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ELECTRIC INFRASTRUCTURE PROTECTION

E-PRO® HANDBOOK III

Electric Infrastructure Protection (EPRO®)
Handbook III

Cross-Sector Coordination and Communications in Black Sky Events

EIS COUNCIL

EPRO Handbook

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The ELECTRIC
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A source of peer-reviewed analysis and recommendations to help infrastructure owners and operators, government agencies, and non-governmental organizations bolster resilience against Black Sky hazards.

2

CHAPTER TWO

THE BLACK SKY EMERGENCY COMMUNICATION AND COORDINATION SYSTEM (BSX™)

Assessing Communication and Coordination Requirements for Complex Catastrophes

I | INTRODUCTION

Building the collective capacity to effectively handle large-scale power outages and other complex catastrophes requires many simultaneous lines of effort from public and private sector stakeholders. As indicated in Chapter I, carefully integrated planning across the many interdependent critical infrastructure sectors and their partners at all levels of government will be critical.

Building coordinated, prioritized multi-sector strategies for critical resilience investments will be an important part of this planning, and must be implemented well before a Black Sky event. Similar coordination will also be required to guide infrastructure restoration and population sustainment after catastrophe strikes. However, in disasters on this scale, all normal telecommunications, internet, and related services will fail. As a result, infrastructure sustainment and restoration operations will not be possible. This represents one of the most fundamental challenges faced by modern nations. If not addressed aggressively, the U.S. risks unprecedented infrastructure failures and the breakdown of societal continuity.

The classic scenario faced by planners addressing extreme events is a subcontinent-scale power outage. Such blackouts, especially when caused by malicious threats like cyber or EMP attacks, could be associated with extensive and widely-distributed damage to power grid facilities. Given the scale of such outages, this damage will take significant time to assess and repair. Power restoration after such an outage will require "black start," a largely manual process which, given the inevitable disruption and likely damage in such a large-scale outage, will take time.

In a Black Sky event, black start power restoration will take – at best – weeks, or longer, to implement, and will only be possible *if* adequate, broadly-distributed and interconnected emergency telecommunications are available to host that process. Without such communications capabilities, the process could take months or years. Meanwhile, other multi-sector efforts essential to sustain the minimal resources and services needed for population sustainment will rely on precisely the same capabilities.

If modern nations wish to be capable of surviving large-scale complex catastrophes, implementing a widely-distributed, Black Sky-compatible emergency communication and coordination system is the first, most fundamental requirement they must address.

If modern nations wish to be capable of surviving complex catastrophes on this scale, implementing a widely-distributed, all-sector Black Sky-compatible emergency communication and coordination system is the first, fundamental requirement they must address.

A Black Sky-compatible emergency communications system represents a fundamental, enabling capability or toolset, without which all other planning for severe, large-scale emergency scenarios will not be implementable.

1. Communication

As reviewed in Chapter I, large-scale, long-duration power outages can only be surmounted by new approaches to prioritized resilience investments, and by adapting existing coordination structures to span the unprecedented needs such events will have for cross-sector planning and operational coordination. Yet, as described below, power outages of this scale will also result in the failure of most or all normal telecommunications systems throughout the affected area. Such new multi-sector coordination approaches will not be viable without communications systems that can survive a Black Sky event, and even under such circumstances, interconnect nearly all sectors, including key segments of their supply chains.

Developing, implementing, and deploying such a system – designed to survive a long-duration outage and continue to operate without depending on a functional power grid or normal, national telecommunications assets – is a fundamental test of the credibility of a nation's national continuity planning and national security, as broadly defined in the 2017 U.S. *National Security Strategy*.[1]

2. **Coordination:** Situational Awareness and Multi-Sector Modeling and Simulation

Without grid power and communications, our infrastructure and resource networks – the interdependent, tightly-linked systems that generate and distribute the resources needed to support power restoration and sustain populations – will fail, precisely when they are needed most.

A widely-distributed, self-powered emergency communications network will therefore be essential in Black Sky outages. However, the multi-sector coordination authorities to whom this capability will be particularly critical will need help to enable "manual" sustainment and restoration operations for a critical subset of those infrastructure and resource networks.

> The multi-sector deployed, self-powered emergency communications system will need to host additional tools to enable "manual" sustainment of normally self-sustaining resource flows to support restoration and sustain the population.

Given the scale of effort required to support multi-sector infrastructure restoration and sustain modern megacities, this help – which may also be

1 The National Security Strategy of the United States of America (December 2017) employs an all-encompassing definition of national security that goes beyond the nation's fundamental military challenges. In contrast to national defense, this definition includes threats to critical infrastructure and critical supply chains, the economy, intellectual property, etc. See: President Donald Trump, National Security Strategy of the United States of America, December 2017, p. 1.

characterized as "machine assistance" – will need to include approaches to provide several additional tools and capabilities, including:

- Adequate situational awareness
- Multi-sector modeling and "mapping" of cross-sector interdependencies
- The multi-sector simulation and forecasting that will be essential to provide decision support capabilities

And since each of these tools will themselves require widely-distributed, real-time communications connectivity, they will need the same type of Black Sky-compatible emergency communications system to host their operation and provide a seamless user interface for users and decision makers. This chapter reviews examples of tools that provide these capabilities, the Situational Awareness Network Diagnostic (SAND™) System and the Global Infrastructure Network Optimization Model (GINOM™)[2], in the context of the Black Sky Emergency Communication and Coordination System (BSX™) designed to host their operation.

2 For more information on the SAND™ and GINOM™ initiatives, please write to info@eiscouncil.org.

3. Developing an Emergency Communications Tactical Network: Working Toward a National-Scale All-Hazard Emergency Communications System and Tactical Network, Interoperable with Existing Emergency Communications Systems

The viability of the new initiatives and organizational realignments proposed in the previous chapter will depend on a widely-distributed and interlinked communication and coordination system that can survive a Black Sky event. This system must be able to operate for weeks or months in the absence of grid power. It will also need to operate without depending on the national telecommunications backbone, which will fail in a long duration grid outage.

> In Black Sky events, coordination will be required between many interdependent sectors to sustain minimal service, support infrastructure restoration, and contribute to population sustainment operations.

Of course, multiple public and private sector emergency communications systems already exist to support disaster operations. In many sectors, infrastructure owners and operators are improving the diversity and survivability of these systems. Government emergency communications systems for disaster response (especially those managed by FEMA and the National Guard) are also becoming more resilient. Typically, however, private sector systems are structured to sustain connectivity with an organization's own facilities, critical assets, and subsector partners. In Black Sky events, nearly all organizations will need support from many interdependent sectors to sustain even minimal service, support infrastructure restoration, and contribute meaningfully to population sustainment operations. At present, where independent emergency communications systems are available, they have little capability for interoperability.

Emergency communications systems maintained by the National Guard and other governmental organizations suffer from an equivalent shortfall. These systems are focused on serving government users. They rarely provide direct links to infrastructure owners and operators and essential resource and service providers, even though infrastructure sustainment and restoration will be *the* most important factor for saving and sustaining lives in Black Sky events.

Nor are most existing communications systems – whether the regular societal systems, or the localized emergency systems described above – equipped to operate for a month or more in the absence of power from the electric grid. And after some period of time – certainly less than 72 hours – the back-up power systems for the "normal" national telecommunications backbone (e.g., the internet, landline and cellphone systems, and the ground segments of satellite communications systems) will run out of power and shut down. Even satellite phones will not operate indefinitely in the absence of power at the satellite control stations.

4. Looking Ahead

Given the increasing interdependence of infrastructure sectors, and the broad array of public and private sector partners essential to help sustain and restore essential services, deploying a Black Sky-compatible communication and coordination system to all critical sectors, key partners, and relevant supply chains will be vital to prepare for extreme events. To be effective, such a system must be interoperable with any available emergency communications systems, including those of the military, police, first responders, and security personnel.

Our analysis has indicated that a fully-deployed Black Sky emergency communications system would need to include approximately 200,000 nodes across the United States. The system could therefore also be used as a limited, emergency-oriented data network (at much lower bandwidth than conventional societal systems), sufficient for the early stages of sustainment and restoration operations following a Black Sky event. As deployment increases and node-to-node ranges decrease across the mesh network anticipated for such a system, the system could incorporate shorter-range, higher-bandwidth components to provide capabilities comparable to a limited "emergency internet."

5. Hosting an Emergency Financial Accounting System

One of the most fundamental needs for a Black Sky-compatible emergency communication and coordination system in a complex catastrophe scenario would be to support an emergency financial accounting system. Given the inevitable, severe disruption of normal monetary institutions and networks, a backup financial strategy will be essential to allow for continuity of the critical backbone of commerce needed to support utility restoration, and to save and sustain lives. As corporations, banking institutions, and government stakeholders consider emergency credit liquidity concepts and other approaches to develop an emergency monetary system, very broad multi-sector communications connectivity and coordination support will be essential. The BSX™ system, described in detail in this chapter, can provide such connectivity and coordination.

> A Black Sky-compatible, fully interoperable communication and coordination system will be essential in all key infrastructure, resource, service, first-responder, and government sectors, as well as their critical supply chains, to allow managers at all levels to communicate in extreme events.

6. The Black Sky Emergency Communication and Coordination System (BSX™): An example of a Black Sky-compatible system architecture

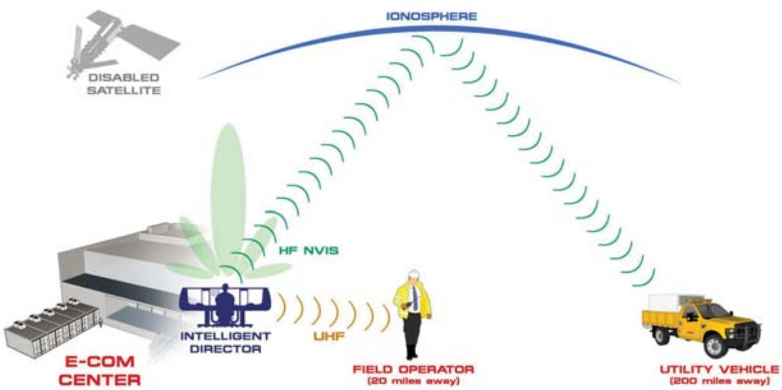
This chapter provides an analysis of the BSX system, whose design is currently being developed by the Electric Infrastructure Security Council. Making use of technologies originally invented for the U.S. Army's highly-successful Blue-Force Tracker Command, Control, and Communication System, BSX nodes will be configured to operate with or without externally supplied power,[3] and without external communications or other infrastructures, supporting national-scale interconnection of approximately 200,000 nodes.

3 Power supplies for BSX nodes will vary depending on the site at which it is situated. Many critical facilities will be developing plans and capabilities to sustain the supply of emergency power (and thereby facilitate continued operation) in extended outages. This can be accounted for in the deployed BSX configuration for such installations, as BSX nodes will rely on these capabilities where possible. BSX sites without adequate emergency power supplies can choose from a range of potential power module configurations. This issue is examined in detail in Section IV (D).

Fundamentally, BSX is a scalable system architecture, utilizing an intelligent director-enabled mesh network configuration to support the unique capabilities needed for Black Sky communication and coordination. This gives the system a robust capability to incorporate a wide range of communication components, and to evolve to stay current with the best available technologies.

It is designed to operate as a standalone emergency communications system, and to provide connectivity with any existing emergency communications systems that survive a Black Sky event. This allows BSX to act as a "bridge," providing for inter-communication between these previously incompatible emergency communications systems.

Now in the early stages of prototype development, BSX will perform three critical functions following Black Sky events.



a. Essential BSX System Functions

- **Nationally Deployed, All-Sector Emergency Communication:**

  Provide voice and data communications to enable infrastructure support, population sustainment, and response operations, as well as other Black Sky activities.

- **Hosting a Situational Awareness Hub**

  BSX will be able to host operation of the Situational Awareness Network Diagnostic (SAND™) System, now in initial development. SAND is designed to remotely acquire diagnostic data from both current and newly deployed sensors embedded in critical infrastructure, resource, and service sectors and their supply chains. This critical capability provides a unique multi-sector, real-time view that will be essential for decision makers in Black Sky events.

- **Hosting a Multi-Sector Model and Simulation**

  BSX is also designed to host operation of the Global Infrastructure Network Optimization Model (GINOM™). GINOM is a software-driven, multi-infrastructure modeling and simulation framework. Such a system will be essential to assist decision makers in all sectors, as they work to "manually" support the wide array of (normally self-sustaining) resource flows needed to enable infrastructure restoration and sustain the affected population. Given the complexity of this task, interdependency mapping and artificial intelligence (AI) support from GINOM will be essential to help guide these managers to optimize prioritized, time sensitive decisions in responding to the vast array of unpredictable events and the many dimensions of intricate challenges that will emerge in complex catastrophes of this magnitude.[4]

b. BSX System Design Summary

BSX is an interoperable, Black Sky hazard-protected emergency communication and coordination system designed to operate without requiring connectivity to the nation's telecommunications networks. Designed with an array of options to ensure adequate off-grid power at all nodes for 30-60 days of operation, BSX is designed to easily interconnect with and supplement available organization-specific emergency communications systems, supporting ubiquitous, multi-sector deployment of 200,000+ nodes across the United States, and, over time, similar deployments internationally.

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4 The "BSX resource family" includes both the BSX™ system itself and the Global Infrastructure Network Optimization Model (GINOM™) initiative, a multi-sector model providing both interdependency mapping and AI-enabled simulation and forecasting capabilities. GINOM also includes: 1) the Situational Awareness and Network Diagnostic (SAND™) system providing multi-sector, real-time status information; and 2) the Complex Adaptive Network Optimization Engine (CANOE™), providing iteratively reoptimized recommendations to decision makers, based on an AI-enabled layer of the GINOM system. These initiatives will be described in greater detail in subsequent EIS Council publications.

The BSX system, communications protocols, and network management software will be designed and maintained to support evolving requirements for interconnected, Black Sky operations spanning all infrastructure, critical resource supplier, and mass-care NGO sectors, as well as state and Federal emergency management agencies and a range of other government organizations. The deployed BSX network and its subnets will provide ubiquitous, all-sector voice and limited data rate connectivity to support the critical, initial stages of emergency response, infrastructure restoration, and population and environment sustainment following wide-area regional blackouts (when most or all other national communications systems will typically be unavailable).

> BSX is an interoperable, scalable system architecture, not a set of communication components. It is designed to support the unique communication and coordination needs of Black Sky scenarios, with a flexible design that can incorporate a wide and evolving range of communication technologies and components.

BSX development is planned to occur in stages, beginning with initial, Block I Limited Operational Capability (LOC) deployment for selected corporate and government customers. Designed to support initial voice operations and limited data transmission, Block I is being rolled out to a limited number of early adopters. Knowledge gained from Block I LOC will be leveraged to improve the BSX network, with future stages supporting advanced situational awareness and decision support capabilities. To this end, future deployments will host the SAND™ all-sector Black Sky situational awareness framework, with a network configuration designed to support and enable the evolving GINOM™ all-sector simulation model that will provide both multi-sector interdependency mapping and an AI-driven, real-time decision support engine for use in complex catastrophe scenarios.

The system uses a mesh, internet-like network configuration adapted for the special conditions of long-distance radio, providing communication path flexibility and high reliability voice and data communication.

As the BSX system's deployment expands, or if deployed node density is increased in selected, key areas, data rates will also expand, enabling the system to offer added capability. Ultimately, especially in urban areas with high node densities, higher data rates will enable operators to use the evolved BSX network as a Black Sky Emergency Internet, giving users access to a searchable emergency network, including specially-designed emergency network websites which can operate under all-hazard conditions.

A preliminary version of a BSX controller interface, displayed in EPRO SECTOR Winter, 2017 at PJM Headquarters, Audubon PA.

c. Current Status of the BSX System

In 2017, EIS Council and its partners, Neil Siegel, LLC, and Applied Minds, LLC, completed architecture development and conceptual design of the BSX System. Key elements of a system prototype were developed in support of the Electric Power Research Institute's Emergency Communication Research Project. These key elements and their capabilities were successfully demonstrated at the EPRO SECTOR Executive Committee Winter 2017 meeting at PJM Interconnection Headquarters in December 2017.

The next step in the development of this multi-sector system will be BSX Block I Limited Operational Capability (LOC) Build deployment. This entails building interconnectable, near full-scale networked groups of prototype nodes with limited operational capability for corporate and government users in different regions of the nation.

d. Evolving BSX Requirements

The BSX system is designed to support a number of key requirements that emerge from a systems engineering-based analysis of the needs for a Black Sky-compatible communication and coordination system. These requirements will be reviewed in detail in later sections.

Key requirements, for example, include:

- **Black Sky hazard protection:** This includes provisions to ensure hardening against cyber, EMP, and IEMI threats.
- **Autonomous network power management:** BSX nodes are being designed to ensure availability of more than 30 days of power through a combination of duty cycle management[5] and a range of power module configuration options.
- **Autonomous communications backbone:** BSX will not utilize existing, national telecommunications backbone systems.
- **Widely-distributed network:** As a core feature of the system, BSX is being designed for deployment at approximately 200,000 sites within the United States, spanning the locations required to interconnect all infrastructure sectors and their critical supply chains, critical facilities, government agencies, mass-care NGOs, and other key stakeholders to support restoration and sustainment operations.
- **Coordination system hosting:** The BSX nodes and network management system are being designed to host Black Sky-compatible situational awareness framework and infrastructure simulation decision support systems, such as SAND and GINOM.

The architecture, hardware elements, and network management software of the BSX network are all pre-designed to evolve and change. As new information becomes available, including, for example, lessons learned from the catastrophic infrastructure collapse in Puerto Rico following Hurricane Maria, the BSX architecture can continue to evolve.

The core BSX architecture is based on a long-distance radio network (HF/ UHF) for delivery of voice and basic data services. This provides a

5 The BSX network management system, in combination with continuing GINOM assessments of projected network usage levels, will make or recommend node-by-node adjustments to power duty cycle (i.e., what fraction of each hour or each day a particular node's radios will need to be active and drawing power). Power management planning will also be used when nodes are first deployed, taking into account a node's average expected usage and the expected availability of ~30-day emergency power capability at the deployment site. These factors will be used in making recommendations for the type, configuration, and size of each node's power module.

pragmatic solution for mission-critical communications requirements in a Black Sky environment. Survivable voice communications will be essential to restoration support and population sustainment operations in Black Sky outages, as will the situational awareness and decision support capabilities the BSX network is being designed to host.

e. Flexible Communications Device and Data Rate Options

The BSX system design process was based on an extensive trade study. This study examined the suitability of a range of technologies for the unique long duration, stand-alone requirements of the envisioned BSX, and ultimately identified the radio communications system as the best candidate for a nationally-deployed mesh network. The core design provides, even in a relatively sparse network, the voice capabilities and modest data capacity that will be needed in catastrophic scenarios.

In the event of a national emergency, the Federal Communication Commission's policy is to make additional radio frequencies available (as they have done in the aftermath of the catastrophic 2017 hurricanes in Puerto Rico), thereby increasing the capacity of the baseline BSX configuration. In addition, the Department of Homeland Security can provide designated frequencies for emergency management, which has a similar effect. With the system's flexible, open, and interoperable architecture, BSX can also include high-density deployments or subnets that can support relatively high data rates in specific regions.

The system is also designed to provide a capability to utilize and interconnect available emergency communications systems. The BSX "smart router-based" design (described below) allows for such additional communications devices to be connected to the BSX system. Those additional devices can be used when available, and compatible with both users' budgets and needs. Once tied into the system, no actions by the BSX operators are required to select them when they are required to optimize a particular communication path; this selection is entirely automatic.

Examples of such additional communications devices could include:

- High-frequency radios with directional antennas mounted on utility poles
- Mid-frequency radios (including LTE base stations) whose signals are passed via airborne relay units (which are mounted on tethered or free-flying balloons)

- Mid-frequency SATCOM services (such as those now used by the Army Blue-Force Tracker)
- Dedicated fiber-optic links; dedicated LTE sub-networks
- Software Defined Radios (SDRs), as confidence in their reliability within large-scale mesh networks grows

Structure of this Chapter

This chapter explores the BSX system in detail. Section II provides a brief examination of the communications systems and networks in place today, and an assessment of their adequacy for Black Sky operations.

Section III analyzes the intended users of the BSX system. In particular, following proven systems engineering and design methodologies, this section provides a "social architecture" study for the BSX system. Sometimes referred to as "mission requirements" or "user requirements," this section specifies four categories of top level user requirements for the system.

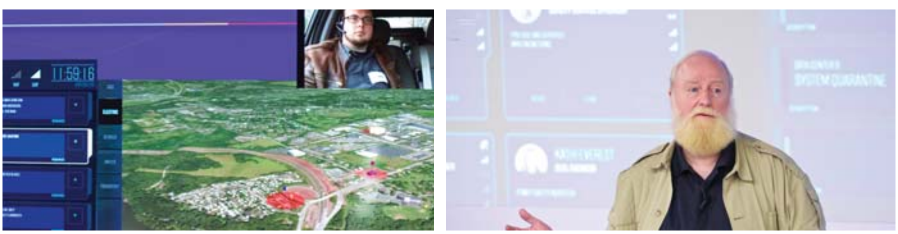
Social Architecture: Top-level user requirements

1. Who will use the system
2. Under what conditions the system will be used
3. How, and for what purposes, the system will be used
4. The constraints under which that use will occur

Based on that assessment, Section IV uses systems engineering methods to define and assess alternative approaches to the BSX design through "systems engineering trade studies."

Section V outlines the preliminary design for BSX, with separate subsections for each of the major elements of the proposed system.

Section VI then provides a summary and a set of preliminary conclusions about the BSX system, including recommendations for next steps.



BSX Demo at PJM. On right: Bran Ferren demos system during EPRO SECTOR Executive meeting

Damage from the Florida hurricane | Image: Jodi Jacobson

II | NATURE OF THE CHALLENGE

The current emergency communications landscape consists of an enormous number of stand-alone communications systems. First responders across the nation, for example, currently use over 10,000 disjoint networks for voice communications, with varying capacity for interoperability between them.[6] *There are also several additional, dedicated emergency management systems and networks. However, no such system – nor a combination thereof – will be sufficient to coordinate Black Sky sustainment and restoration operations.*

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6 AT&T, "AT&T Selected by FirstNet to Build and Manage America's First Nationwide Public Safety Broadband Network Dedicated to First Responders," March 30, 2017, http://about.att.com/story/firstnet_selects_att_to_build_network_supporting_first_responders.html.

A. Lessons Learned and Major Challenges

Catastrophes less severe than a Black Sky event have demonstrated both the fragility of the existing commercial communications infrastructure, and the importance of communications during major outages. Hurricane Katrina, for example, was devastating to communications systems, leaving emergency managers "without a reliable network across which they could coordinate."[7] Emergency plans and communications assets at the local, state, and Federal levels were both insufficient and inadequately integrated for an effective response, verifiably impeding coordination.[8] The command structure of the responders broke down as a result, and communications disruptions "had a debilitating effect on response efforts in the region and the overall national effort."[9] Indeed, the current lack of survivable electronic communications will undermine critical sustainment and restoration operations in the aftermath of a Black Sky event, intensifying the effects of the resulting catastrophic outages, and could lead to further cascading failures. The effect is cyclical and compounding.

> In a "bounded" Black Sky event, Hurricane Maria knocked out nearly all cell sites and internet access in Puerto Rico. The director of DHS' Office of Emergency Communications testified that first responders were unable to respond to calls on their own systems.

Despite policy changes and greater investment in emergency capabilities prompted by the events of Katrina, a catastrophic event will still cause significant communications infrastructure failures.[10] Significant gaps between

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7 U.S. Assistant to the President for Homeland Security & Counterterrorism, The Federal Response to Hurricane Katrina: Lessons Learned, February 23, 2006, http://library.stmarytx.edu/acadlib/edocs/katrinawh.pdf.

8 Ibid.

9 Ibid.

10 As shown by the EIS Council's Black Sky simulations. The Cascadia Rising (2016) exercise also found that the post-event environment will feature "severely degraded communications." See: Washington State, 2016 Cascadia Rising Exercise After Action Report: Catastrophic Earthquake and Tsunami Scenario, October 21, 2016, https://assets.documentcloud.org/documents/3152696/CR16-State-AAR-Final-Draft-Oct-21-2016.pdf

the survivable systems and the capabilities required to navigate Black Sky response operations remain as well.

Hurricane Maria demonstrated the enduring destructive potential of catastrophic events for communications systems, as the storm knocked out nearly all cell sites and internet access in Puerto Rico.[11] The director of DHS' Office of Emergency Communications testified that first responders were seemingly unable to respond to calls on their own systems, as a result of the damage caused by the storm's severity.[12] Due to the lack of communications capabilities on the island, intended recipients of relief supplies were unaware of deliveries by emergency managers.[13]

1. Current status and Black Sky capability gaps with deployed emergency communications systems

Some emergency communications systems intended to operate without cellular connectivity remained intact after Maria made landfall. For example, under Emergency Support Function 2 (ESF-2), emergency managers delivered 100 satellite phones to support "essential response personnel supporting communications restoration efforts" in Puerto Rico.[14] However, such an ad-hoc communications system will not be sufficient in particularly catastrophic events, where cross-sector prioritization of critical infrastructure sustainment and restoration will mandate all-sector inter-communication capabilities. In addition to basic functionality issues (e.g., satellite phones do not operate well, if

11 Jason Abbruzzese, "Internet, mobile networks reportedly down in Puerto Rico after Hurricane Maria," Mashable, September 21, 2017, http://mashable.com/2017/09/21/puerto-rico-mobile-internet-hurricane-maria/#kKqizOLbuOqL.

12 Matt Leonard, "What's really slowing the restoration of Puerto Rico's communications?," GCN, October 16, 2017, https://gcn.com/articles/2017/10/16/puerto-rico-communications-infrastructure.aspx.

13 Arelis Hernández, Dan Lamothe and Joel Achenbach, "When Hurricane Maria hit Puerto Rico, 'everything collapsed simultaneously'," The Washington Post, October 2, 2017, https://www.washingtonpost.com/national/when-hurricane-maria-hit-puerto-rico-everything-collapsed-simultaneously/2017/10/02/a945dfa4-a79c-11e7-850e-2bdd1236be5d_story.html?utm_term=.464f5e7490c8

14 "Overview of Federal Efforts to Prepare for and Respond to Hurricane Maria," Federal Emergency Management Agency, last updated October 16, 2017, https://www.fema.gov/blog/2017-09-29/overview-federal-efforts-prepare-and-respond-hurricane-maria?utm_source=hp_promo&utm_medium=web&utm_campaign=disaster.

at all, indoors), inter-communication among many tens of thousands of phones vying for bandwidth would substantially exceed the capabilities of such systems. Moreover, most satellite communications systems cannot operate indefinitely if their ground stations are without power.

a. Power Limitations

While Hurricane Maria was not nearly as severe as a true Black Sky event, the response efforts in her aftermath are evidence of remaining gaps in emergency communications capabilities. These gaps could lead to a catastrophic inability to adequately address needs in more severe incidents.

These gaps can also be observed in major earthquake scenarios, which – though they may not always emulate Black Sky events – simulate response operations in some of the most similarly disrupted conditions. Some common themes have emerged in major earthquake exercises.

> Satellite phones will not be sufficient in catastrophic events, where cross-sector prioritization of critical infrastructure sustainment and restoration will mandate all-sector inter-communication. Nor will these devices be useful without provision for recharging in long outages, or if their ground stations are without power.

The extended duration of Black Sky outages will overwhelm backup and emergency communications capabilities. While participants in the 2011 National Level Exercise (NLE-11) had some success establishing emergency communications channels, for example, their success was measured over a theoretical 48-72 hours. The NLE-11 AAR found that, in a more-extended outage, communications infrastructure would steadily degrade as emergency assets ran out of generator fuel.[15] The Cascadia Rising exercise, simulating a 9.0 earthquake and subsequent tsunami in the Pacific Northwest, also found that emergency managers and coordination centers are ultimately

15 Federal Emergency Management Agency, National Level Exercise 2011 (NLE 11) Functional Exercise: Final After Action Report (AAR), October 28, 2011, p. 16-17.

"not prepared to operate in a degraded communications environment over an extended period."[16]

b. Interoperability Shortfalls

Interoperability between current public and private systems is another key impediment to successful coordination in Black Sky outages. As the previous chapter noted extensively, infrastructure owners and operators will need significant, ongoing communications with government emergency management personnel at multiple jurisdictional levels. Doing so, however, has proven to be a challenge. Private sector participants in the 2014 CAPSTONE-14 earthquake exercise, for example, found that requesting resources and sharing information with the State EOC was "nearly impossible" due to a lack of interoperability between the government and private emergency communications systems.[17]

All-sector, public-private interoperability will be a key requirement for a Black Sky emergency communications system. Given the repeatedly-experienced difficulty of achieving a truly useful level of interoperability between differing communications systems, having all sets of actors interlinked into the *same* system would be the most effective way to achieve this wide interoperability.

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16 Washington State, 2016 Cascadia Rising Exercise After Action Report: Catastrophic Earthquake and Tsunami Scenario, October 21, 2016, https://assets.documentcloud.org/documents/3152696/CR16-State-AAR-Final-Draft-Oct-21-2016.pdf

17 Central United States Earthquake Consortium, CAPSTONE-14 AFTER-ACTION REPORT, September 2014, http://www.cusec.org/capstone14/documents/CAPSTONE-14_AAR.pdf.

Due to the nature of many leading government emergency communications capabilities and infrastructure, however, this is not currently possible. The National Guard's Disaster Incident Response Emergency Communications Terminal (DIRECT), for example, links National Guard forces, first responders, emergency managers and state and Federal authorities.[18] Notably absent, however, are the utility owners and operators who will be at the forefront of response operations.

Similarly, FEMA's Mobile Emergency Response Support (MERS) vehicles, which can provide response officials with a combination of communications capabilities[19], do not include interoperability with the utility owners and operators that will have primary responsibility for sustaining and restoring critical infrastructure in Black Sky events. Successfully coordinating Black Sky response operations will require a single system that can interconnect all relevant sets of users.

c. Black Sky Hazard Hardening

Emergency communications systems must also be resilient against adversary efforts to undermine them. Attacks on critical infrastructure are likely to involve cyber and/or physical attacks on communications systems, given the criticality of the capabilities they afford to incident response efforts. Indeed, the Federal Communications Commission (FCC) acknowledges cyber threats as "perhaps the largest vulnerability … of the national communications infrastructure."[20]

All parties involved in sustainment and restoration operations in the aftermath of a Black Sky event may face the additional threat of electronic jamming technologies. Jamming can impair GPS, radio, and other wireless systems, threatening situational awareness and coordination efforts.[21]

18 U.S. Army (PROGRAM EXECUTIVE OFFICE COMMAND CONTROL COMMUNICATIONS-TACTICAL) "WIN-T INCREMENT 1: DIRECT," last updated March 6, 2017, http://peoc3t.army.mil/wint/direct.php.

19 Federal Emergency Management Agency, "Disaster Emergency Communications," last update March 3, 2016, https://www.fema.gov/disaster-emergency-communications.

20 Federal Communications Commission, Public Safety Tech Topic #19 - Communications Interdependencies, n.d.a, https://www.fcc.gov/help/public-safety-tech-topic-19-communications-interdependencies.

21 "2016 First Responder Electronic Jamming Exercise," Department of Homeland Security, n.d.a., https://www.dhs.gov/sites/default/files/publications/WSMR_Electronic-Jamming-Fact-Sheet-508.pdf.

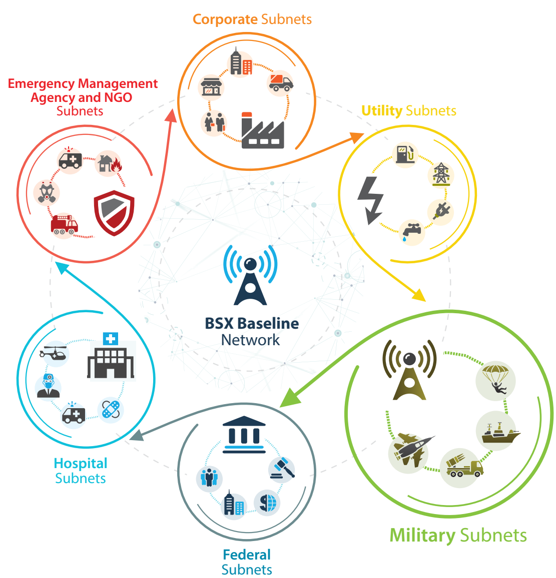
DHS is only beginning to examine anti-jamming techniques and tools to lessen the likelihood that their communications in a catastrophe will be obstructed or delayed.

B. Incorporating Current Systems

Despite the shortfalls of current systems, government departments and agencies are unlikely to abandon them outright. The BSX system has therefore been designed with the ability to incorporate them, along with significant interoperability planning and testing, to ensure existing capabilities can interconnect. BSX would also benefit from including relevant government stakeholders in system development and implementation to catalyze this process. For radio-based legacy emergency communications systems, integration should be relatively simple, as such interoperability is already being incorporated into the BSX design.

Some organizations may plan to depend on less-survivable systems. To address the risk of loss of internal communications when such systems predictably fail, such organizations could deploy additional BSX nodes, which include an embedded LTE base station that can provide local tie-in capabilities for cellphone users.

The BSX design calls for deployment to ultimately span all key infrastructure sectors and supply chain entities, as well as government agencies and other critical facilities and stakeholders. In total, our system analysis estimates that



deployment of approximately 200,000 nodes will be needed across the United States (see figure XX, above). Any locally-provided emergency communications equipment that already exist at these sites can be retained and interconnected to the BSX system, to provide additional capability.

The National Public Safety Broadband Network (NPSBN) has significant potential value in terms of complementing the envisioned BSX system. The NPSBN – which AT&T won a contract to build in March 2017 – will be a "nationwide wireless broadband network dedicated to America's first responders," intended for both day-to-day use and disaster response operations.[22]

However, in addition to deployment limitations (i.e., only to first responders and certain pre-selected additional facilities),[23] NPSBN is overlaid on top of the existing AT&T cellular network. This network will not continue to operate for the long durations required to address a subcontinent-scale power outage, nor is it specified to survive Black Sky hazards such as EMP or sophisticated cyberattacks. Nevertheless, this data transmission-focused system could play an important role in supplementing an all-sector deployed BSX network during the brief period when the cell networks may be available, immediately following a Black Sky event.

> Systems like the National Public Safety Broadband Network (NPSBN), while limited in deployment and lacking other Black Sky compatibility features, could potentially serve to supplement BSX – especially if efforts are made to enhance synergy during the design phase of such systems.

However, such complementarity must be planned before a Black Sky hazard strikes; it cannot be improvised after the onset of such an event. By transferring lessons-learned from the BSX design to that of the NPSBN, pre-planning may also help ensure that NPSBN infrastructure will be more resilient against Black Sky hazards, have access to some of BSX's emergency power capabilities, and potentially be tied in to the all-sector connectivity planned

22 FirstNet, "FirstNet Partners with AT&T to Build Wireless Broadband Network for America's First Responders," March 30, 2017, http://www.firstnet.gov/news/firstnet-partners-att-build-wireless-broadband-network-americas-first-responders.

23 Ibid.

for BSX. Given that the NPSBN is still in development, a valuable time window exists to add these features and overall interoperability in the design stage, rather than tacked on as an addition at the end of its development.

C. Emergency Communications Policy

Those primarily privately-owned segments of critical infrastructure sectors that will need to survive in Black Sky scenarios will generally require the widest deployment of (and have most urgent need for) BSX nodes. Nevertheless, local, state, and Federal government agencies will also need to be tied into such a system to ensure they will be able to effectively communicate, maintain adequate situational awareness, and benefit from the hosted decision support system.

> Utilizing BSX and its hosted situational awareness and coordination capabilities to help Federal agencies meet legislative and policy requirements could offer special benefits, especially for Black Sky attacks on the grid tailored to jeopardize U.S. national security.

The Federal government should also consider improving emergency communications-related policy. The current primary document, the 2014 National Emergency Communications Plan (NECP), does not sufficiently consider the primary role industry will play in critical infrastructure sustainment and restoration following Black Sky events, and therefore their level of involvement in emergency communications. Indeed, the NECP states that 'Communications for Incident Response and Coordination' are "primarily government-to-government functions…[24]

This, however, will not be the case in Black Sky scenarios, or even in more extreme gray sky situations. As became clear in Puerto Rico, without pre-

24 Department of Homeland Security, National Emergency Communications Plan, 2014, p. 11.

planned Black Sky-compatible resilience investment and operational multi-sector coordination, all sectors will collapse. Electricity, food, fuel, water, finance, health care, pharmaceuticals, transportation, security, and all other sectors, primarily made up of corporate suppliers, will be the main focus for infrastructure restoration and population sustainment following a Black Sky event.

The NECP also largely provides strategic, rather than operational, direction for the emergency response community. The detailed, pre-event coordination and operational planning required to successfully navigate Black Sky events will therefore likely need to be addressed in a separate (but complementary) effort. This operational guidance should, however, be developed in tandem with BSX or a comparable platform.

In addition to the NECP, Executive Order 13618 (Assignment of National Security and Emergency Preparedness Communications Functions) guides high-level emergency communications planning. EO 13618 codified specific requirements for relevant Federal departments, officials, and committees, as well as testing and reporting requirements, and created a National Security and Emergency Preparedness Communications Executive Committee co-chaired by DHS and DOD.[25] Enabling the BSX initiative to help Federal agencies meet these requirements could offer special benefits in Black Sky events, especially those involving attacks on the grid that are tailored to jeopardize U.S. national security.

25 Executive Order 13618 – Assignment of National Security and Emergency Preparedness Communications Functions, July 6, 2012, https://obamawhitehouse.archives.gov/the-press-office/2012/07/06/executive-order-assignment-national-security-and-emergency-preparedness.

III | BSX USER REQUIREMENTS ("SOCIAL ARCHITECTURE")

The first step in designing a system that can fill the gaps in existing emergency communications and coordination systems lies in developing a "social architecture" for the BSX. This social architecture identifies the users and customers for BSX, determines how they define value within their operational context and, in general, captures the information necessary to create a system that is both effective and suitable for their mission.[26]

26 "Effective and suitable" is the terminology used in the U.S. Federal Acquisition Regulations, or FAR. See "Federal Acquisition Regulation (FAR)," General Services Administration, last updated January 19, 2017, https://www.acquisition.gov/?q=browsefar.

A. Anticipated BSX Users

The social architecture starts with the question of "who?" – i.e., who will be using this system? Specific details about the intended users are also critical. What are their objectives? What are their needs? What are their skills? What constraints are imposed upon them?

The recommendations in Chapter I provide the starting point for establishing the system's user base. Critical personnel from the public and private organizations described in the previous chapter's revamped disaster response architecture will all be key users of the BSX network. However, the full scope of organizations that will need to be tied into this system must replicate, at a carefully defined, reduced level, the full range of organizations involved in the production, distribution, marketing, and management of all the resources and services needed to sustain millions of affected people, and to restore, supply and resupply all essential infrastructures.

- **Government Users: Federal, State, Local, Tribal, and Territorial**
  For the Federal government, users would include: the National Response Coordination Center (NRCC); ESF Coordinators and Sector-Specific Agency leadership; the organizations in operational support roles such as the National Infrastructure Coordinating Center, the National Operations Center, Office of Cyber and Infrastructure Analysis, National Business Emergency Operations Center and Joint Field Offices; and key White House personnel. It will also be critical to include state, local, tribal, and territorial (SLTT) leaders and

emergency managers, as recommended by the National Emergency Management Association.[27]

- **Regional Reliability Administrators: An Expanded Role**

  Consistent with the realigned structure of FEMA as proposed in Chapter I, regional Reliability Administrators (RAs) would take on an expanded role in Black Sky response operations. These RAs will provide coordination guidance in support of infrastructure sustainment and restoration in each FEMA region and be trained to use the BSX system in disaster operations. In particular, the RAs would utilize the BSX-hosted coordination capabilities, including the situational awareness and decision support functions, to help prioritize and manage infrastructure operations throughout all phases of an event. These teams would also benefit from participation in cross-sector exercises that utilize BSX nodes, or simulations of such nodes.

> BSX's key role is to enable infrastructure restoration and population sustainment by hosting communication and coordination capabilities for all public and private sectors, as well as mass care NGOs.

- **Mass Care NGOs**

  Mass care NGOs will have a particularly vital need for the BSX system. Their services will be very much in demand in complex catastrophes of this scale, and the wide-ranging support roles they will need to play will only be possible if they are fully linked into a Black Sky-compatible communication and coordination system.

- **Private Sector Users**

  In the private sector, essential users will include Cross-Sector Coordinating Council (CSCC) leadership, as well as operations

27 National Emergency Management Association, Building Operational Public Private Partnerships: A Community Reference Guide for Emergency Management Agencies and Private Sector Partners, July 2017, p. 5.

personnel from corporations and other organizations in all critical infrastructure sectors (e.g., electric power, water treatment, water pumping, sewage treatment, natural gas main-line operation, food, health care, and security, transportation) who will be carrying out prioritized sustainment and restoration operations.

Corporations involved in the production, storage, and distribution of resources and services in carefully-defined segments of critical supply chains will also be essential in Black Sky scenarios, and will need to be included as BSX users.

As the BSX system's deployment evolves, BSX training will become an important addition to training programs in user organizations. It will also be essential to include key managers in cross-sector exercises which utilize either BSX or a simulated version of the system.

B. Phasing of Sustainment and Restoration Operations: Implications for BSX Design

Based on this wide range of users, this study identifies primary examples of "use-cases" for BSX in support of restoration, sustainment, and emergency response operations.

1. BSX Use-Cases

Overall, the system must provide voice and (limited) data communications to assign, coordinate, and perform actions required for ongoing service sustainment and restoration operations.

- **Cross-Sector Communications for all Infrastructure, Resource, and Service Suppliers:** Provide cross-sector voice communications capabilities to coordinate essential restoration operations and address interdependent, cross-sector support requirements. This would include: communication among many cranking path sites, including corporations providing loads for black start operations; the delivery of water to electric facilities; prioritized power restoration for water facilities; food and pharmaceutical distributors to support restoration teams and their families, etc.

- **Situational Awareness Data Gathering:** Support both automated and manual forms of situational awareness data gathering for use by the BSX-hosted SAND™ system.
- **Private Sector – Government Coordination:** Provide for voice and modest data communications between infrastructure, resource supplier, NGO, and service sector users with local, tribal, state and Federal agencies.
- **Family Communication:** Provide communications between employees at work and their families, perhaps indirectly through an intermediary such as the Red Cross or other NGOs.
- **Transportation:** Support the coordination of emergency response operation logistics and supply actions across multiple sectors, e.g., communicating with those who are moving or allocating scarce resources and/or personnel.
- **Cross-Sector Coordination Organizations:** Support the operations of corporate and government cross-sector coordination bodies, such as those described in Chapter I.

2. Sustainment and Restoration Operations Phases

The following overview of sustainment and restoration "phases" provides a framework which can be helpful in identifying different requirements for an emergency communications system. In practice, many or perhaps most of these phases would overlap, and each phase would encompass far more complex interaction with other sectors than that summarized below.

a. Phase I: Alert and Protective Measures

Sustainment and restoration operations will proceed in stages. The first stage consists of a two-part process. Initially, all personnel will need to be alerted that the event will require Black Sky protocol to activate the associated teams and initiate appropriate, predefined actions. This very early stage may, in part, be accomplished with normal telecommunications systems during the first minutes and hours after a Black Sky event, if they are still functional during that period.

The second stage of Phase I will be the adoption of *protective measures*, in which utility, resource, and service supplier personnel will take configuration actions that protect equipment against further damage. Emergency personnel will use BSX communications capabilities to provide status updates to key decision makers in all sectors, including power grid Reliability Coordinators, FEMA Regional Administrators, and officials in Joint Field Offices, allowing them to understand the configuration of key infrastructure assets.

Critical infrastructure service providers and supply chain companies will have a designated emergency manager using the BSX system to coordinate their efforts with regional coordinators and relevant managers in all other sectors. In turn, such managers will work with their peers in other sectors and regions, with state and Federal emergency managers, and with other relevant response stakeholders.

b. Phase II: Status Assessment and Repair

The next phase is the *status assessment and repair*. In this phase, response teams determine the location, severity, and system impact of specific infrastructure damage; share status updates; and work both within their organization and with others, as required, to implement necessary repairs, replacements, or workarounds for damage. For infrastructure and resource suppliers that must sustain limited operation, this phase will take place in parallel with the initial "protection" phase.

c. Phase III: Restoration / Ongoing Sustainment Operations

This phase will differ significantly for infrastructure, resource, and/or service suppliers involved in restoring systems that have shut down, vs. those that are working to sustain limited operation.

- **Restoration**

  For entities involved in restoration, the electric subsector provides a primary example:

  Electric company operators, initially, will need to reach out over the BSX system to security organizations and local and state institutions that can help secure roadways to ensure both essential personnel and critical assets can be transported to key work sites. Efforts in this phase will also typically include communication with suppliers of those key assets, including diesel fuel for black start generators, food and pharmaceutical supplies for workers, coordination calls with mass care organizations to ensure adequate shelter is available for families of key workers, etc.

Following this step, company operators will use the BSX network to facilitate internal operations and work with other power companies and facilities that will receive power ("load" companies) to coordinate manual black start operations. Each stage in this effort will involve extensive voice communications among the many teams and facilities along a black start cranking path.

> The electric subsector will have an intensive need for basic, widely connected communications. The manual black start process will involve verbal coordination of multiple teams distributed along a "cranking path."
>
> Such widely connected systems will also be vital for resupplying critical consumables, as well as transportation and security support for electric subsector restoration operations.

Operators will use the BSX system continuously during this process to synchronize actions: e.g., setting relays, starting generators, and configuring the designated electric loads. This process is complex and communication-intensive, typically involving hundreds of switching operations spanning the many facilities of even the simplest black start cranking path.

As the process takes place, operations teams will likely also use the BSX system to request replacement parts, request the loan of specialized personnel, call for requisite consumables (along with transportation and security support), and provide status reports and predicted recovery timelines to decision makers at higher levels in multiple sectors.

Conceptually, initial power restoration may be visualized as concentrating on restoring "islands" of relatively small service areas, implemented via direct links from generation stations to major, critical users of electric power. For this phase, voice communications and modest data (e.g., photos of key equipment configurations) will be the primary need.

As information about the status of power lines and substations is accumulated, corporate operations managers can communicate over the BSX network with their counterparts in other regions – if national telecommunications "back haul" systems are not yet restored– to re-establish "island-to-island" interconnections. Electric utility operators will transition the restoration from a set of discrete islands back towards the "power grid" of nominal operations. This will allow restoration of power to customers that may not have been included in the islands. There may not be electricity provided to residences and businesses during the initial "islanding" phase of recovery operations, as priority will be placed on restoring power, for example, to natural gas pipelines, water and wastewater plants, and other critical facilities.

As summarized above, while this section (and the associated figure) focused on electric subsector restoration as an example, BSX is designed to support, in a similar way, restoration of all relevant sectors.

- **Ongoing Sustainment Operations**

  It will be essential for most critical sectors to continue the production and distribution of at least some minimal resources or services during long duration power outages. This will include, for example, continued (though reduced) operation of water and wastewater plants, critical subsets of food and pharmaceutical production and distribution, operation of critical military and security facilities, and many others, likely relying on emergency power generation. This continued operation will rely extensively on cross-sector support, and, therefore, on the BSX system for coordination.

> Most infrastructure sectors will primarily be working to sustain production and distribution of critical products and services. This will involve a particularly complex use of the BSX system, since all production and distribution involves supplies and support arising from many different sectors.

For this scenario, the water sector may be used as a primary example. As soon as a water company becomes aware that a power outage is expected to continue for a long duration, operations managers will need to implement Black Sky protocols for their systems. For a megacity, for example, this might mean resetting control valves and instrumentation to minimize system pressure; shutting down service to higher-altitude regions of a community that require power-intensive water system pumps ("lifts"); and taking steps to reduce water treatment to pre-arranged minimal levels that can provide potable water, while minimizing the need for replacement of diesel fuel for emergency generators and the need for chemical consumables.

That initial step will require extensive communication within a water company, as well as coordination with relevant government agencies. However, once Black Sky protocols are implemented, communications needs will change. While there will be an ongoing need for communication with support teams at different locations in the field, there will now be an urgent need for cross-sector communication to ensure government emergency response personnel are working to bring in replacement fuel and treatment chemicals before existing stocks are exhausted. And, as in the previous example, throughout this process, water system operators will also be reaching out to other sectors to acquire transportation and security support, as well as food and shelter for sustainment teams and their families.

While the restoration and sustainment operations outlined above are proceeding, emergency managers at all levels of government and across all industry sectors will be in regular communication, reviewing the situational awareness information provided by the SAND system, and jointly considering prioritized actions recommended by GINOM (where the time-sensitivity of an action permits such discussion). These decision makers would be coordinating closely with mass care NGOs and supporting other emergency response efforts, including security, fire suppression, and transportation teams – both internal and external to their organization – through the BSX nodes deployed within those organizations. At the same time, they may also use BSX, as required, to communicate with senior political decision makers at all jurisdictional levels.

Enabling this process requires continued availability of key consumables and other goods and services from supply chain providers. These providers will need to be "Black Sky-certified" to ensure that they have the ability to operate in extended outages. In addition, such Black Sky-certified organizations will need BSX nodes which enable them to communicate with emergency management agencies and key operations managers in the corporations they supply. The need for such supplies, given their extremely limited availability in Black Sky outages, will be a key focus of GINOM's AI-enhanced decision support capability, hosted by the BSX network. In complex catastrophes of this magnitude, the need for such "machine assistance" is amply supported by research and analysis of less severe scenarios.[28]

C. BSX User Requirements: Social Architecture Analysis

In developing the social architecture or "user requirements," the BSX team consulted with domain knowledge experts in different sectors, including operations managers of utility sectors. High-level conclusions from this process are summarized below.

1. Social Architecture: User Requirements for BSX

a. Set up time and labor

BSX should be designed so that a single trained operator can set up the emergency communications suite at a designated location (i.e., implement

28 Siqing Shan and Qi Yan, Emergency Response Decision Support System (Singapore: Springer, 2017), 4; Richard Breton and Éloi Bossé, "The Cognitive Costs and Benefits of Automation," Paper presented at the RTO HFM Symposium on "The Role of Humans in Intelligent and Automated Systems", Warsaw, Poland, October 7-9, 2002, p. 1-1; Thomas H. Davenport and Jeanne G. Harris, "Automated Decision Making Comes of Age,"MIT Sloan Management Review, July 15, 2005, http://sloanreview.mit.edu/article/automated-decision-making-comes-of-age/.

the transition from the long-term storage configuration into the operating configuration) in 4 hours or less.

This limitation on setup time and labor requirements drove the down-selection process on how the emergency communications equipment is configured for long-term storage, the portability of system modules, the complexity of integration and alignment requirements, and a range of other, subsidiary criteria.

b. High reliability

BSX should be designed so that – unless there has been physical damage sustained at a particular node – 99% of the locations should be able to operate (in at least a partial capacity) after being brought out of long-term storage. Achieving this level of reliability and availability will require some pre-deployment of selected spare parts at every site.

c. Automated network establishment

The emergency communications system should be designed so that if at least 90% of the nodes in a region are brought into operation, along with at least 75% of the nodes in adjacent regions, then at least 75% of the emergency communications system nodes within that region should automatically discover a route to designated key system hubs and decision makers (Joint Field Offices, key coordination facilities in critical sectors, etc.).

Additional nodes can achieve connectivity[29] to the local emergency communications system hub through manual operator actions. Achieving this high level of reliability and connectivity will require the use of multiple data paths for most of the point-to-point linkages needed by users. This in turn implies a need for multiple communications devices of different types at most node sites.

d. Voice and limited data connectivity, and prioritization

Push-to-talk voice communication (both one-person-to-one-person and "conference calling") serves a high portion of the emergency

29 Connectivity, in this context, means "achieve at least push-to-talk voice and a modest data" capability.

communications system use-cases encountered in the research that defined the baseline, core system configuration. The next-most-important capability is the ability to send digital photographs between nodes. More generalized data service is a still-lower priority. These priorities will be used to establish dynamic priority-of-service within the emergency communications system.

As indicated earlier in this chapter, higher data rate options can be provided as required, regionally, by system users, by investing in additional dedicated nodes that support such data rates.

e. Power requirement optimization goal

As indicated above, when the BSX system reaches full deployment, the BSX social architecture analysis identified the need for approximately 200,000 system nodes across the United States. Cost per site is therefore a design consideration. Initial cost sensitivity assessments suggest that the 30 to 60-day power requirement is a significant contributor to the cost of a fully deployed system. As the technical design evolves through multiple "block" deployments, this represents an area that will require careful optimization with each user and user community to reduce the power requirements and make case-by-case implementation decisions that minimize cost without decreasing operational availability.

f. Hosting situational awareness

Although extensive pre-event planning will be required for Black Sky scenarios, no plan will survive the first hour of an actual event without requiring extensive modification. A design compatible with hosting a capability like the Situational Awareness Network Diagnostic (SAND™) system, which provides evolving, real-time situational awareness is therefore essential. Decision makers in all sectors will use this information to adapt plans to the actual situation on the ground, and to communicate the altered plan to those in the field.

g. Hosting multi-sector modeling and simulation for decision support

Despite the criticality of real-time situational awareness for decision making, the scale of infrastructure and resource sustainment and restoration requirements will far exceed the capabilities of operators and decision makers without machine assistance. As a single, interoperable, widely deployed, multi-sector system with provisions for long-duration power and hosted situational awareness capabilities, BSX is also an ideal host for a simulation model that can provide interdependency mapping and AI-enabled decision support in Black Sky scenarios, such as the Global Infrastructure Network Optimization Model (GINOM™). The BSX network, computer resources, and user interface are therefore designed to support such a simulation engine.

h. Multi-sector deployment scale

In a Black Sky outage, response operations – including the prioritized sustainment and restoration of critical infrastructure, resource, and service suppliers and their tiered supply chains, as well as population sustainment – will require significant planning, and eventual "Black Sky protocol" certification for a complex web of stakeholders. This may include corporations, government offices, and NGOs spanning the most important public and private sectors. Since communication across this full range of organizations will be essential, BSX nodes or node clusters will need to evolve to include deployment with selected, regionally-distributed organizations in all such public and private sectors. The current estimate for the ultimate scale of BSX deployment across the United States is greater than 200,000 nodes, and the scale of deployment necessary is likely to expand over time. The BSX system and network's architecture is designed to be compatible with further scaling, as required.

i. Multi-sector deployment socialization

BSX may be compared, metaphorically, to a nervous system. In this case, it is the "emergency nervous system," activated in Black Sky conditions to replace the normative telecommunications / internet nervous system of the organically interconnected infrastructure sectors and resource and service suppliers that support our modern world. Thus, a critical requirement for the viability of such an emergency communications system is wide, multi-sector deployment. Moreover, nearly all contemporary supply chains are international. Although initial BSX deployment will be focused on encouraging development of a sparse network across the United States, ultimately, deployment of an emergency communication and coordination system that can serve this need – either BSX or some compatible, comparable system – will be needed internationally.

Successful BSX deployment mandates an expanding socialization process that can successfully reach out across nearly all public and private sectors in the U.S. and, eventually, in partner nations. Given EIS Council's mission to host multi-sector, coordinated planning for Black Sky events, the organization, at all levels, is committed to using its unique cross-sector and international presence and connectivity to help drive this socialization process.

IV | SYSTEMS ENGINEERING TRADE STUDIES

Following the framework of user requirements or “social architecture” summarized above, the next step in system design was to map the associated requirements and goals to candidate solutions in a series of systems engineering trade studies. This process was undertaken through several steps:

- Identifying candidate communications technologies
- Developing a list of key issues and risk areas
- From that list, identifying a set of associated technical trade studies
- Developing candidate designs, together with methods and metrics for selecting among those candidate designs
- Using those methodology and metrics, making the initial design selection, along with an assessment of the feasibility and performance of the selected design.

This five-step process is summarized in the corresponding sections, below.

2. Candidate Communications Technologies

The BSX development team identified an array of communications technologies as initial BSX candidates based on the team's systems engineering analysis and experience in implementing a variety of high-reliability communications systems[30]. These candidates included:

- Network-supported HF radio
- Network-supported UHF radio
- Network-supported VHF radio
- Network-supported higher-frequency radio
- Network-supported meteor-burst radios
- Use of power lines to carry communications signals
- Dark fiber communications cables[31]
- Commercial satellites (low-Earth orbit)
- Commercial satellites (geo-stationary orbit)
- Various combinations of the above

3. Key Issues and Risk Areas

Given the results of the social architecture and the above list of candidate technologies, the BSX development team identified a number of key risks to be addressed through the technical trade study process. Through that process, a condensed list of issues and risk areas were identified, summarized below, representing a combination of likelihood and potential impact that made them possible key system disablers if not properly addressed and mitigated.

Issues and risk area summary

a. How to provide power for the emergency communications system at each location for the specified 30 to 60-day period?

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30 Including the emergency communications system in the City of New York, and the U.S. Army's "tactical internet" and Blue-Force Tracker. See: Neil G. Siegel and Azad M. Madni, "The Digital Battlefield: A Behind-the-Scenes Look from a Systems Perspective," Procedia Computer Science Vol. 28 (2014).

31 Fiber optic communications cables that are installed but not in active service.

b. What spectrum (RF frequencies) would be available for the emergency communications system during emergency operations? Not all of this spectrum allocation need be available for use during nominal (non-emergency) use.
c. What techniques and materials would allow the emergency communications system equipment to be stored for long periods of time (years or decades), yet still be periodically tested, maintained, and support periodic training?
d. How to allow the emergency communication and coordination system to adapt, ideally almost automatically, to the likely differences between the anticipated emergency conditions and those that actually come to pass?

4. Technical Trade Studies

Given the above list of significant risk areas, the BSX development team identified key trade studies that would be required.

- How to provide 30-day self-contained power with a long storage life, reasonable maintenance requirements, and high availability at need.
- Assess spectrum availability during emergencies and, based on that assessment, select the actual communications mechanisms (and eventually the actual devices) for the core network. Also required is the selection of an enabling network design that will permit smooth evolution to incorporate new technologies and devices as they become available with adequate, demonstrated reliability.
- Determine the approaches and materials required to achieve effective long-term storage of the emergency communications system equipment.
- Identify techniques to support self-adaptation of the emergency communications system.

The results of these trade studies led to a candidate solution, presented below, which also permitted reasonable technical approaches to mitigate all risk areas. Though there was no explicit "design-to" per-site cost, the selected approaches, at top level, were assessed to allow cost effective implementation options.

One area that will require coordinated optimization between user and supplier will be selecting optimum, specific implementation of the "30 to 60-

day power" capability appropriate for the needs of different users and sites. Where nodes cannot depend primarily on facility-provided emergency power, the specific mix of technologies selected will vary from site to site. Selections for each site will be made from a range of options, depending on specific user and site requirements.

V | THE SELECTED, CANDIDATE SOLUTION

This section describes the candidate design, along with the trade studies that validated the efficacy of that design.

The systems engineering process, described above, allowed the BSX development team to select an optimum overall network architecture, along with key technical parameters (such as radio frequencies and transmission polarizations for the system's core network). More detailed parameters will be selected during detailed design of each anticipated deployment block (e.g., exact RF power levels, antenna sizes, and manufacturers).

Finally, this section assesses the technical feasibility of the proposed design and estimates key system parameters such as availability, network connectivity rates, and storage life.

A. Top-Level Summary of the Selected BSX Design Solution

Resulting from a review of the identified user requirements and analysis of the full array of key concerns and issues, a subset of key requirements were identified as design drivers:

BSX System Design Drivers

- The BSX network and nodes must survive the onset of a Black Sky event, no matter which of the identified hazards caused the event.[32]
- All nodes must operate for 30 to 60 days without grid-provided power.
- The BSX network must support deployment of at least 200,000 sites ("nodes") across the United States, and appropriately-scaled system deployments in other countries over time.
- BSX must provide the capabilities needed to support sustainment and restoration operations in complex catastrophes. This includes hosting situational awareness and decision support systems, for use by a hierarchy of users distributed across all infrastructure, resource, and/or service supply sectors, and their government and NGO partners.

32 For a detailed assessment of broadly accepted hazards that could take place at the Black Sky level, see "Black Sky Hazards," EIS Council, n.d.a., http://www.eiscouncil.com/BlackSky.

Figure E | Elements of the BSX design solution

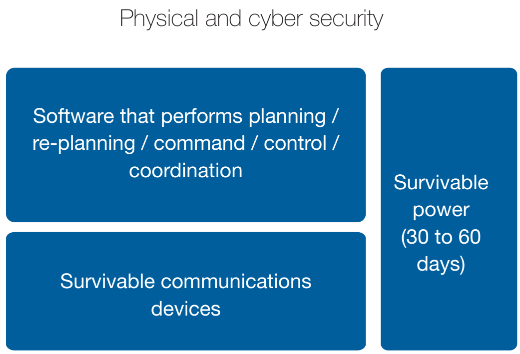


Figure E depicts the elements of the selected BSX design solution. As the figure shows, the

selected BSX system architecture may be summarized as four interactive elements and capabilities.

BSX System Elements and Capabilities

- Black Sky hazard survivable communications devices.
- Black Sky hazard survivable emergency power (i.e., designed to survive the actual Black Sky event, and capable of operating for many weeks), either self-contained or available from the facility where deployed.
- Hosting capability for situational awareness and multi-sector modeling for decision support.
- Features that provide physical, cyber, and EMP protection to the BSX system. These will be necessary both during the long period while it is being stored, prior to the onset of a Black Sky event (potentially decades at unmanned locations), and during and after the event, as the BSX system is being used to implement sustainment and restoration efforts.

Consistent with the design drivers and the resulting, selected approaches reviewed above, specific components were selected as primary elements of the core Black Sky-survivable BSX communications subsystem.

- Core devices at each BSX node location
  - HF NVIS radios, with small magnetic antennas
  - UHF radios
  - Packet routers equipped with special, mission-specific software agents
  - Network management software to implement and control the above functions
  - A power module, baselined to utilize vanadium redox flow batteries, with control circuitry to enhance reliability, supplemented at many locations by solar panels. The system must be compatible with alternative power supply options, as well as alternatives to solar panels for supplemental power (e.g., wind-powered generators).
- Regional coordination centers and other, selected, node clusters will also include:
  - An "intelligent director:" A packet router equipped with additional special, mission-specific software agents.
- The emergency communications system may optionally include the following components:
  - Mobile emergency communications system nodes (e.g., trucks or other vehicles that are equipped with emergency communications equipment, a packet router, and appropriate power equipment).
  - Other enhancement features, where required, such as an NTE base-station to permit tie-in of local cell phones at short ranges.
  - Mobile emergency power modules, which can also be used to power other types of equipment, if needed.
  - Tethered drone nodes to enable longer distance use of UHF devices, especially where judged helpful due to unique requirements, terrain, or atmospheric transmission issues.
  - Additional devices dedicated to higher bandwidth communication, where required, typically in special, higher node-density regions.

B. Network and System Design

The devices summarized above will be linked in a mesh network, capable of scaling beyond hundreds of thousands of nodes or node clusters.

1. Network and System Design Characteristics

a. Site to site communications

BSX will leverage the strengths of HF and UHF radios to provide site-to-site communications. UHF provides very high-quality service, but at a shorter range than HF. HF radios, however, can operate beyond line-of-sight. Both frequencies are therefore included. The disadvantage of large size traditionally associated with HF radio antennas is corrected through the use of magnetic antennas.

b. Power module

If on-site emergency power is not available, nodes will provide stand-alone power for 30-60 days. Power module sizing will be based on projected requirements of the radios' duty cycle for each node. The size of stand-alone power modules, where required, will therefore vary from site to site. In such cases, BSX software will manage the site's power consumption based on input from GINOM regarding projected use timelines for a given node.

Users will also select from a range of power module configurations. At many sites, the size and cost of the power module may be decreased by the addition of solar panels or, where suitable, wind power or other approaches.

c. Mobile nodes

Vehicle-mounted emergency communications system configurations will be important for many user categories. The UHF component could be configured to operate on-the-move, though the HF NVIS component will likely be configured only to operate at-the-pause (i.e., when the vehicle is parked). Power for the emergency communications system equipment on these vehicles will be provided by a combination of batteries and enhanced vehicle alternators.

d. Accessory, portable power modules

For nodes that require power modules, a range of configuration options could provide for long duration power storage, including a battery technology that allows storage, fully charged, for many years. Battery-based power storage provides a unique advantage for urgent, high-criticality equipment or facilities that may experience a sudden power outage extending beyond the capability of their emergency generator(s) and/or available fuel reserves. Users may therefore wish to have accessory BSX modules available for use in such unforeseen events, providing them with a portable power source that can be moved from site to site during an emergency. These accessory modules could also function as spares for a user's BSX node cluster.

e. Communications protocols

The single-hop, direct site-to-site communications success-rate is improved through the use of error correction coding, and other higher-level communications protocols. These are implemented in the packet router located at each emergency communications system site.

f. Automated, optimized radio selection

There are two independent radios on different frequency bands at each site, utilizing different modulations. This provides a basic type of communications path diversity, and thereby improves system reliability. The router at each site determines which radio to use for each transmission attempt (whether voice or data) based on its radio "visibility" to adjoining sites. No manual action is required by the emergency communications system user to select the best radio for each transmission, as this is accomplished for them automatically. Emergency personnel will not be required to have RF propagation expertise.

g. Automatic multi-hop path selection

The packet router also uses the same visibility information to implement multi-hop communications for both voice and data. A communications link need not be "direct," meaning the data may be routed through other emergency communications system sites as intermediate nodes. The finding and utilization of such paths is automatically accomplished by the packet routers. No manual action is required by the emergency personnel to find and implement such multi-hop paths.

h. Interoperability with non-BSX devices or networks

BSX will link in and use other existing communications systems if they are available. If a local organization (e.g., utility) has provisioned an emergency communications system for their own facilities, that system can be linked into the BSX network by connecting it to the packet router at a BSX site and incorporating a special "bridging" software agent at that router.

This capability allows the BSX network to interconnect any available emergency communications systems as subnets, which then have availability to interconnect with all other nodes on the BSX system.

i. Frequency selection

Frequency selection is based on time-of-day, atmospheric conditions and other factors. An "intelligent director" (a packet router equipped with mission-specific software agents) controls and coordinates this process, providing direction to the packet routers, which in turn command the radios to use the appropriate frequencies and other radio settings. No manual action is required by emergency personnel to account for day/night frequency preferences or other, related frequency selection factors.

The overall policy for frequency utilization must be coordinated with regional and national civil officials. This coordination, however, is also implemented in the intelligent director; no manual action is required by emergency personnel to comply with ever-changing radio-frequency policies.

j. Hosting Situational Awareness and Decision Support

Coordinating bodies and decision makers in all sectors will be tasked with manually "replicating" at least minimal portions of the self-sustaining infrastructure and resource supply networks that, under ordinary conditions, deliver all products and services used in modern societies. However, they will be tasked to do so in a highly disrupted environment. This will not be possible without extensive, multi-sector situational awareness information, available, in a digestible format, to most decision makers. The SAND™ system, referenced above, provides an example of such a capability.

Even with such situational awareness, however, the sheer number of decisions required, and the vast array of data that will need to be "manually" monitored, will greatly exceed capabilities of human operators without machine assistance. In a Black Sky event, industry and government personnel conducting infrastructure sustainment and restoration operations, or addressing the needs for population sustainment, will require a model which includes both interdependency mapping and an AI-enabled simulation, as well as a forecasting engine that could provide decision support functionality. The GINOM™ initiative, referenced above, is an example of this two-level capability.

Since BSX is envisaged as an interlinking system that connects to all such sectors, designed to survive and operate in Black Sky scenarios, the system is ideally placed to host both of these capabilities.

2. Design Validation

The next step in the systems engineering process is to validate the overall design outlined above.

To do this, the BSX team developed a performance model using inputs based on sample product specifications (for key elements of the system design) and on the overall system requirements and goals summarized above.

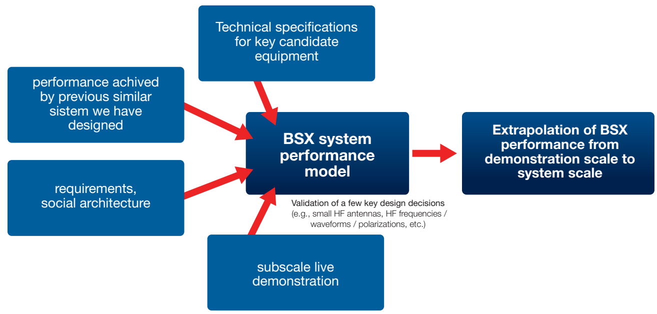
Figure F depicts the methodology used to implement this process, providing a preliminary validation of some of the key technologies selected for the survivable communications element.

A system performance model makes various assumptions about certain aspects of the system it is modeling. Drawing upon actual performance achieved by similar systems to refine these assumptions is essential for creating a high-credibility model. This was a key consideration in BSX model development. Dr. Neil Siegel, for example, the principal author of this chapter, was a key part of the development team. Dr. Siegel was also the program manager for the U.S. Army "Blue-Force Tracker."[33] This Army system uses VHF and UHF radios interconnected via local routers to implement its communications network, similar in some critical ways to the communications systems selected for

33 Formally known as "Force XXI Battle Command Brigade-and-Below", or FBCB2.

BSX. The Army system was fielded in 1999,[34] and has been in successful and continuous operational use since that time.[35]

Figure F | BSX Performance Model



Dr. Siegel, working in partnership with Bran Ferren, co-founder of Applied Minds LLC, has deployed and successfully used similar emergency communications systems in a variety of locations worldwide. The emergency communications system which, uniquely, operated successfully during the Superstorm Sandy blackout represents one of many examples of their joint efforts. By working together in support of EIS Council's BSX development, Neil Siegel and Bran Ferren were able to apply lessons learned from several relevant projects, and thereby ensure that the BSX design leverages this full range of experience. Many of the key features selected for BSX have been validated through their use in these prior systems.

The motivation for the design of the above-mentioned Army system, in particular, was similar to that which underlies the goals for BSX. Requirements included very high levels of reliability, and the design solution was to achieve this via communications path diversity – multiple radios, on different frequencies, using different waveforms, with the best path determined in real-time by the attached routers.[36]

34 Neil Siegel, "FBCB2 / BFT – Experience in Combat, and Strategic Directions" (keynote address at the Force Tracking Conference, Las Vegas, Nevada, September 2005).

35 Neil G. Siegel and Azad M. Madni, "The Digital Battlefield: A Behind-the-Scenes Look from a Systems Perspective," Procedia Computer Science Vol. 28 (2014).

36 Neil Siegel, "Digitizing the Battlefield," in Fateful Lighting: Perspectives on IT in Defense Transformation (Information Technology Association of America, 2002).

In one cardinal way, the Army system was much more difficult than the BSX: most of its nodes must operate while on the move, and therefore had to deal with continuously-changing line-of-sight interruptions, interruptions caused by terrain masking and foliage masking, and other related issues. Most of the operating locations for BSX are, in contrast, at fixed sites and do not face these difficulties. On the other hand, the envisioned BSX sites are on average farther apart than the units for the Army system. This led the BSX team to select HF radios as a key element of the core architecture used within BSX nodes, as HF can achieve longer single-hop communications distances than the VHF and UHF radios used in the Army system.

Key elements and capabilities of a BSX prototype were successfully demonstrated in a subscale field test as part of the EPRO SECTOR Executive Committee Meeting, Winter 2017. This demonstration took place on December 12, 2017, at PJM Interconnection headquarters in Audubon, Pennsylvania.

As noted at the bottom of Figure F and shown in the image below, the BSX team successfully conducted a subscale live demonstration of certain critical aspects of the BSX candidate design. The HF radios and their magnetic antennas were one critical element in this testing, selected because they are the principal component-level difference from the Army system mentioned above. This demonstration validated the above-summarized assumptions about the performance of HF radio with the magnetic antennas. The BSX team also successfully performed a live performance-measurement field test using a pair of UHF radios.

As part of the design validation, the development team collected quantitative data on HF NVIS radio performance. Given the ranges and packet-completion rates provided therein for HF NVIS and the measurement results with the UHF radios (together with comparable radio performance data for UHF), estimates were made for BSX system-level performance by using system-modelling methodologies.

The results of this design validation process were quite consistent with expectations, fully supporting the BSX architecture and system design approaches, and indicating the BSX system should perform very well. For additional validation, the modelling and data were also evaluated in comparison with similar capabilities of the above-described U.S. Army system, whose architecture is similar.

C. Hosted Data Processing

This section considers the key data and processing elements to be hosted by the BSX platform. Specifically, the section examines the situational awareness data that BSX users will want and need, its bandwidth hosting requirements, and design approaches for engaging users with that data. As a communications platform, BSX will be capable of hosting other software applications; however, in consideration of innate Black Sky environment requirements and communications capacity limitations, it is important to ensure that this is limited to only the most vital software systems The key data and software elements that BSX is designed to support are detailed here.

1. **BSX Hosted System Data:** Hosting Requirements for SAND™

This sub-section considers the question:

> *"What data will the users of the BSX system need to accomplish their mission of guiding and implementing sustainment and restoration operations?"*

During a Black Sky outage in the continental United States, the Federal, state, local, tribal and territorial emergency management communities will be tasked with providing support to a large population, for an extended period of time, over a large geographic region. Such an event would cause unprecedented disruptions to essential services, not only within the power sector, but also for transportation, water, wastewater, healthcare, communications, and essentially all other infrastructure, resource, and service supply sectors. As discussed above, availability of the communications systems that these organizations use every day will be limited to a few hours or, at most, a few days following a Black Sky event.

To help the planning efforts for recovering from catastrophic outages, a systems analysis approach was used to identify the data requirements for Black Sky operations across multiple disciplines required to support infrastructure restoration and sustain populations in such scenarios. These data requirements are included as part of the SAND™ system, to be hosted by the BSX tactical network. SAND will provide a sensing and reporting framework to supply essential situational awareness data to decision makers and service providers when it is least available, yet most necessary.

As a result of this analysis, Black Sky operational mission requirements were developed, corresponding to three mission-critical functions.

Black Sky Operational Mission Requirements: Mission Critical Functions

- Execution of Strategic Mission Priorities
- Cross-Sector Planning and Coordination
- Resource Request and Acquisition

The corresponding information requirements were organized based on the use-case for this information, addressing each of the three mission-critical functions. Information types include:

- Event Characterization
- Consequence Analysis
- Decision Support

The development team then aligned data requirements (individual data elements) with each information requirement to define the most appropriate and comprehensive source of that information. Data requirements represent the underlying granular datasets (e.g., infrastructure of concern in the impacted area, or population with durable medical equipment) needed to meet each information requirement. Most information requirements are fed by multiple data requirements, representing the collation of those data into response-relevant information that is operationally useful. Each data requirement was described by its relative information transfer load within a Black Sky-functional communications system, in terms of the number and type of fields required for tabular data and text, and the number and type of geospatial elements and metadata fields required for maps.

These specifications allow the total relative data load requirements for a communications system to be estimated, which then allows the total data requirement to be compared to the capacity provided by the proposed emergency communications system.

2. Information Management Framework

In Black Sky emergency response efforts supporting the "whole of community," an information management framework is required to serve the operational coordination and management functions required of the emergency management community at all jurisdictional levels. The primary management requirement during a Black Sky event, or any other emergency, is to understand the situation, what tasks are required to mitigate losses, and the process by which the response and recovery efforts can most effectively mitigate those losses. The primary coordination task is to determine how organizations can best work together to coordinate the prioritized delivery of services to support the "on the ground" operational response and recovery apparatus of private and public organizations.

The proposed BSX data coordination approach explicitly respects the roles and responsibilities of each organization and asset owner to execute Black Sky emergency plans within their respective chains of command, while also addressing the need for national-level coordination.

This coordination involves multiple sectors and requires macro-level alignment of planning and preparatory efforts. Notably, this section posits that macro-level coordination may co-exist with micro-level coordination, defined as that which is managed from within an organization that may have greater tolerance for traditional communications-and-coordination approaches.

Therefore, the proposed approach to effectively manage and coordinate Black Sky response efforts includes the definition of clear operational mission requirements that shape and drive the functions of management and coordination, as well as data requirements that serve the missions of national, regional, and local efforts.

3. **Data Analysis:** Based on the FEMA Response Federal Interagency Operational Plans (FIOPs)

For this analysis, the Black Sky operational phases were drawn directly from the FEMA Response Federal Interagency Operational Plans (FIOPs).[37] The FIOPs are built upon the concepts outlined in the National Response Framework and serve as operational documents specifying how various Federal agencies work and interact to support national preparedness. There are five FIOPs, each describing one of the preparedness mission areas: Prevention, Protection, Mitigation, Response, and Recovery.[38]

The National Response Framework and the five FIOPs articulate a comprehensive vision of how the numerous agencies comprising the preparedness community can work together using common language and operational procedures, thereby aligning their mission-specific practices with those of the overall community. In support of this integration strategy, the three emergency management phases (e.g., steady-state, response, and recovery), and eight sub-phases used in this document have been pulled directly from the FEMA Response FIOP, as illustrated in figure G, below:

Figure G | FIOP phases of emergency management.

37 The remainder of this subsection draws extensively from Ellie Graeden and Joel Thomas, "A Systems Integration Framework for Interdisciplinary Black Sky Operations" (paper presented at the 15th Annual Conference on Systems Engineering Research Disciplinary Convergence: Implications for Systems Engineering Research, Redondo Beach, CA, March 23-25, 2017), pp. 4-5.

38 The FIOPs are available at "Federal Interagency Operational Plans," FEMA, last updated December 2, 2016, https://www.fema.gov/federal-interagency-operational-plans.

For each Black Sky operational sub-phase, a series of three information categories was provided to broadly scope and define the related operational information and data requirements. These three information categories are: event characterization; consequence analysis; and decision support.

Event characterization models and analyses convert raw observational data into situational awareness information describing the location, timing, and/or severity of an event. Event characterization performed prior to a hazardous event may predict, for example, the cities or regions likely to be affected and to what degree. Event characterization may occur before, during, or following an event to support long-term planning for a hypothetical event, rapid assessment of an ongoing event, or extent validation of an event which has already occurred, respectively.

The actions that must be completed are summarized by the various coordination and decision-making entities after a Black Sky event, in order to support infrastructure restoration and population sustainment. Each of these actions requires certain data, which were identified in the design process.

A detailed analysis was then conducted on those data:

- Users of the information
- Name of the information item
- Description of the information item
- Whether this information item is likely to be required, or only desired
- Form the information item will take
- Frequency of measurement or data acquisition required to support the mission
- Accuracy / quality requirements
- Source(s) for this information item
- Rationale for the need / desire for this information item

4. **BSX Data Processing:** Hosting Requirements for GINOM™

The data discussed above will be essential as a basis for decision makers and service providers to "manually" replicate and repair the systems and processes that normally provide critical services and resources. Nevertheless, in practice, these individuals will require significant "machine assistance" in order to successfully replicate even a portion of these highly complex, autonomous, and interconnected functions.

GINOM

The GINOM™ software package, currently in development, is being designed to fill this need while operating within the data capacity limitations of the BSX communications platform. Utilizing the SAND situational awareness framework to acquire the required data, GINOM will need to consume and process this diagnostic data to provide user-friendly situational awareness information and decision support, mapping out complex infrastructure supply chain interdependencies and forecasting the consequences of particular resource allocation plans.

5. Effective and Suitable

The challenge of building a user-friendly system, however, is not an insignificant one. One might assume that the success of such a system would be based exclusively on the value of the information that it supplies to its users. However, while the quality of that information is important, it will not be the most critical factor in determining whether or not the system proves successful.

An insightful statement from the Federal Acquisition Regulation (FAR)[39] illustrates this point. The FAR states that a system should not be fielded until it has been found to be *both* "effective" and "suitable." By using this phrasing, the FAR acknowledges that a system could be effective without being suitable, or suitable without being effective. In this context, "effective" means that the system meets its established specification; this is an objective assessment that all mandatory requirements have been successfully implemented and verified

39 "Federal Acquisition Regulation (FAR)," General Services Administration, last updated January 19, 2017, https://www.acquisition.gov/?q=browsefar.

through an appropriate test program. "Suitable," on the other hand, means that the system is appropriate for its intended purpose and users.

Experience indicates that this concept of "suitability" is vital to the success of users depending on complex systems such as BSX, SAND, and GINOM. This is inherently somewhat of a subjective assessment: Do users like it? Can the system be operated in the actual highly-stressful environment for which it is intended, by the actual users (given their knowledge and skill)? Is the system consistent and reliable? Does it respond quickly to user commands? Can it do all of these things without putting an undue burden of computer science expertise onto those users? Can it do all of these things at the scale necessary (i.e., 200,000+ points of BSX presence and millions of components in the infrastructure network supply chain)? Can it do so while providing the necessary very high level of reliability?

While the quality or effectiveness of information provided to users is important, that represents only one factor for determining if a given system is successful. As the Federal Acquisition Regulation (FAR) states, a system should not be fielded until it has been found to be ***both*** "effective" and "suitable."

If a system passes these tests, experience repeatedly indicates that such a system will be liked and accepted by the user community and utilized operationally. The information content (even if not ideal in its initial instantiation) can be adjusted over time based on feedback from those users. But if the system fails these tests, it does not matter how complete the information that could be displayed is; it will not be liked, trusted, or operated appropriately during actual emergency operations.

In this regard, while it remains essential to understand what data will *effectively* allow emergency management and service providers to perform their missions, assuring that the BSX-hosted, combined SAND and GINOM systems highlight and provide data and associated decision support that is *suitable* will be a greater technical challenge. To be sure, it will be crucial to achieve both. The insight offered by the aforementioned portion of the FAR, however, is that one must focus separately on both of these goals; accomplishing one does not automatically result in accomplishing the other.

6. Key goals and challenges for achieving a BSX-hosted system of systems that is *both* effective and suitable

This sub-section addresses the key goals and challenges in making the BSX and the hosted SAND and GINOM systems *suitable*, as well as *effective* for its intended users.

Consider the following summary of planning and response task categories to be performed by GINOM, supported by the BSX system:

a. Black Sky preparatory task categories

- Black Sky Protocols: Pre-plan Black Sky day tasks and actions, i.e., outline of emergency restoration tasks for infrastructure personnel to sustain and restore critical services, and for emergency management to coordinate response operations.
- Black Sky Training: Support training scenarios to allow emergency personnel to practice coordinated Black Sky plans in a risk-free environment.

b. Real-time, post-event task categories

- Critical, Real-Time Events: Provide a continuously updated "ground truth" model identifying events that are "on the critical path" for mission effectiveness as conditions change and restoration proceeds, allowing for effective coordination.
- Interdependency Mapping: Provide network analysis tools to track in-sector and inter-sector supply chain pathways to inform efficient prioritization of resources.
- Prioritization / Decision Support: Forecast effects of potential resource prioritizations on the complex infrastructure supply chain to support alignment of recovery plans with dynamic "ground truth."

Emergency managers and operations personnel in all major sectors will be the key users of an emergency communication and coordination "system of systems:" the BSX network, and the SAND and GINOM systems it hosts. The users of this system of systems will include two primary groups:

- Those whose tasks relate primarily to *coordinating* the recovery action, but who do not personally take actions to restore service; and
- Those whose tasks relate primarily to specific actions to *restore service*.

Operators within two defined role categories will require substantially different information and tools in order to be successful.

c. Information requirements and tools, as a function of user role

- **Users providing coordination functionality:** The Need for a Coordination Interface

  Those who are coordinating and communicating about recovery efforts will need status information, analysis, and planning tools. This may include: visualization of systems' operational status; tools for tracking cross-sector supply chains; resource requirements for recovery operations; estimates about task completion times; resource provider information; forecasting services to predict overall effects of task prioritizations; etc.

Most detailed planning must occur long before a Black Sky event. Yet, real-time tasks must be dynamically added and removed depending on the state of critical supply chains. This constantly-updated operating picture will need to be synchronized across all GINOM clients in order to avoid potentially crippling disorder and inefficiencies.

- **Active users, "in the field:"** The Need for a Task Management Interface

  Those who are performing the actual recovery efforts will need information about the tasks themselves. This may include: prioritized task lists for recovery operations (e.g., black start); lists of emergency resource suppliers (people, parts and equipment, and information) for each task; a system for coordinating whether all necessary personnel and resources are in place to perform coordinated tasks; a means to record what has been completed for feedback through SAND back into the GINOM database; etc.

These views – a coordination interface and task management interface – therefore become the core windows into the GINOM system. Each of these will provide user-tailored insight into the tasks at hand based on an underlying framework that is constantly tracking changes to the overall system state, maintaining a digital copy of the "ground truth," and providing analysis and network forecasting services.

Much of the detailed planning for recovery tasks can only be performed long in advance of the emergency – both with regard to task definitions and the necessary trained personnel and equipment required to complete them. Yet, during the actual emergency, the priority of tasks will need to be adjusted as a function of the overall scenario. Tasks will be dynamically added and removed depending on the current supply chain state, creating new relationships within the network. This constantly-updated picture will need to be synchronized across all BSX and GINOM clients in order to avoid potentially crippling disorder and inefficiencies.

The synchronized operating picture will also be critical in informing coordination with relevant stakeholders, including political authorities (and through them, the general public), police and fire departments, and NGOs operating in the area.

The synchronized operating picture will also be critical in informing coordination with relevant stakeholders, including political authorities (and through them, the general public), police and fire departments, and NGOs operating in the area. This operating picture will also inform decision-makers of the status of the parts, equipment, information, and personnel needed to undertake recovery actions. It will thereby allow for the facilitation of recovery efforts, both by those at higher echelons of government and those outside of the affected area.

In this regard, while the SAND and GINOM software will necessarily be decoupled from the BSX platform from a *technical* standpoint, their *suitability* will be tightly linked. While reliable communications are a core requirement of any recovery operation, effective recovery will depend on both meaningful data and a coordination and planning system to keep complex, distributed efforts in sync.

Conversely, these diagnostic data and coordination systems will be useless without a reliable communications platform synchronizing situational awareness and task prioritization among the emergency management and service provider user base. Together, the BSX, SAND, and GINOM platforms will thereby constitute a tiered, hardened restoration and sustainment framework for extreme events.

Fortunately, the U.S. has yet to face an event that triggered subcontinent-scale outages. The procedures and standards that currently facilitate power restoration have been shaped by decades of experience with outages at the city, state, and regional levels. However, as we continually upgrade our critical infrastructure systems to increase their scope and improve efficiency, we create a new class of vulnerabilities as expanding interdependencies and decreasing overall resilience lead to heightened potential for cascading failures.

Fortunately, the U.S. has not yet faced an event that triggered a subcontinent-scale outage. However, as we upgrade critical infrastructure to increase scope and efficiency, expanding interdependencies and decreasing overall resilience lead to heightened potential for cascading failures.

Because we have not had to face an actual event at this scale, there is little "push-back" to widespread efforts towards increasing efficiency at the expense of resilience in our critical societal systems. As a result, any major attack or natural event that disrupts elements of the electrical grid on a multi-region scale will present challenges that greatly differ from those that existing restoration systems have been designed to combat.[40]

For this reason, a coordinated recovery framework supporting emergency communications, diagnostic data acquisition, situational awareness, and decision support will be essential as society continues to move forward.

40 Paul Stockton, Superstorm Sandy: Implications for Designing a Post-Cyberattack Power Restoration System (Johns Hopkins University Applied Physics Laboratory), 2016, http://www.jhuapl.edu/ourwork/nsa/papers/PostCyberAttack.pdf.

D. Networking Rule-Sets

Clear, prioritized networking rule-sets will be critical to ensure BSX fulfills its intended function. These rule-sets will be essential for managing communications and data transfer over what, in time, will become the BSX network. The rule-sets will necessarily need to be enforced autonomously to ensure seamless operation for all users. This section, therefore, reviews key aspects of the BSX network configuration, and hidden automation processes designed to balance ease of use and reliability in the BSX system.

In particular, in a Black Sky outage, the nation will be depending on the BSX system to host an interactive restoration and sustainment process of unprecedented complexity. In a subcontinent (or larger) scale blackout, BSX and the situational awareness and decision support systems it will host will need to support widely-dispersed decision makers in mediating recovery operations spanning tens of infrastructure sectors and a vast array of associated supply chains. The system will also need to ensure the delivery of resources critical to public health and safety to sustain the affected population, all in a highly disrupted environment.

In a Black Sky outage, the nation will be depending on the BSX system to host an interactive restoration and sustainment process of unprecedented complexity.

It will need to support widely-dispersed decision makers in mediating recovery operations spanning tens of infrastructure sectors and a vast array of supply chains.

When users log into the BSX network management system, the system will characterize them based on embedded data. This data includes: their location, BSX assets available, their roles in use of the network and in the overall recovery process, and the relevance of those roles to their location. In coordination with situational awareness and decision support guidance from the hosted SAND and GINOM systems, this allows the BSX to adjust available network resources, and support overall use of the system.

1. Network Management and Operation

The BSX network, as described above, will depend on radios as its primary communications link- bearers. Radio systems have great flexibility in emergency operations, as system operators do not need to define all network nodes in advance. That very flexibility, however, introduces complexity in the establishment and maintenance of the network configuration.

To address this complexity, the system itself needs to automatically perform these establishment and network configuration tasks. This will shift the inherent complexity of network configuration from system users to the system developers. This is a non-trivial task, and therefore forms one of the key aspects of the design, aimed at making the BSX both suitable and effective.

This capability is implemented via specialized software which builds and maintains linkages between the various BSX sites.

a. Communication linkage types between BSX users

- One-to-one voice communications
- Voice conferencing
- Reporting and collection of a limited set of machine-to-machine data, e.g., SCADA signals
- Operator-initiated data messages, including status reports, task assignments, movement and re-supply planning and status, etc.
- Automatic data messages that synchronize databases at different sites

The network management and operations software will accomplish the following tasks:

- Find and build “paths” to other BSX nodes, adjusting over time as the system configuration changes
- Allocate (limited) network bandwidth to the various types of services and missions, including:
  - Voice
  - Data
  - Task management
  - Meetings / calendaring
  - Movement and re-supply planning
  - Background tasks (e.g., machine-to-machine coordination)

These tasks will be performed in conjunction with other capabilities described in previous sections, and while providing a security/ authentication overlay suitable for the Black Sky mission.

b. Layered network architecture

Achieving a survivable, widely deployed communications system independent of any existing legacy infrastructure requires a layered network architecture. While each of these layers are relatively simple, they combine to provide a robust data transmission capability. These layers include single-hop reliability, frequency selection, communications path diversity, and multi-hop communications, each of which is described below.

i. Single Hop Reliability

The success rate of single-hop, direct site-to-site radio-based communications is seldom adequate for providing reliable network operations. It is common practice, therefore, to allocate a small additional portion of the available communications capacity to a mathematical coding scheme that can detect and automatically correct errors in the data stream. This technique is called error-correction coding. Within BSX, this error-correction coding will be combined with packet-level correction protocols: the information to be sent is separated into small sections ("packets"), and the failure of the packet to arrive correctly can be detected. If the error-correction coding cannot reconstruct the correct version of the packet, the system can automatically request that the single missing or incorrect packet be re-sent.

Through a combination of such mechanisms, the single-hop, direct site-to-site communications success rate can be improved to the desired level using only a small portion of the available communications capacity. These techniques are implemented in the packet router located at each BSX site.

ii. Radio selection

Each BSX site will house two independent radios, on different frequency bands, utilizing different radio modulations. This provides an important level of communications path diversity, and further improves system reliability.

The router at each site determines which radio to use for each transmission attempt (for both voice and data) based on its radio "visibility" to adjoining sites. No manual action is required by the BSX operator to make this selection, which is implemented in the packet router located at each BSX site.

iii. Multi-hop communications

The packet router uses the same visibility information to implement multi-hop communications for both voice and data, allowing communications links to be established through the use of intermediate nodes.

iv. Frequency and modulation selection

Particular radio transmission frequencies and modulations will work better in some atmospheric conditions than others. The BSX network will select frequency and modulation based on time-of-day, atmospheric conditions, and other factors. An intelligent director controls and coordinates this process, providing direction to the packet routers at each BSX site. The local packet routers in turn command the radios to use the appropriate frequencies and other radio settings. No manual action is required by BSX operators to account for frequency and modulation preferences.

In addition to transmission considerations, radio frequency spectrum is a shared resource whose use is governed by Federal law and regulation. The BSX network's frequency utilization policy will be coordinated with regional and national civil officials. In fact, the rules governing frequency utilization are different during major emergencies than during nominal times. The network must account for these differences, limiting its frequency use during nominal situations (e.g., during routine training and testing activities) to the frequencies and transmission power levels allowed during normal situations.

The system, however, will take advantage of the larger range of frequency and transmission power levels permitted during emergency situations. The appropriate regional and/or Federal officials may allocate or de-allocate the use of certain radio frequencies as a situation evolves in order to de-conflict the use of particular radio frequencies; BSX must be able to accept such frequency-utilization guidance during emergency operations. These capabilities are also implemented within the intelligent director. No manual action is required by BSX operators to comply with such changes in radio frequency policy.

2. Operating Within Available Network Capacity

All electronic communications systems have capacity limits. Even when operating at full capacity, there is a maximum amount of data that can be moved per unit of time. Some communications systems have different capacity limits for short and long-term periods, akin to the difference in speed achieved by someone running a mile, as compared to that person running a 100-yard dash.

Given knowledge of the data that will be moved around the system, and a model of where and how frequently each item must be moved, one can create a model of information flow. From this model, predictions of the necessary communications capacity can be derived.

It is also the case, however, that not all techniques for organizing, formatting, and moving the data impose the same demands upon the electronic communications system. There are, in fact, a variety of techniques that move the data around in a fashion that uses less data capacity than others. This section identifies a set of such techniques that are appropriate for the BSX system. These design techniques will allow BSX users to accomplish their missions within the limitations of the communications devices and networks described in previous sections.

In addition to improving the network's overall capacity, the BSX network will also utilize optimization techniques to reduce the overall requirements for such capacity. Techniques available include bit-oriented messaging, multicast transmission, and dynamic allocation of bandwidth to users, missions, and data categories.

E. BSX Network Power Management Options

With grid power unavailable over large areas, BSX nodes will need to include provisions to ensure adequate emergency power will be available for 30 to 60-days of operation. Mobile, truck-based nodes will typically utilize power generated by the vehicle's alternator to operate the BSX communications package. For conventional gasoline-fueled trucks, the vehicle's (enhanced) alternator would provide power, depending on the truck's fuel tank for energy storage. For sites using mobile nodes, logistics planning for vehicle fuel would need to take such use into account.

> For fixed site deployment, adequate emergency power will be needed to allow for 30-60 days of operation.
>
> BSX addresses this through a combination of different network power management approaches, including: Node/ facility power budgeting and Supplemental power module options.

For fixed site deployment, however, the BSX system will address this need through a combination of different approaches. The approach for a given site will be selected based on the overall needs for the emergency communications network, and on the specific needs of each node within its hosting facility. These network power management approaches include ***node/ facility power budgeting,*** and the provision of a range of ***supplemental power module configurations***, subject to user requirements.

1. **BSX Network Power Management Planning:** Node / Facility Power Budgeting

In reviewing the power budget for BSX nodes, radios entail, by far, the highest power utilization. Computers and other devices in a given node will require far less power. This represents an important opportunity for overall network power management, which will be incorporated as a basic feature of the full-scale network management system.

In particular, using projected facility power availability at each node as a key parameter, the BSX network system will coordinate adjustments to the "duty cycle" of radio use for each node. These adjustments will be further configurable according to GINOM or user-forecasted requirements for increased communication windows.

As a simple example, some facilities are not staffed for portions of each day; radios at these nodes will not be powered on when the facility is vacant. In the more general case of continuous staffing, the duty cycle of a node's radio availability will be a key data point provided to the overall BSX network management system. Users attempting to communicate with such facilities will be alerted as to their next "window" of availability. Initially, this may be implemented by using a "baseline duty cycle" for all nodes with limited power storage capabilities, with all such nodes sharing a common "on" window for coordinated messaging. Over time, BSX network management software, with guidance based on configured operational need, can provide far more sophisticated allocation.

> Critical facilities will typically require emergency power availability for 30 – 60 days to perform their Black Sky mission(s). In many cases, this power could be used as a primary power source for the facility's BSX node.
>
> While not generally met today, this emergency power requirement represents a change in overall doctrine which will need to be implemented to effectively address Black Sky events.

This approach can substantially cut the overall power needs for nodes "challenged" by available stored power. However, such limitations may not be required for many nodes due to the continued availability of adequate emergency facility power.

a. Baselining Emergency Power Requirements at Critical Facilities

The starting point for defining power requirements for the overall BSX network as well as individual nodes is to consider the availability of emergency power at the primary facilities that will utilize the system.

In each infrastructure, government, and NGO sector, and for major corporations in critical supply chains, the most urgent need for BSX nodes will be at critical operations, dispatch, control, and coordination facilities. For major service providers like hospitals, government institutions, and security offices, co-location in the primary facilities of such service providers will be essential.

In each of these cases, basic operation of the facility itself – that is, its ability to perform its fundamental mission, separate from its need for emergency communications – will require secure, continued availability of emergency facility power for the 30 to 60-day period identified above.

This represents a significant change from current standard practice. Yet, this will be essential to allow such facilities to perform their critical Black Sky restoration and sustainment missions. Though not representative of today's reality, evolution to meet this need must be accommodated by new public and private sector Black Sky policy, doctrinal changes, and investments if such critical facilities are to be capable of supporting the restoration and sustainment roles that they, uniquely, will serve.

b. Matching BSX Power Needs to Anticipated Emergency Facility Power

While the overall power needs for BSX nodes can be "adjusted" by the network's management software through changes in factors like radio duty cycle, nodes at critical facilities may have far less constraining requirements. Deployment of nodes in such facilities will need to include an assessment of the facility power budget. If the facility's emergency power source(s) can adequately meet BSX requirements in addition to other essential functions, the BSX node's radios can operate at a 100% duty cycle without the need for supplemental power modules (other than for backup purposes).

2. BSX Network Power Management Planning: Supplemental Power Module Configurations

For smaller fixed site facilities that require a BSX node, facility power may only be intermittently available, or too low to provide a significant portion of the BSX node's needs. In these cases, the BSX node will be accompanied by a supplemental power module, with the user deciding – based on the particular facility's needs – the type and size of module required.

A renewable power source such as solar cells may also be used to add additional capability, depending on user requirements. This option, reviewed in detail below, is applicable for both supplemental power module configurations.

a. Conventional Emergency Power Devices

As one example, users may choose to utilize conventional emergency power solutions, such as emergency generators. Some emergency generator configurations may have limited operational lifetimes, and this must be accounted for in the selection process.

In addition, most commonly-available generators utilize diesel fuel. There are various considerations which may make storage of 30 day+ supplies for these generators difficult or impractical – especially due to the limited storage life of diesel fuel and limits to on-site storage imposed by building and operating permits at many facilities. However, with most large-scale critical facilities likely to depend on emergency diesel generators for years to come, the new Black Sky coordination frameworks discussed in Chapter I will need to develop planning for nationwide distribution of such fuel as a primary priority, and this may make diesel generators for some BSX nodes more practical.

Emergency generators using compressed natural gas storage are also available, which may offer another alternative. This fuel does not have the same short storage lifetime limitations associated with diesel.

b. Long Duration Battery Power

Given reliability and fuel limitations for conventional supplemental power configurations, the BSX design team developed an additional option: a long duration battery storage configuration.

For the busiest BSX sites, estimated total power requirements for a 100% duty cycle with heavy use in transmission mode would be a maximum of 28 KWh per day, as shown in Figure H. Actual deployment decisions may take into account anticipated duty cycles of radio use and/or expected use in power-intensive transmission vs. simple monitoring modes. As discussed above, duty cycle timing may also be pre-determined by decision makers to arrange for pre-planned operating periods, distributed throughout the day.

For a 30-day capability with no secondary power source (such as solar), a heavy use site working at a 100% duty cycle will require a power source sized at just over 800KWh. Most of the BSX sites, however, will likely require much less power capacity due to a significantly lower duty cycle anticipated for use of their radios – the primary power drain for a node – or for those operating mostly in "monitoring" mode.

3. Battery Technology Options

There are multiple current options available for users who require a substantial, battery-based power module. Additional options may become available over time. Battery technology, however, has generally advanced far slower than electronics technology; the system should therefore not rely on dramatic improvements in batteries. Nevertheless, current battery options include:

a. Li-ion batteries

The 129 MWh Powerpack battery, provided by Tesla, integrated into the power grid in South Australia. While far larger than required for the purposes of BSX, this installation illustrates the scalability of Li-ion battery technology. | Image: Tesla

While constrained by limits on the number of charge / discharge cycles they can support, Li-ion batteries (LIB) are increasingly used in the power industry, and widely used commercially. For example, the 129 MWh Powerpack project in South Australia, currently the largest battery in the world, is designed as a "virtual powerplant" with capacity orders of magnitude larger than required for BSX.[41]

41 For more information, see: James Ayre, "Tesla Completes World's Largest Li-ion Battery (129 MWh) In South Australia (#NotFree)," Clean Technica, November 23, 2017, https://cleantechnica.com/2017/11/23/tesla-completes-worlds-largest-li-ion-battery-129-mwh-energy-storage-facility-south-australia-notfree/.

Tesla Powerpacks and the grid | Image: Tesla

At a more appropriate size, Tesla's LIB "Powerwall home battery",[42] for example, provides 13.5 KWh. Four such units, advertised by Tesla at a total retail cost of approximately $25K, would fit within a half cubic meter volume, providing over 50 KWh of capacity.

	One Day	30 Days	60 Days
Radio Power Requirement (KWh)	24.00	720.00	1,440.00
Computer Power Requirement (KWh)	2.0	60.0	120.0
Total Losses	1.68	50.40	100.80
Inverter Losses (5%)	1.20	36.00	72.00
Transmission Losses (2%)	0.48	14.40	28.80
Implied total BSX Power Capability (KWh)	27.68	830.40	1,660.80

Figure H | **Power Capability Estimate for BSX Nodes**

b. Flow batteries

Flow batteries were another alternative evaluated by the BSX design team.

Vanadium Redox flow batteries, commercially available at costs similar to LIB technology for comparable capacity, have certain advantages. While requiring a far larger volume / deployment footprint, such flow batteries have both much longer storage life and a lower charging degradation cycle

42 For more information on the Tesla Powerwall battery, see "Powerwall," Tesla, 2018, https://www.tesla.com/powerwall.

than Lithium ion batteries,[43] which will be significant considerations for some BSX users. Vanadium redox batteries are commercially offered by companies such as UniEnergy Technologies[44] and Schmid.[45]

1 MW 4 MWh containerized vanadium flow battery owned by Avista Utilities and manufactured by UniEnergy Technologies

In particular, the primary advantages of vanadium redox flow batteries include:

- Simple energy capacity scaling, through use of larger electrolyte storage tanks
- Batteries can be stored fully charged for long periods without degradation
- If electrolytes are accidentally mixed, the battery suffers no permanent damage
- A single state of charge between the two electrolytes avoids the capacity degradation due to a single cell in non-flow batteries
- The electrolyte is aqueous and inherently safe and non-flammable
- The generation-3 formulation, using a mixed acid solution developed by the Pacific Northwest National Laboratory, operates at a high temperature, allowing for passive cooling[46]

43 For example, see: Sophie Vorrath, "VSUN edges closer to home storage market for vanadium batteries," One Step off the Grid, August 30, 2017, https://onestepoffthegrid.com.au/vsun-edges-closer-home-storage-market-vanadium-batteries/.

44 "Technology," UniEnergy Technologies, 2016, http://www.uetechnologies.com/technology.

45 "VRFB Technology," Schmid Group, 2016, http://schmid-group.com/en/markets/energy-systems/vrfb-technology/.

46 "Vanadium redox battery," Wikipedia, last updated September 16, 2017, https://en.wikipedia.org/wiki/Vanadium_redox_battery.

- Maintenance requirements are also low. As an example, backup pumps may be stored at the site in the event that the system's pumps fail and need to be replaced.

For typical, fixed site nodes, flow battery technology was selected as the optimal for a long duration battery-based supplemental power module.

In all, the BSX design team evaluated more than 20 battery chemistries. Other battery technologies may become available, over time. As an example, Zinc Air batteries currently in development[47] See, for example, Duracell, Zinc Air Technical Bulletin, 2004, https://d2ei442zrkqy2u.cloudfront.net/wp-content/uploads/2016/03/Zinc-Air-Tech-Bulletin.pdf.

for BSX nodes. These metal-air batteries, powered by oxidizing zinc with oxygen taken from ambient air, promise relatively high energy densities and are said to be relatively inexpensive to produce.

c. Supplemental Solar Cell Power Supply

For those nodes and node clusters with basing anticipated in appropriate climatic zones, BSX power modules will include solar panels to complement battery energy storage and reduce the required size of the battery package. As an example, using the average U.S. solar power density of 4.5 kWh/m2/

47 See, for example, Duracell, Zinc Air Technical Bulletin, 2004, https://d2ei442zrkqy2u.cloudfront.net/wp-content/uploads/2016/03/Zinc-Air-Tech-Bulletin.pdf.

day, placing solar panels on top of a standard 20-foot shipping container (14 m2 surface area) would yield about 63 kWh/day. The actual electricity generated by these solar panels, however, varies materially depending on geographic location (see Figure H for typical solar-resource at various locations across the U.S.). A flow battery solution in this same shipping container form-factor could easily provide 45 kWh/day. A LIB battery of comparable capacity could fit in a far smaller volume, making rooftop deployment for solar panels a likely approach for such configurations.

Therefore, the 63 kWh/day solar configuration, together with suitable battery storage, would provide more than adequate continuous emergency power indefinitely for the 100% duty cycle case of 28 kWh per day at a given site. Any battery configuration of this capacity would provide a 38-hour reserve for periods with minimal or no sunlight. Correspondingly, for lower duty cycles (e.g., the 10 minute / hour example), this configuration would allow for substantial margin to address reduced solar availability periods or other contingencies.

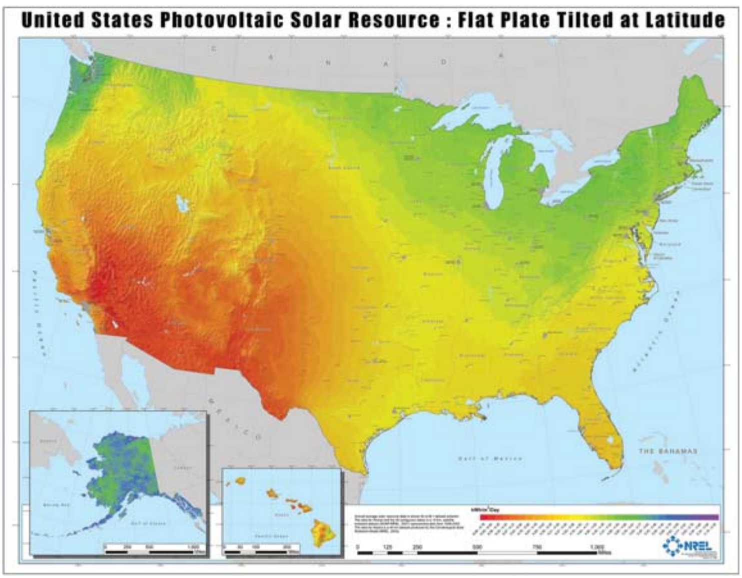


Figure H | U.S. Photovoltaic solar resource maps.

Wind power systems may also be utilized in appropriate locations and could supplement BSX power modules in regions where site surveys find that surging winds of >15 mph are relatively common. However, the dependence of wind power systems on moving parts results in far shorter storage lifetimes, lower availabilities, and higher maintenance requirements than approaches without such a dependence.

Site-specific designs (see Figure H, which uses data from the National Renewable Energy Laboratory[48] and U.S. Department of Energy) would lead to optimal sizing of BSX power elements at each specific facility, and final selection from the mix of approaches reviewed above.

48 "Home," National Renewable Energy Laboratory, n.d.a, http://www.nrel.gov/.

VI | SUMMARY

As reviewed in Chapter I, national continuity through Black Sky outages will require thorough, well-coordinated planning spanning most infrastructure, resource, and service sectors, and their government and mass-care NGO partners. However, that same well-integrated multi-sector coordination will need to continue in real time following a Black Sky event to guide infrastructure restoration and population sustainment.

With all normal telecommunications, internet, and related services offline, this will only be possible if nations deploy a Black Sky-compatible emergency communications system to interconnect nearly all sectors, including key segments of their supply chains. Yet even with such a system, “manual” guidance on subcontinental scales – without the autonomous processes that normally provide all of society’s goods and services – will be impossible without multi-sector situational awareness and decision support.

Developing, implementing, and deploying such a system – designed to survive a long duration outage and continue to operate without depending on a functional power grid or normal, national telecommunications assets – is a fundamental test of the credibility of a nation's national continuity planning and national security, broadly defined.

Appendix

Appendix B

List of Acronyms

AAR	After-Action Report
BSPL	Black Sky Prioritization List
BSX	Black Sky Emergency Communications and Coordination
CSCC	Cross-Sector Coordinating Council
CIKR	Critical Infrastructure and Key Resources
CSIP	Cybersecurity Strategy and Implementation Plan
DOD	Department of Defense
DOE	Department of Energy
DHS	Department of Homeland Security
DMORT	Disaster Mortuary Operational Response Team
E-ISAC	Electricity Information Sharing and Analysis Center
EAGLE-I	Environment for Analysis of Geo-Located Energy Information
EEI	Edison Electric Institute
EMP	Electromagnetic Pulse
EO	Executive Order
EOC	Emergency Operations Center
EMAC	Emergency Management Assistance Compact
EPRI	Electric Power Research Institute
ESCC	Electricity Subsector Coordinating Council
ESF	Emergency Support Function
ESFLG	Emergency Support Function Leaders Group
FAST	Fixing America's Surface Transportation
FCC	Federal Communications Commission
FEMA	Federal Emergency Management Agency
FIOP	Federal Integrated Operational Plan
GINOM	Global Infrastructure Network Optimization Model
GMD	Geomagnetic Disturbance

HEMP	High Altitude Electromagnetic Pulse
HSPD	Homeland Security Policy Directive
HVA	High Value Assets
IAC	Integrated Analysis Cell
ICT	Internet and Communications Technology
IOC	Infrastructure of Concern
IoT	Internet of Things
ISAC	Information Sharing and Analysis Center
JFO	Joint Field Office
LPT	Large Power Transformer
MEF	Mission Essential Function
NBEOC	National Business Emergency Operations Center
NCIPP	National Critical Infrastructure Prioritization Program
NCIRP	National Cyber Incident Response Plan
NERC	North American Electric Reliability Corporation
NGO	Non-Governmental Organization
NICC	National Infrastructure Coordinating Center
NIMS	National Incident Management System
NIPP	National Infrastructure Protection Plan
NISAC	National Infrastructure Simulation and Analysis Center
NLE	National Level Exercise
NOC	National Operations Center
NRCC	National Response Coordination Center
NRF	National Response Framework
NSTAC	National Security Telecommunications Advisory Committee
OCIA	Office of Cyber and Infrastructure Analysis
OMB	Office of Management and Budget
ONG	Oil & Natural Gas
PCII	Protected Critical Infrastructure Information Program
PPD	Presidential Policy Directive
PSA	Protective Security Advisor

RRAP	Regional Resiliency Assessment Program
SCC	Sector Coordinating Council
SICC	Strategic Infrastructure Coordinating Council
SIEC	Strategic Infrastructure Executive Council
SSA	Sector-Specific Agency
THIRA	Threat and Hazard Identification and Risk Assessment
TSP	Telecommunications Service Priority
TTWG	Transformer Transportation Working Group
UAV	Unmanned Aerial Vehicles
UCG	Unified Coordination Group
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture