators -Medical	-Celebrations -Census	
Information		-Communication: -Factories -Lines -Towers -Command & Control Systems -Internet Services -Cellular Phone -Postal Service -Print Shops -Telephone	-Internet Access -Printed Materials: -Journals -Newspapers -Magazines -Books -Flyers -Radio -Television -Text Messaging -Websites	-Media Groups -Government -International Coordination Agencies	-Decision Makers -Leaders -Spokespersons -Newspaper Publishers -Journalists -Embedded Media	-News Cycles -Press Conferences	

	Areas	Structures	Capabilities	Organizations	People	Events	Other
Infrastructure	-Hydroelectric Power Facility -Fossil-Fuel Electric Power Facility -Nuclear Electric Power Facility -Marine Transport -Rail Transport -Air Transport -Warehousing & Storage -Food/Agriculture -Energy -Chemical	-Hydroelectric Dam -Pumped Storage Facility -Run-of-River Generator -Coal Fired Generator -Natural Gas fired Generator -Oil Fired Generator -Light Water Reactor Power Plant -Other Reactor Power Plant -Electricity Transmission: -Line -Substation -DC Converter -Generation Dispatch & Transmission Control Center -Electricity Distribution: -Line -Substation -Control & Dispatch Center -Chemical/Hazardous Chemical Processing Plant -Hazardous Chemical Transport Pipeline& Control Center -Crude Oil: -Storage -Transport, Pipeline, & Control Center - Petroleum: -Processing Plant -Product Storage -Product Transport, Pipeline, & Control Center - Natural Gas: -Supply Facility -Processing Plant -Liquefied Natural Gas Plant -Storage -Transport, Pipeline, & Control Center -Coal: -Mine -Processing Plant -Transport -Emergency Services: -Police Facility -Fire, Rescue, & Emergency Service Facility -Emergency Medical Facility -Information Technology: -Operation Centers -Computing Centers -Internet Routing Infrastructure	-Power Generation -Clean Water -Communications -Medical -Sanitation -Chemical Production -Energy Production -Defense Industrial Base -Emergency Services -Information Technology	-Regulatory, Oversight, and Industry Organizations			-Electricity Generation -Hydroelectric Power -Fossil-Fuel Electric Power -Nuclear Electric Power -Electricity Transmission -Electricity Distribution

	Areas	Structures	Capabilities	Organizations	People	Events	Other
Infrastructure (cont.)		-Communication Facility: -Wired -Wireless -Satellite -Internet -Postal Shipping Facility -Healthcare & Public Health: -General Hospitals -Surgical Hospital -Children's Hospital -Psychiatric & Substance Abuse Hospital -Critical Access Hospital -Ambulatory Facility: -Outpatient Mental Health & Substance Abuse Centers -HMO Medical Centers -Kidney Dialysis Centers -Freestanding Surgical Care Centers -Urgent Care Facility -Rehabilitation Facility -Birthing Centers -Prosthetic Limb Centers -Community Healthcare Centers -Occupational Health Clinics -Nursing Care Facility -Residential Care Facility -Hospices -Health Practitioner Offices and Clinics -Public Health Agency -Healthcare Educational Facility -Health Supporting Facility: -Medical & Diagnostic Laboratory -Blood, Organ, & Tissue Facility -Pharmaceutical/Biopharmaceutical -Medical Supplies, Devices, & Equipment -Medical Research Facility -Fatality/Mortuary Facility: -Morgues -Funeral Homes and Crematoriums -Transportation: -Aviation Facility -Railroad Facility					

	Areas	Structures	Capabilities	Organizations	People	Events	Other
Infrastructure (cont.)		-Maritime Facility: -Ports -Military & Strategic Seaports -Maritime Supporting Facility -Waterways: -Navigation Locks -Dams -Mass Transit -Pipelines -Water: -Treatment Facility -Treated Water Storage -Treated Water Distribution Systems: -Pumping Station -Treated Water Monitoring System -Treated Water Distribution Control Center -Wastewater Facility: -Lift/Pump Station -Treatment Plant -Treated Wastewater Monitoring System					

Appendix B: DNB and NCC VIIRS Data and Filenames for Dhaka on 1–3 November 2014

SDR- DNB	EDR- NCC	Local time at satellite overpass	Blackout timeline	SDR-DNB file (geocorrected and mitigated bowtie effect)	EDR-NCC file (raw data)
		Sat, 1 Nov 2014, ~1 am local time Blackout occurs between these two overpasses	12:00 local time- initial failure on transmission lines from India Some areas restored by the afternoon but had to be shut down again.	GDNBO-SVDNB_npp_d20141031_t1928164_e1933568_b15598_c20150822102001055249_noaa_ops_DNB_Radiance.dat	GNCCO-VNCCO_npp_d20141031_t1928022_e1934105_b15598_c20150822073750308177_noaa_ops.h5
		Sun, 2 Nov 2014, ~1 am local time	Sat night Dhaka "mostly dark." Backup power to major government hospitals, presidents' house, Prime Minister residence, businesses with backup power in place. Power restored by 1 am local time, according to Dhaka control room official.	GDNBO-SVDNB_npp_d20141101_t1910462_e1916266_b15612_c20150822102017920253_noaa_ops_DNB_Radiance.dat	GNCCO-VNCCO_npp_d20141101_t1910320_e1916403_b15612_c20150822002948320725_noaa_ops.h5
		Mon, 3 Nov 2014, ~00:00 (midnight) local time	Power anticipated to have returned elsewhere in the country by Sunday afternoon, local time.	GDNBO-SVDNB_npp_d20141102_t2035416_e2041219_b15627_c20150822102405905022_noaa_ops_DNB_Radiance.dat	GNCCO-VNCCO_npp_d20141102_t1853017_e1859118_b15626_c20150822002946737072_noaa_ops.h5
		Wed, 5 Nov 2014, ~2 am local time			GNCCO-VNCCO_npp_d20141104_t1954452_e2000535_b15655_c20150822002522321564_noaa_ops.h5

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14. ABSTRACT
Infrastructure variables required for a community or society to function include basic facilities, services, and installations; and these variables can impact many aspects of daily life. The structure and functionality of the electrical grid in an operating area can affect multiple operational variables. Other infrastructure sectors that rely on the electrical grid can fail when electricity is disrupted. Thus, the impact of electricity in a society is vital for prosperity and security and expands the broad impact on economic and social well-being.

This study used remote-sensing data to examine the electrical system and power-grid functionality for Dhaka, Bangladesh. We focused on the transmission and distribution networks, the network patterns, and the electrical capacity. In addition, we used the pattern of a power outage (i.e., the 1 November 2014 blackout) and the duration of the outage to assess the affected neighborhood and the power-production disruptions at other major power stations within the country. When we combined the Visible Infrared Imaging Radiometer Suite (VIIRS) data with the panchromatic sharpening of WorldView-2 imagery, we were able to focus on the affected areas, thereby narrowing the search for electrical-grid components. This study is an example for understanding the dynamic physical environment relevant to military operations.

15. SUBJECT TERMS
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