Project Report
TIP-197

Satellite Remote Sensing in Disaster Relief: FY23 HADR Technical Investment Program

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C.L. Council
S. Anklam
R.S. Legge

13 June 2024

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

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Massachusetts Institute of Technology
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EXECUTIVE SUMMARY

Disasters annually cost the U.S. billions of dollars in direct costs and economic loss. In particular, the increasing frequency and intensity of natural hazard incidents, such as hurricanes, tornadoes, floods, and wildfires, strains the nation's emergency management enterprise. Knowing that the current approach to emergency management is unsustainable, practitioners and policy makers look to use new tools and technologies to mitigate, prepare for, respond to, and recover from disasters. One of those technologies is satellite remote sensing.

As persistent assets with a wide area collection ability and a variety of viable sensing modalities, satellites seem positioned to shed light on the nature of disaster impacts and support decisions made in the first 24 hours after disasters happen. Satellites are particularly promising for providing information on incidents that occur slowly and in rural areas. However, satellite imagery supports early response decisions and operations for only the most severe incidents in the U.S.

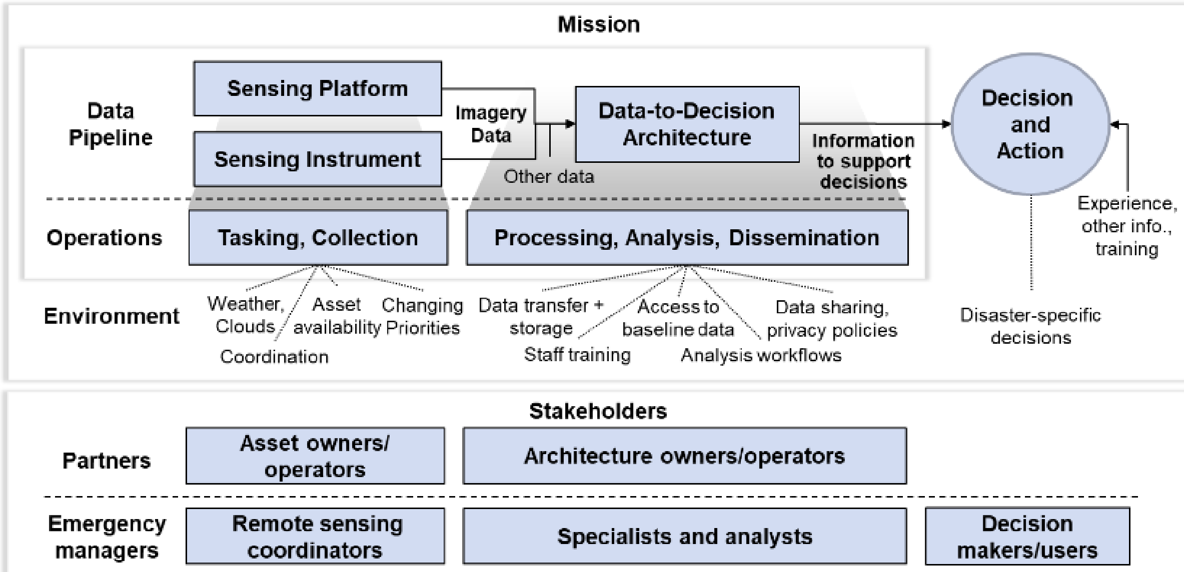
This report explores reasons satellite imagery is under-utilized in domestic disaster response and proposes ideas toward solutions. Through systems engineering, combined with quantitative modeling and prototyping, this report offers the following.

1. An analysis of stakeholder decisions and use cases for satellite remote sensing in disasters

2. An evaluation of requirements for imagery and derived data products to support decisions

3. A description and demonstration of a concept of operations and high-level system architecture

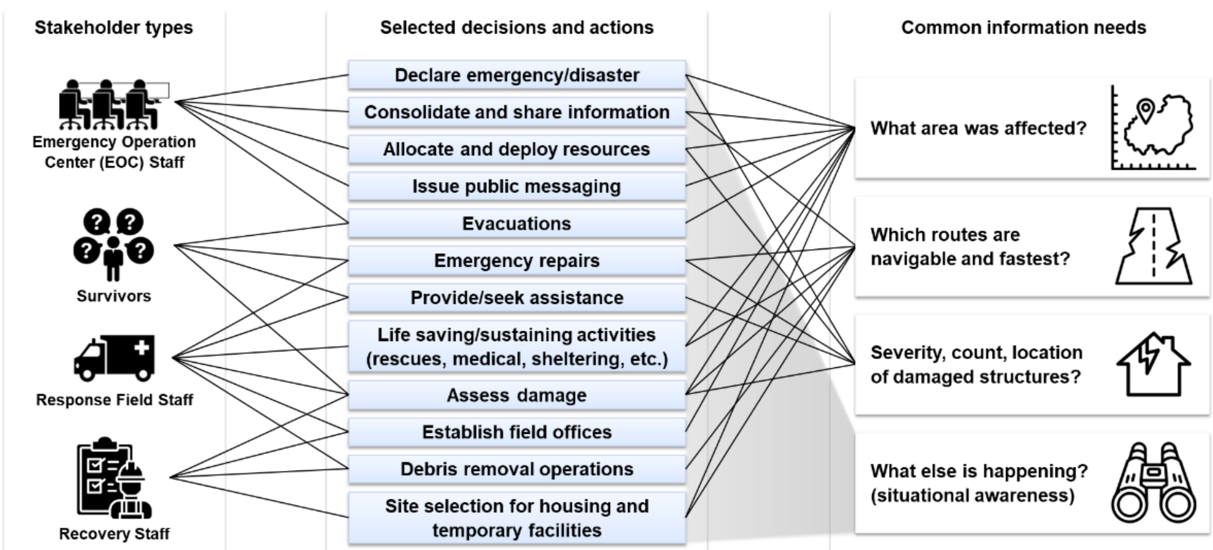
We present a vision for a socio-technical system, visualized in the figure below, of dedicated space-based remote sensing assets, workflows, and derived products that provides early information to support response decision-making during every disaster. A well-coordinated "DisasterSat" system would enable earlier, more confident decisions for a wider range of incidents. Although feasible with commercial technology, we currently lack the coordination structures, information technology systems, and dedicated workflows to carry out this vision. This report aims to equip practitioners and researchers for action toward systematic use of satellite remote sensing in disaster response at every level of government and civil society.



Socio-technical system map of satellite remote sensing in disasters.

USE CASES FOR SATELLITE REMOTE SENSING IN DISASTERS

If we had satellite imagery for every disaster, what would emergency managers do with it? How would it make a difference? To answer this question, we analyzed doctrine, practitioner resources, and academic literature to understand selected use cases for satellite imagery in disaster response.



Visual summary of stakeholders, selected decisions, and information needs.

Selected stakeholders fall into four categories: emergency operations center (EOC) staff, disaster survivors, field staff, and recovery program staff. For each stakeholder, we developed user stories, specified decisions and actions relevant to their roles, and identified pieces of information used to inform those decisions. Common information needs include identifying the affected area, identifying passible roads, assessing damage to residential structures, and gaining situational awareness.

We then developed concepts for four corresponding imagery products and geospatial data products that could provide needed information. Hazard boundary products would provide early awareness of the geographic extents of floods, fires, wind fields, and other disaster impacts. Road navigability products would enable rapid routing in affected areas and road repair triage. Residential damage assessment data supports response mass care services, issuing disaster declarations, and recovery grant programming. Finally, imagery products delivered in red-green-blue coloration provide broad situational awareness.

REQUIREMENTS FOR IMAGERY AND DATA PRODUCTS

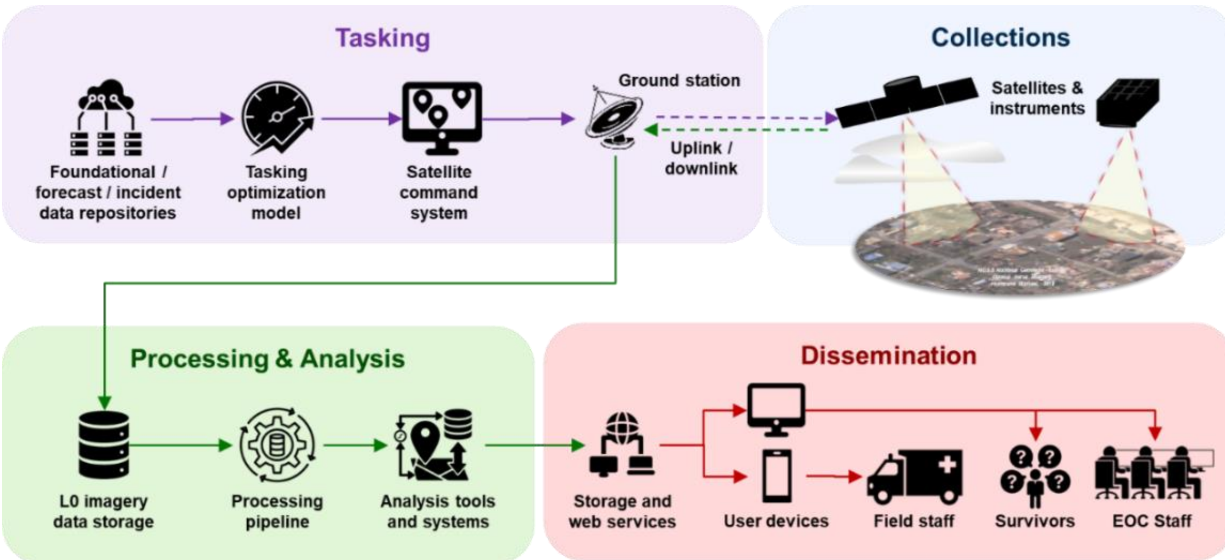
We then developed a set of recommended requirements for imagery and data products. Using system analysis methods, we considered the trade space for spatial resolution, timeliness, and area coverage of data products that would successfully meet needs. In addition, we describe a set of human factors requirements that must be met in order for data products to be most useful, including delivery format, access, and cost. For each category, we identified desired, acceptable, minimum, and unacceptable specifications. Multispectral imagery and synthetic aperture radar are both mature technologies currently available in space that could perform well in delivering data products that meet requirements. Ideally, these requirements would drive the development of space systems and accompanying workflows to deliver data products that provide useful information during disaster response.

Summary Of Requirements and Acceptable Ranges for Satellite Imagery-Based Data and Information Products

Category	Desired	Acceptable	Minimum	Unacceptable
Resolution	≤0.25 m GSD	1 m GSD	1.5 m GSD	3 m GSD <
Daily Area Coverage Capacity	≥20,000 sq mi	10,000 sq mi	3,000 sq mi	<100 sq mi
Time from Incident to Deliver First Product	≤12 hrs	24 hrs	48 hrs	>72 hrs
Delivery Method	User friendly interactive web interface	REST service	Data download, annotated PDF	Screenshots, L1 or L2 image data
Data Access	Shared with the public	Shared with partners	Shared within requesting organization	Cannot be shared at all, classified
Cost Model	Proactive tasking, free to all or most end users	Task orders on a per-incident basis under indefinite delivery vehicle, free to all or most end users	Task orders on a per-incident basis under indefinite delivery vehicle, paid access for each user	Separate procurement for each incident and each organization

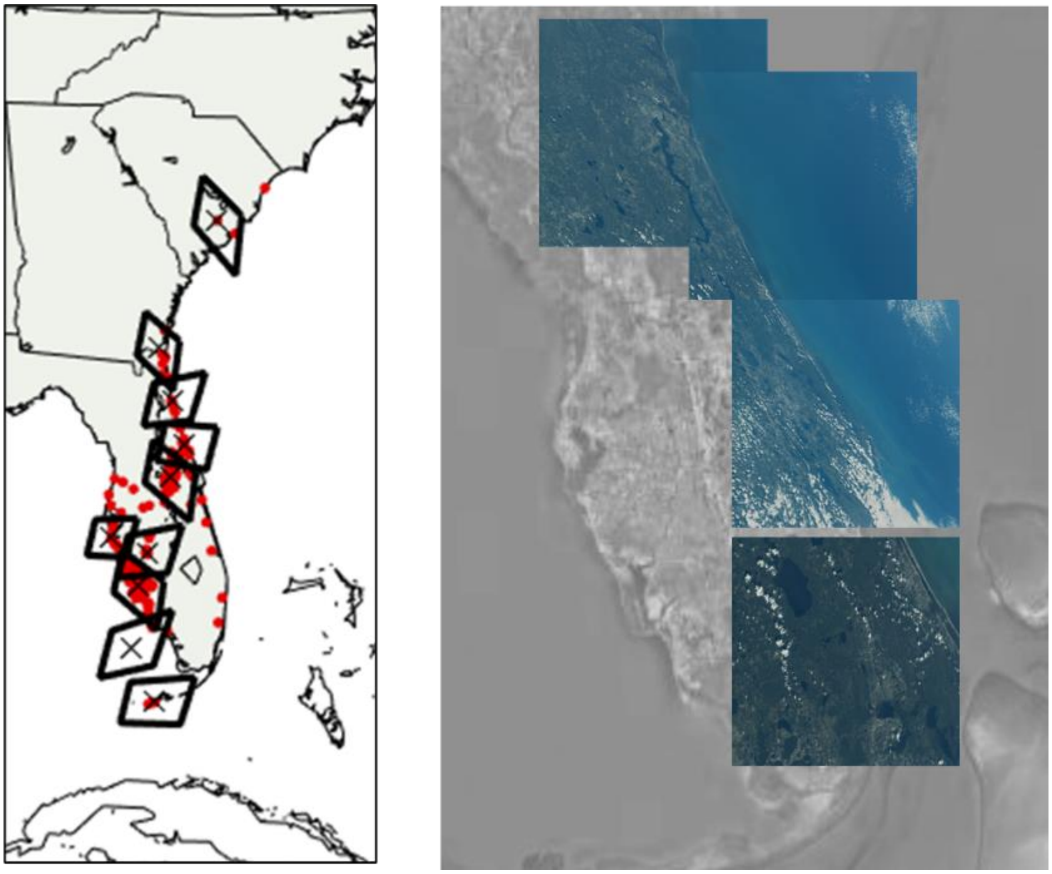
CONCEPT OF OPERATIONS AND ARCHITECTURE DESCRIPTION AND DEMONSTRATION

Elaborating on the traditional tasking, collection, processing, exploitation, dissemination (TCPED) process, we suggest a concept of operations and accompanying architecture for a "DisasterSat" system. Key elements of this system, unique from standard processes developed for other industries, including a tasking optimization model for wide-area collections, automated processing and analysis, and dissemination of final products to a large, geographically dispersed, non-technical user community whose members change with every incident.



Visualization of core architectural components in the TCPED concept of operations for satellite remote sensing in disasters.

To demonstrate this concept, we created a prototype architecture for use with the MIT Lincoln Laboratory Agile MicroSat (AMS). A tasking optimization model was used to target AMS collections over areas as large as northern Florida to the Carolina coast. In addition, a novel change detection and analysis workflow was developed to identify areas of possible damage and illustrate how derived products might provide actionable information. Though AMS had a fairly low-resolution camera (~25 m GSD from 500 km altitude), the demonstration illustrated the end-to-end workflow, from tasking to dissemination. We completed one "blue-sky" test and responded to several disaster incidents in real time.



Images tasked and collected with the Agile MicroSat after Hurricane Ian in 2022.

CONCLUSION AND FUTURE

The concept of using satellite imagery effectively during disaster response is not new, but recent advances in space technology, remote sensing, and computing systems make it possible to establish a dedicated, high-resolution, rapid disaster imaging capability that provides actionable information in the first day of an incident. Current systems are not integrated, and poor coordination leads to frequent disappointment in the quality or availability of satellite imagery during disasters. This report describes use cases, requirements, a concept of operations, and architecture to enable systematic use of satellite remote sensing in disaster response. To bring a “DisasterSat” system into existence, partners must establish a tasking optimization system, automated data processing and analysis system, dissemination tools that can be used to deliver imagery to users, and coordinated procedures. Regardless of which institution might lead coordination to establish this system, a shared vision is the cornerstone of success.

FORWARD

The year was 2020. I was a mid-level program analyst in FEMA's Response Geospatial Office, working to improve the use of geospatial technologies and geographic information systems (GIS) in FEMA's Response Directorate. When national-level disasters happened, I also supported crowdsourcing and remote-sensing coordination in FEMA's National Response Coordination Center (NRCC).

The year 2020 started off with Earthquakes in Puerto Rico, achieved peak chaos early with the COVID-19 pandemic, saw several severe tornado outbreaks, and dragged on through another record-breaking hurricane season with 30 named storms, around 10 of which impacted the U.S. I logged more than 90 days in the (mostly virtual) NRCC—more than a third of my work days that year—and, like many FEMA employees, was deeply burned out by the end.

Despite the strain COVID-19 placed on our nation's emergency management systems, it created unique opportunities to use new technologies. Rather than send staff out to the field and put them at potential risk, programs sought technology that allowed staff to do field jobs remotely. GIS and remote sensing were in the spotlight, and a large portion of my job consisted of meeting with program staff to understand their processes, explain remote sensing, discern how these technologies could assist with program delivery, and amend policies to enable the use of new systems.

Despite the sudden desire for more and better overhead imagery, we were constantly disappointed. Incident after incident, we coordinated ad hoc with any organizations that happened to task or collect imagery. We would receive imagery data, but often they were too late to be useful, too low resolution, covered the wrong area or a limited area, were use-restricted, or arrived in a format that required specialized knowledge to utilize. It was extremely frustrating. Imagery that could have provided invaluable information was perennially just out of reach.

I couldn't help but wonder: why? How can it be that our nation's emergency managers lack the ability to rapidly collect and analyze imagery during disasters? In particular, why was satellite imagery so disappointing when we have tools like Google Earth at our fingertips? What would it be like if we had a constellation of satellites dedicated to post-disaster imaging? What would it take to build such a capability?

I arrived at MIT Lincoln Laboratory in early 2021, following a desire to move closer to home and return to an academic environment, still driven by enthusiasm for and frustration over what I perceived as a widespread deficit in—and huge opportunity for—the use of remote sensing in disaster response, recovery, and resilience activities. Satellites seem an obvious choice for routine use, given their persistent presence, frequent passes, and growing market. With the support of MIT Lincoln Laboratory's Technology Office and the expertise of my colleagues Chad, Sean, and Robert, we have pursued answers to the questions of what value satellite remote sensing offers to emergency managers, under what conditions that value can be achieved, and, if necessary, what a custom-built "DisasterSat" constellation might look like.

This report documents the team's work from October 2021 to October 2023 and posits to answer these questions for emergency management practitioners, academicians and remote-sensing scientists, and companies seeking to serve the emergency management community through satellite remote sensing and data management services. For inquiries and commentary, please reach out to me, Katie Picchione, or my colleagues at the MIT Lincoln Laboratory Humanitarian Assistance and Disaster Relief Systems Group.

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ACKNOWLEDGEMENTS

The DisasterSat team consisted of four primary contributors. Sean Anklam served as the resident remote-sensing expert, compiled data on observables and commercial satellite providers, and built the R-IR-MAD change detection tool. Robert Legge facilitated collaborations with the Agile MicroSat (AMS) team, developed the DisasterSat tasking optimization tool, and assisted with orbital analysis for a proposed DisasterSat constellation. Chad Council leveraged extensive experience in emergency management to facilitate translating operational needs into technical requirements and to develop useful data product concepts. He also analyzed potential cloud cover, compiled an extensive review of existent machine-learning models, and served as a regular sounding board for ideas throughout the program. Katie Picchione designed and managed the program.

Thanks to the AMS team for their generosity in allowing us to task AMS and assisting with data pipeline development. In particular, Rebecca Keenan, the AMS technical lead, and Dan Cousins, the AMS program manager, included us in meetings and allowed the use of resources. Nicholas Fink, Clayton Baumgart, and Erin Main implemented numerous processing steps and systems to provide the DisasterSat team with access to AMS data. Thanks also to Andrew Cunningham and Andrew Stimac for their support.

Several interns made significant contributions. Samuel Scheele developed a georegistration script for the AMS data-processing pipeline. Emily Streiff analyzed a beguiling set of federal contract data to estimate the cost of disaster housing inspections. Kristine Bridge and Kyle Guerre explored concepts for small satellite spacecraft design.

This program would not have been possible without funding from the MIT Lincoln Laboratory Technology Office. Thank you to Heidi Perry, Chelsea Curran, and Jesse Linnell, and John Aldridge for your continued support.

Finally, thanks to the MIT LL Humanitarian Assistance and Disaster Relief (HADR) Systems Group Office. Brent Casella and Liz Bernardo provided invaluable administrative support. Travis Riley maintained our IT systems and helped us navigate several bureaucratic hurdles. Adam Norige, Jessica Reid, and John Aldridge frequently provided guidance and feedback. Most importantly, a huge thanks to Patty Selfridge for managing program finances and reporting.

Although this report was primarily penned by Katie Picchione, sections authored by other contributors are noted throughout.

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1. INTRODUCTION

Disasters annually cost the United States billions of dollars in direct costs and economic loss. In particular, the increasing frequency and intensity of natural hazard incidents, such as hurricanes, tornadoes, floods, and wildfires, strains the nation's emergency management enterprise. Knowing that the current approach to emergency management is unsustainable, practitioners and policy makers look to use new tools and technologies to mitigate, prepare for, respond to, and recover from disasters. One of those technologies is satellite remote sensing.

As persistent assets, satellites offer a unique prospect to deliver overhead imagery to emergency managers within hours of a disaster occurring. Overhead imagery provides insight on the nature of disaster impacts that can help emergency managers and first responders make better-informed decisions. This information is most useful within the first 24 hours after an incident occurs, filling in knowledge gaps as field staff begin to understand the nature of disaster impacts. Although small, unmanned aerial systems (sUAS) and manned aircraft are used to collect overhead imagery, satellites are already positioned for data collection, have the ability to cover a larger area, and offer sensing modalities that are weather-agnostic. Satellites are particularly promising for providing information on incidents that unfold slowly or occur in rural areas. In practice, however, emergency managers in the United States do not systematically use satellite imagery collected during the incident to support response decision making.

This report explores systemic and technological reasons that satellite imagery is underutilized in emergency management and describes a prototype end-to-end data pipeline that could meet needs. Sections 2 and 3 provide a review of literature and explanation of our research questions, respectively. Sections 4 and 5 present detailed analyses of use cases and requirements for satellite remote sensing in disasters. Section 6 articulates the concept of operations and architecture needed to task, collect, process, analyze, and disseminate satellite imagery and data products during disasters. Finally, we present several considerations for bringing forth a socio-technical system dedicated to providing consistent satellite imagery and derived information products for every disaster.

The scope of this study is limited to domestic disaster response. The terms *emergency management* and *disasters* are used interchangeably throughout. Emergency management is the professional practice of responding to, recovering from, mitigating, and planning for disasters of any kind, while disasters themselves are incidents that destabilize society, often because of damage to infrastructure and property, and may lead to loss of life. This work focuses on disasters caused by natural hazards, including hurricanes, tornadoes, wildfires, storms and strong winds, Earthquakes, and floods, which are the most common types of disasters in the United States. Although the focus and motivation for this study is on natural-hazard disasters, technological and biological disasters also stand to benefit from improved situational awareness through satellite remote sensing.

Throughout, the term *natural disaster* is used to refer to disasters that follow from environmental, meteorological, and geologic processes. Current discourse in emergency management practice and scholarship urges a reconsideration of this term since it diverts focus from the social and human systems that lead to negative outcomes. We recognize that the built environment and human activities are the progenitors of fragility and vulnerability. Since the intended audience of this report is emergency management practitioners, researchers, and remote sensing organizations, and no suitable replacement term has yet been proposed, we have selected to continue using *natural disasters* to refer to these incidents.

2. BACKGROUND: REMOTE SENSING IN DISASTERS

During and immediately after disasters, emergency managers conduct search and rescue operations; provide emergency food, water, shelter, and medical services; repair roads, power, and communications infrastructure; ensure security and safety amid instability and uncertainty; and provide emergency housing and financial assistance to affected families. Decisions to expend resources are based on information available at the time the decision must be made. Traditionally, information is collected by field staff reporting from the impacted area and communicated to the broader emergency management community through operational hierarchies. However, field reporting is time consuming, labor intensive, and myopic, resulting in large amounts of unstructured text-based information produced by independent actors. Information is also highly perishable, incomplete, and occasionally erroneous or miscommunicated.

Remote sensing technologies seem an obvious choice to assist emergency managers in understanding the nature of disaster impacts while alleviating administrative burden. Sensors capture measured data about the physical environment, which can be converted into information through both manual visual analysis and automated processes. Remote sensing of the Earth is regularly used for monitoring meteorologic and geologic activity and for predicting natural hazards, including floods, tornadoes, and hurricanes (see, e.g., resources from NOAA and USGS). unmanned aerial vehicles (UAVs), manned aircraft, and satellites are now widely available for civil applications and increasingly used in disaster management.

This chapter provides an introduction to remote sensing concepts and terminology for non-technical readers, followed by a brief historical account of remote sensing in disasters and an extended review of literature on the use cases for remote sensing in disaster relief. The chapter concludes by describing the value proposition for satellite remote sensing in disasters, specifically, gaps in current practice, and the systemic challenges faced with satellite remote sensing in disasters.

2.1 REMOTE SENSING CONCEPTS AND TERMINOLOGY

Remote sensing can be defined as the science of detecting and identifying objects or features using reflected electromagnetic waves. Although the definition of remote sensing varies across domains, in this report, we use the term to refer to observations of the Earth from sensors mounted on overhead platforms, including unmanned aerial vehicles (UAVs), aircraft, and satellites. These sensors detect reflected electromagnetic waves of varying frequencies using electro-optical detectors or antennas. Data are then processed to develop digital images of the ground and other objects, or *observables*. For a comprehensive treatment of remote sensing physics, see *Microwave Radar and Radiometric Remote Sensing* [1].

2.1.1 Sensing Modalities

Though many sensing modalities exist, multispectral imagery, hyperspectral imagery, panchromatic imagery, light detection and ranging (LIDAR), and synthetic aperture radar (SAR) are most relevant to disasters. Sensing modalities may be considered *passive* or *active*. Passive sensors detect light emitted or reflected from another source, typically the Sun, though sometimes radiated from the objects observed.

Active sensors emit a signal, for example, in the near infrared or microwaved frequencies, and detect the reflected photons.

Another way to categorize sensing modalities is by the frequencies of light they detect, which determines the sensor design. *Optical sensors* capture photons traveling at visible light and infrared frequencies using lenses and focal plane arrays, like a digital camera. *Radars* transmit and/or receive data using antennas. Each sensor is designed and manufactured to capture specific frequency ranges, or *bands* of the electromagnetic spectrum. The sensor then registers all photons traveling within each band—these data points essentially are ascribed the same value. For example, if a sensor is designed to detect “red” light, it will register all photons traveling at wavelengths of 610–700 nm the same way. The more bands a sensor can distinguish, the higher the *spectral resolution* of the data. Every material reflects light differently. A material’s *spectral signature* is the unique intensity with which it reflects photons at different frequencies across the electromagnetic spectrum. Similar to how we see color based on the way a material reflects red, green, and blue light, a sensor with high spectral resolution can be used to identify materials precisely based on their spectral signatures.

Panchromatic imagery is a passive, optical sensing modality that generates high-resolution grayscale images. Panchromatic sensors typically capture all light traveling at visible light frequencies within one band. This means that a lot of data points are captured—creating high spatial resolution data—but colors cannot be distinguished.

Multispectral imagery (MSI) is a passive, optical imaging modality that detects photos in the visible and near-infrared frequencies. MSI instruments capture several bands, typically three or more. With blue, green, and red bands, MSI imagery appears as full-color data. Additional bands can be used to further distinguish between objects and ground features.

Hyperspectral imagery (HSI), like MSI, is a passive, optical imaging modality that captures multiple frequency bands. Although MSI instruments typically detect 3 to 5 large bands, HSI instruments are designed to detect numerous smaller bands, usually 20 or more, increasing the spectral resolution of the data. HSI is optimal for identifying materials, especially land cover types. With smaller bands, however, the spatial resolution of the data is reduced. With less light detected in each spectral band, the signal-to-noise ratio is significantly reduced.

Light Detection and Ranging (LIDAR) is an active sensing modality that uses pulses of focused infrared or visible light to calculate geometry. A pulse is emitted from the instrument, reflects off objects, and returns to the sensor. With data on the timing and phase of returned photons, the data can be used to generate three-dimensional images. Satellite laser altimetry, which operates on the same principle, has been used to detect shifts in land masses over time. High-resolution LIDAR imaging from aircraft is regularly used to develop digital terrain elevation models. FEMA has also explored the use of high-resolution LIDAR from MIT Lincoln Laboratory to detect structural damage.

Synthetic aperture radar (SAR) is an active sensing modality that emits and receives microwave radar signals using an antenna, typically a phased array. The antenna emits a radio signal and detects the timing, phase shift, and frequency shift of reflected signals. The signal reflected back to the sensor is called *backscatter*. Backscatter intensity and phase can be used to distinguish between materials on the ground at high spatial resolution. Though SAR sensors do not capture bands the way optical sensors do, materials reflect and emit radio signals according to their *dielectric constant*, which is a material property conveying electric permittivity and conductance. Microwave frequency waves can penetrate cloud cover and poor atmospheric conditions, making this sensing modality ideal for space-based applications. Specialized knowledge is needed for interpreting SAR images. A point of confusion arises when talking about applications of SAR in emergency management. Search and rescue is also abbreviated as SAR. In this report, the acronym SAR is used to refer only to synthetic aperture radar to avoid confusion.

2.1.2 Data Products

A *product* is any dataset, map, visualization, or web application derived from remotely sensed or other geospatial data. This section defines terms commonly used to describe imagery data products.

Nadir – The point directly overhead any given point on Earth. Nadir images are taken with a camera looking straight down at a 90-degree angle to the plane tangent to the Earth's surface. Nadir imagery sees only the tops of buildings and other objects.

Orthorectification – Nadir images are only truly overhead in the center of the image, due to curvature of the Earth, camera distortion, and the angle between the camera and edge of the scene it captures (the field of view). We can computationally adjust images to correct for this distortion in a process called orthorectification. Orthorectified images are "nadir at every point," meaning a viewer will seem to look straight down at all points. Google Earth images are orthorectified.

Oblique – Oblique images are captured at an angle to the ground other than 90 degrees. Images taken at an oblique angle look sideways and can see the sides of buildings, trees, hills, etc.

Oriented Photography – An "oriented" image is typically a single still frame taken at an oblique angle. Often this term is used in reference to collections of images for which the angle to the ground is highly oblique, unknown, or varied among the images in the dataset.

Mosaics – Images taken from satellites and manned aircraft are typically large files with some overlap. Images can be stitched together to create a mosaic, a seamless product that covers the entire area collected. We're used to seeing mosaic imagery in mapping and GPS apps. Both orthorectified and oblique images can be combined into mosaic products.

Image Tiles – Large files are difficult to analyze and transmit. Large images and mosaics can be divided into tiles, or gridded squares, to compress the data and load more quickly.

Point Clouds – When multiple images are taken of the same thing from different angles, we can compute the geometry of a structure or surface on the ground. From this and similar processes, we can generate "point clouds," three-dimensional sets of point data that reveal the geometry of structures or topology of terrain. Point clouds can be created from optical imagery, SAR, and LIDAR

2.1.3 Acquisition Process

The geospatial intelligence community often considers a five-step process for collecting imagery referred to as TCPED [2, 3].

1. Tasking – identifying targets, planning collections, generating flight commands, and sending commands to the bus

2. Collection – satellite operations, camera functions, data downlink

3. Processing – image formatting, color balancing, orthorectification, georegistration

4. Exploitation (analysis) – deriving useful information from imagery, either manually or with automated tools; developing geospatial data layers, situation reports, and other data or information

5. Dissemination – web hosted REST services, web maps and applications, user access, site curation

The intelligence community (IC) developed the TCPED process to describe how imagery data provides operational information to stakeholders. Under intelligence and military operations, assets would be tasked specifically to collect imagery over targets of interest. Exploitation, or analysis, is largely done manually, often by a trained image analyst sitting at a computer. Although IC operations are typically directed hierarchically, from the top down, emergency management operations are highly networked, relying on cooperation and coordination between a large number of independent and sovereign organizations. Consequently, imagery tasking is done by committee, or by independent actors, and is done in anticipation of requests from leadership, rather than in accordance with specific requests.

Though information technology has simplified and streamlined some steps, TCPED remains a useful framework for organizing and executing remote sensing acquisitions. Now, analysis often happens after the image product is delivered. In emergency management, imagery is not useful until a processed product has been delivered and exploited. However, a challenge in emergency management is that, even when a single entity like FEMA requests imagery from a government or commercial partner, different organizations are responsible for each step of the process.

2.2 KNOWLEDGE MANAGEMENT AND DECISION MAKING IN DISASTERS

In the United States, emergency management organizations loosely follow the Incident Command System (ICS), which offers an organizational structure for coordinating information collection and sharing, planning, resource management and logistics, and operations. Long-term planning is an important part of preparing emergency managers to operate in chaotic environments and identify decisions that will need to be made. It also provides a common framework for coordinating across numerous sovereign organizations that differ incident to incident.

Part of the planning process entails developing an information collection plan. Emergency managers identify essential elements of information (EEIs) that provide actionable grounds for decision making. In a common conception of the process for leveraging data for decision making, summarized in Figure 1. Data-to-decision process, information is considered to be facts or statements about the status of the world, which are derived from more granular data points or observations. EEIs are fulfilled through requests for data or information gathered through field observation. That information is then interpreted alongside other pieces of information to provide knowledge—or intelligence—which is frequently defined as the "capacity to act." Decisions and actions themselves can then be made strategically.

Figure 1. Data-to-decision process.

However, due to the wide variation in disasters—geographies, municipalities, hazard types, unique infrastructure, resources available, etc.—knowledge management and decision-making processes are largely decentralized and ad hoc. For many disasters, little information about conditions on the ground is available in the first few days. Emergency managers often make decisions based on experience, training, and instinct given a lack of situational awareness and ground-truth. There is a saying that making the wrong decision is better than not making a decision.

Remote sensing offers a new source of data and observations to drive this data-to-decision process. In this context, many in the emergency management community agree with the sentiment that a picture is worth a thousand words, but only if collected in time, over the right area, and at an acceptable resolution to help fill the information gap.

2.3 A BRIEF HISTORY OF REMOTE SENSING IN DISASTER RESPONSE

The history of remote sensing includes the advent of photographic cameras[1], which were first hefted skyward on balloons, kites, and pigeons [4]. Dodge & Congalton provide an excellent introduction to the history of remote sensing and Earth observation [5]. Over the last 100 years, aerial photography has been increasingly collected after disasters. In 1906, photographer George Lawrence used a kite-lofted film

[1] The term "camera" comes from the Latin term *camera obscura*, meaning *darkened room*. Unrelated to the facility used to develop film, a camera obscura is a dark room with a pinhole at one end. Light bends around the pinhole, or a lens, and projects an enlarged image onto the opposite wall. Camera obscura devices were used by artists to project images for sketching and painting since at least the Renaissance. Photo-chemical plates were first used to capture camera obscura projections in the 1820s, leading to the development of cameras as we know them today [91].

camera to capture aerial images of San Francisco after the city sustained severe damage from a 7.9 magnitude Earthquake. This photograph is regarded as the first overhead image of disaster damage [6].

Figure 2. View of San Francisco after the 1906 Earthquake, regarded as the first overhead disaster image [6].

In the 1950s, 60s, and 70s, remote sensing emerged as a crucial resource for national security. In his seminal 1945 letter *Science the Endless Frontier,* Vannevar Bush, then White House science advisor and former vice president of MIT, made the case that basic research and technological development are essential to national security [7]. Bush focused on military applications, public health, and education, which led to the formation and expansion of federally funded research and development centers, an increase in research at the National Institutes of Health, and the creation of the National Science Foundation. Expenditures for military research increased in the decades after World War II, which included advances in space-based remote sensing [8]. The first satellite imagery intelligence mission, Corona, was launched in 1960 and later operated by the National Reconnaissance Office established in 1961 [9]. Early satellite imagery was captured on film, which dropped back to Earth in canisters.

In the last few decades, the use of remote sensing in severe and catastrophic disasters has become common. Disasters emerged as a national security priority with the formation of the Federal Emergency Management Agency (FEMA) in 1979 and its subsequent inclusion in the Department of Homeland Security (DHS) in 2003. As early as 1970, aerial imagery was collected after domestic disasters to inform response operations and decision-making. The response to the September 11 terrorist attacks on the World Trade Center was one of the first catastrophic incidents in the United States where overhead imagery was used operationally, providing insight on pre-disaster conditions, debris management, fire tracking, and public messaging [10], largely due to successful remote-sensing coordination [10, 11]. Hurricanes Charley and Ivan in 2004 are considered the first major hurricanes in the U.S. for which high-resolution satellite imagery was available [12]. TABLE 1 presents a partial list of documented incidents and the type of imagery collected.

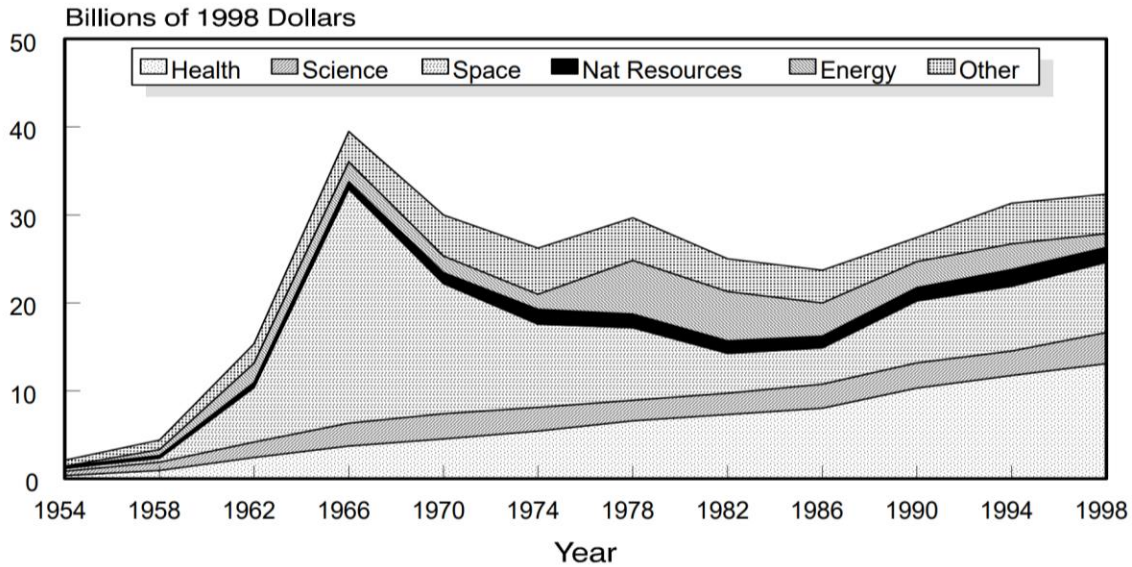


Figure 3. Civilian R&D outlays by function 1954 to 1998, data provided by the Office of Management and Budget [8].

Since 2018, overhead imagery has been collected and used with increasing frequency, especially at the federal level [17]. A major shift occurred in 2020 [18]. As a result of the COVID-19 pandemic, FEMA limited deployment of staff who would traditionally collect information. To avoid putting staff at risk of contracting COVID, many FEMA programs sought ways to use overhead imagery in their program processes instead.

TABLE 1

Timeline of Selected Disasters After Which Imagery was Collected and Used to Inform Decisions

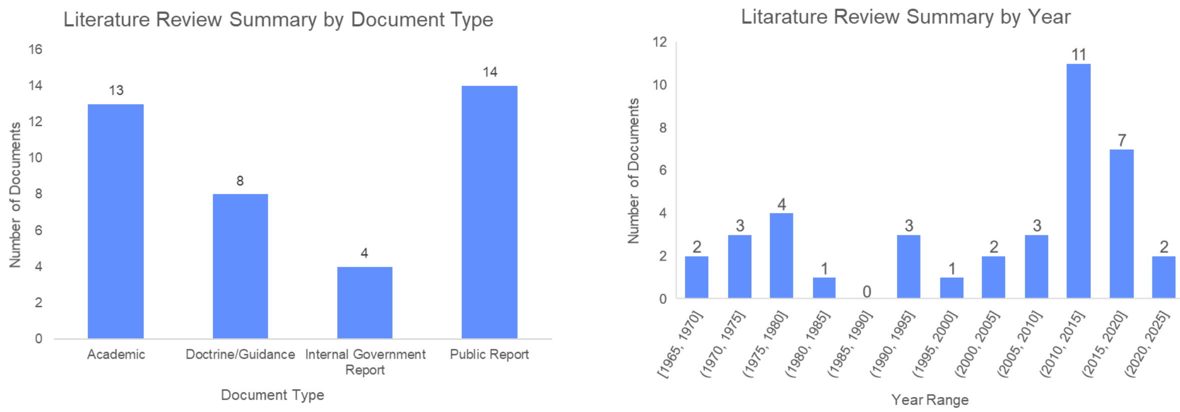
Year	Location	Incident	Imagery Type
1970	Corpus Christi, TX	Hurricane Celia	Aerial: 3000 ft, color, film [13]
1971	San Fernando, CA	Earthquake	Aerial: BW, film [13]
1973	Pierre, SD	Tornado	Aerial: color, film [14]
1974	Xenia, OH	Tornado	Aerial: BW, film [13]
1989	South Carolina	Hurricane Hugo	Aerial: color, infrared, film [15]
2001	New York City	9/11	Aerial: high-res. digital, LIDAR, thermal Satellite: 1 m MSI [10]

2005	Louisiana	Hurricane Katrina	Satellite: pan, MSI, thermal, IR, color, HSI Aerial: color [16]
2008	Galveston, TX	Hurricane Ike	Satellite: ASTER, Landsat [5]
2010	Haiti	Earthquake	Satellite: pan, MSI, color, SAR, thermal, IR Aerial: color, LIDAR [16] Volunteer-generated information (VGI)
2011	Joplin, MO	Tornado	Satellite: color Aerial: color [16]
2011	Minot, ND	Floods	Satellite: pan, MSI, HIS, IR, color Aerial: multi-view color [16]

2.4 USE CASES FOR REMOTE SENSING IN DISASTERS

The idea of *use cases* originated in the 1980s as part of the software development process. In that context, a use case may be defined as, "a description of the possible sequences of interactions between the system under discussion and its external actors, related to a particular goal" [20]. One purpose of use cases and use case models is to establish system requirements [21]. Use cases are typically written documents that capture actors, their goals, and the flow of actions or events to achieve their goal, among other factors important to a given project.

Though examples and case studies point toward the usefulness of imagery in disaster response, there exist few recommend requirements, standards, or processes toward systematizing the use of imagery across responding agencies. A large body of academic work contends with the collection, processing, and analysis of remotely sensed data in the context of disasters, whereas a relatively small number of documents and reports discuss these outputs in relation to practitioner needs. The lack of clear information needs and requirements is cited time and again as a factor that precludes discussion on how to best leverage remotely sensed data in disasters [22, 23]. Since remote-sensing systems are used only opportunistically during disasters, use cases for any given type of imagery or imaging system are poorly codified.



Documents reviewed: 39+ from 1966 to 2023
Activations experienced: 10+ from 2021 to 2023
Semi-structured interviews: 16 from 2020-2021
Unstructured conversations: 20+ from 2021 to 2023

Figure 4. Summary statistics of the type of documents reviewed and their publication dates.

In light of this deficit, we identified and analyzed more than 40 documents, including government reports [24, 25, 26, 27, 28], case studies [29, 19, 16, 30], academic publications [31, 29, 32, 33], and practitioner-oriented documents [34, 35, 36, 37, 38, 39, 40] from the last 50 years that discuss how remotely sensed data can inform disaster decisions, challenges in practice, and conditions that enable successful collection and use of imagery in disasters. We used qualitative research methods, specifically coding and pattern matching, to track perceived and demonstrated use cases for remote sensing in disasters.

Across emergency management literature, the usefulness of imagery is conveyed in various ways, which we have grouped into six categories, discussed in detail in this section.

- **Functional area**: Use cases for imagery are vaguely referred to by type of activity, e.g., “search and rescue” or “damage assessments.”

- **Motivation**: Imagery is used to fulfill an abstract role common across job functions, program areas, and organizations, e.g., provide situational awareness, document impacts.

- **Process**: Use cases are described as specific processing, analysis, or decision-making steps, including the use of information derived from imagery to produce other information, e.g., how to use imagery data to inform site selection, produce a flood map, develop a damage assessment report, manually annotate features of interest, or create a feature service.

- **Observables**: Use cases are described as identifying specific kinds of things to be observed, e.g., “downed power lines” and “road damage.”

- **Information elements**: Imagery is used to create or provide specific pieces of useful information from image data, e.g., location of downed power lines, level of building damage, number of damaged buildings.

- **Decisions and actions**: Use cases for imagery refer to specific types of stakeholders and the decisions or actions they make or perform in the course of operations based on imagery data or information derived from imagery data, e.g., issue a disaster declaration, navigate in the field.

Though different, these various ways of describing imagery utility are interrelated and, when combined, exhibit system-level use cases that draw a logical chain of events from sensor design to decision support.

2.4.1 Functional Areas

Descriptions of function are quite common and broad reaching, though vague. In a 2011 survey, state-level emergency managers responded in the affirmative that imagery is useful for understanding weather conditions, fire extent, flood inundation, crop and vegetative damage, debris characteristics, status of lifelines, and damaged buildings [41]. Other functions include infrastructure damage assessments, residential damage assessments, search and rescue, shelter site selection, and mass care (food, water, shelter, medical supplies).

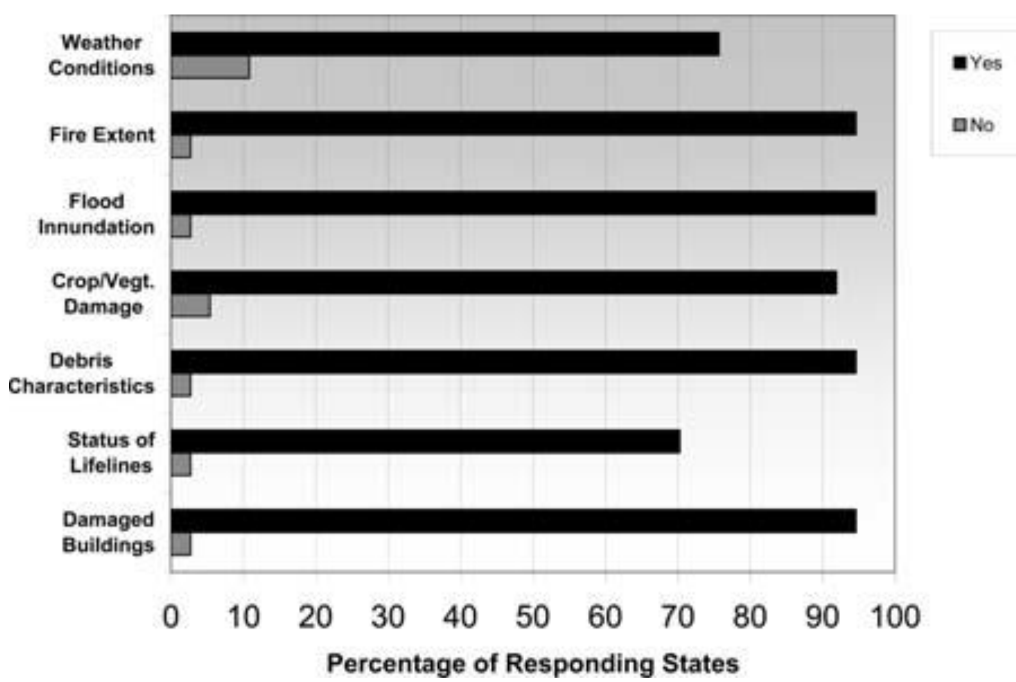


Figure 5. Perceived utility of remote sensing post-disaster, reproduced from [33].

2.4.2 Motivations and Abstract Use Cases

Motivational use cases are summarized as four "abstract use cases" in a recent FEMA report on imagery use cases and system requirements [42]. In this framework, situational awareness, or "sense-making", is using imagery to gain a broad, unstructured understanding or picture of what is happening on the ground during response operations or program delivery. Quantitative or qualitative analysis may be used to derive new data or new information from imagery. Imagery may be used as evidence of disaster damage and to document disaster impacts. Finally, imagery is used to validate, or gain confidence, in third-party reports.

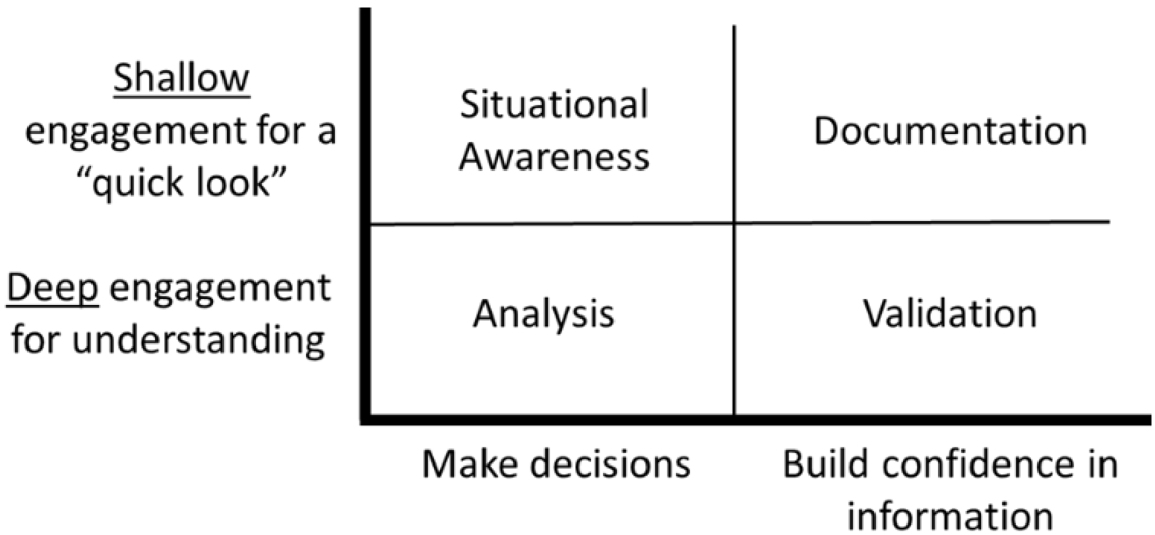


Figure 6. Abstract uses for remotely sensed data in emergency management [42].

These use cases describe reasons for using imagery that are common across stakeholders, functional areas, or specific decisions. For example, different actors might use imagery to validate that damage occurred at a particular time, that flood waters reached a particular extent, or that a facility is in the assumed location.

2.4.3 Process-Based Use Cases

Federal, state, local, and non-profit organizations provide detailed guidelines on how to use remotely sensed data to produce specific types of information or mapping products. For example, sites for shelters may be selected using the following approach [43].

- Shelter site selection criteria
  - The location should be accessible through road with in 2 km
  - It should be located in a village/settlement
  - The area should not be affected by an historic flood incident

    - It should be on a relatively high ground
- Analysis approach
    1. Using the road network, create a 2k m buffer zone around roads
    2. Extract villages/settlements within the buffer zone
    3. Using historic flood inundation data, delineate areas inundated and not-inundated in the last 10 years
    4. Extract selected villages / settlements that were not inundated during last 10 years
    5. Using the elevation data, assign the elevation to each of the settlements

In addition, process-based use cases describe actions or tasks staff with data management or analysis responsibilities may wish to perform with imagery. These actions are done *to* imagery or with metadata.

- Know where imagery will be collected
- Find available imagery for a location
- View image footprints
- View pre- and post- incident imagery
- Download or capture images
- Visually analyze imagery
- Computationally analyze imagery
- Acquire, process, host versatile data types in a single location
- Edit symbology (pixel values)
- Use imagery in models in conjunction with other types of data
- Load imagery into mobile devices
- Load imagery onto laptops
- Serve imagery into GIS and web-mapping applications
- Ingest data automatically
- Manage access

FEMA describes process-based use cases in detail, as related to the design and functionality of information technology systems [42]. A table summarizing requirements is reproduced in Appendix B for reference.

2.4.4 Observable-Based Use Cases

An observable is an object or land feature of interest for which overhead imagery is collected to view. Observable-based use cases relate what can be seen in an image. Observables are frequently mentioned across literature, but are described differently in different contexts [13, 16, 44]. Facilities, including infrastructure, homes, and roads, are observables. Environmental phenomena may also be observables of interest, including clouds, floodwater, soil saturation, and burn scars [44]. TABLE 2 and TABLE 3, reproduced from literature, present non-exhaustive lists of observables relevant to disaster response and recovery.

TABLE 2

List of Observables from [13]

Identifiable Items on Aerial Photographs		
1. Structural Damage Community facilities ○ Hospitals and medical ○ Schools ○ Churches ○ Fire stations ○ Police stations Developed recreational areas ○ Civic buildings ○ Buildings designated as shelters Residential ○ Single family ○ Mobile homes (Trailers) ○ Multi-family 1–3 story ○ Multi-family >3 story Commercial ○ Office ▪ Highrise ▪ Other ○ Retail outlets ○ Motels and hotels	Industrial ○ Large manufacturing ○ Light industrial ○ Wholesale and warehouse ○ Storage tanks Agriculture ○ Farming ○ Forage 2. Damage to Transportation Routes Streets ○ Obstructed trees/poles ○ Structural debris ○ Road washout ○ Disrupted road surface Collapsed bridges Collapsed elevated roadways and subways Disrupted railroad lines Airports ○ Structural damage ○ Damage to runways	Harbors Ports 3. Damage to Utilities Broken water mains Contaminated reservoirs or wells* Damage to pumping stations Broken sewer lines Damaged pumps Damage to treatment plant Power plant damage (atomic, regular) Transformer stations Downed power/phone lines 4. Areas of Inundation 5. Occurrence of ponded water areas (a potential health hazard) 6. Accumulated rubble and brush 7. Fire damage 8. Safe or shelter areas

TABLE 3

Remote Sensing Damage Assessment Observables of Interest [16]

Type of Incident	**Hazard Extent**	**Building Damage**	**Infrastructure**
Flood	• Inundation area • Duration of flooding • Flood surface depth	• Presence of flooding • Depth of flooding above first floor elevation	• Blocked roads • Submerged bridges • Bridge washout/collapse • Overtopped dams and levees • Inundated power plants, factories
Surge and Tsunami	• Presence of debris • Surge extent (wrack line)	• Complete and extensive building damage • Indications of non-catastrophic inundation	• Damage to roads • Blocked roads • Bridge damage • Bridge washout • Displaced oil rigs • Port and marina damage • Nuclear reactor status
Earthquake	• Fault rupture and displacement • Liquefaction • Inundation from subsidence • Landslides	• Complete and extensive building damage • Number and square footage of damaged buildings (leading to estimated loss) • Building debris	• Blocked roads • Bridge damage • Damage to wharfs, ports, and piers
Wind (hurricane and tornado)	• Wind speed estimation • Debris estimation (urban and forestry)	• Complete and extreme damage, some moderate	• Levee failure • Damage to wharfs, ports, piers • Power outage • Offshore oil rig damage/extent

2.4.5 Information-Based Use Cases

Use cases may culminate in the provision of information. Information is organized data. In the words of Green and King, “Data is a set of measurements describing an object or process, whereas information is data that has been analyzed and given context" [45]. Deriving information from imagery typically involves an evaluation of observables or analysis of data extracted from images. Surface-level information includes recognizing the presence, location, or quantity of an observable, whereas subsurface-level information may require distinguishing between categories of similar observables or subsequent imagery-based analysis [46]. EEIs may inform decisions, as discussed in the next section. EEIs commonly requested in disaster response and recovery include [39, 19, 35, 38, 33, 28, 23] the following.

- Extent of impact and geographic extent of visible damage
- Areas of most severe impact
- Hazard locations (e.g., which areas are flooded)
- Impact to at-risk communities
- Potential risks of cascading impacts when spatially related
- Condition of lifeline infrastructure
- Building-by-building damage assessments
- Number of homes damaged (proxy for population affected or displaced)
- Condition of transit routes, bridges, railroads, terminals, runways, overpasses, and tunnels.
- Extent of damage to transportation systems
- Debris or sediment deposits and similar problems that threaten health and life
- Vegetative destruction (forestry, agriculture)
- Environmental constraints that affect operations
- Estimated cost of all damage

A piece of information may have several components, and the needed information varies by user. For example, damage assessments are commonly discussed as a key use case for imagery. However, the essential information elements needed to assess damage differ based on the end user [47, 48, 49]. A damage assessment may include the type of structure, location, severity of damage, time of damage, and in some applications, the number of structures affected to different degrees. TABLE 4 shows how observations of damaged structures can be translated into information about the nature of disaster impacts.

TABLE 4

ImageCat Damage Protocol: Remote-Sensing Damage Classification Scale Utilized in Tuscaloosa/Birmingham/Joplin Tornado Damage Assessments [30]

FEMA DAMAGE CLASSIFICATION			REMOTE SENSING BASED CLASSIFICATION			
DAMAGE LEVEL		OBSERVED DAMAGE	Roof Covering	Roof Diaphragm	Collapsed Walls	Other Considerations
LD	Limited Damage	Generally superficial damage to solid structures (loss of tiles or roof shingles); some mobile homes and light structures damaged or displaced.	Up to 20%	None	None	Gutters and/or awning; loss of vinyl or metal siding
MD	Moderate Damage	Solid structures sustain exterior damage (e.g., missing roofs or roof segments); some mobile homes and light structures are destroyed, many are damaged or displaced.	>20%	Up to 20%	None	Collapse of chimney; garage doors collapse inward; failure of porch or carport Mobile homes could be partially off foundation
ED	Extensive Damage	Some solid structures are destroyed; most sustain exterior and interior damage (roofs missing, interior walls exposed); most mobile homes and light structures are destroyed.	-	>20%	Some exterior walls are collapsed.	Mobile home could be completely off foundation – if appears to be repairable.
CD	Catastrophic Damage	Most solid and all light or mobile home structures destroyed.	-	-	Majority of the exterior walls are collapsed.	-

2.4.6 Using Imagery to Inform Decisions and Actions

Finally, use cases for imagery may be described based on the decision or action a stakeholder would like to make based on information provided by the image. In the context of emergency management, the goal of decision making is to reduce vulnerability to hazards, diminish the impact of disasters, and to prepare for, respond to, and recover from those that occur [43]. Common decisions noted in literature include the following.

- Issue public messages
- Issue disaster declarations
- Navigate in the field; establish routes to shelters, hospitals, and populated areas
- Restore lines of communication, such as roads, streets, telephone lines, and airport facilities
- Select sites for disaster aid stations
- Select food distribution points
- Provide temporary housing
- Validate preliminary damage estimates
- Determine adjustments and grants for property damage

- Eliminate health hazards such as ponded water, exposed breaks in sewer and water lines, broken electrical lines, damaged sewage treatment areas, etc.
- Determine the number, location, and capacity of shelters needed
- Support emergency funding requests
- Determine reseeding and replanting requirements
- Develop mitigation plans
- Prioritize route clearance and repair; designate alternate routes

Considering a use case as the set of activities to transform imagery into information that supports decision making naturally includes numerous of the other use case categories described above. Decision making, or the outcomes of decisions and actions, can be thought of as the teleology of use cases for imagery in disaster response. Observable-based use cases indicate what objects to image. Process-based use cases must be considered when analyzing data to create information. Information-based use cases underpin these final uses cases related to decisions and actions. To demonstrate the latter, TABLE 5 ties specific pieces of information derived from imagery to decisions that are enabled or supported by the information.

TABLE 5

Decisions Supported by Imagery, Summarized from [13]

Information Derived From Imagery	Decisions Enabled
Number of persons dead, persons with injury or illness, persons hospitalized	Scale and locations to provide medical services
Degree of damage to residential structures and businesses	Number of shelters and amount of food required
Damage assessments	Recommend a federal disaster declaration
Damage to transportation infrastructure	Determine routes for bringing in supplies and personnel
Information on recovery of water and sewage infrastructure and damage to transportation systems	More efficient resource allocation and prioritization
Population and area size affected	Scale and locations to provide relief services, issue disaster declarations
Identify standing water	Vector control
[Pre-disaster] Identification of vulnerable facilities	Mitigation and preparedness activities

This list of imagery-informed decisions is certainly non-exhaustive. Each geography and each incident is unique, raising questions and requiring decisions that could not have been predicted. However, for decisions that can be anticipated, and for which imagery can provide supporting information, we can proactively assess what sensor, analysis methods, and dissemination tools can deliver imagery to meet needs [45, 50]. Figure 7 presents a general architecture that leverages specific sensors to support specific decisions. To date, no studies appear to have systematically assess the end-to-end pipeline connecting specific sensors, desired data and analytic products, information, and decisions for broad applications in emergency management.

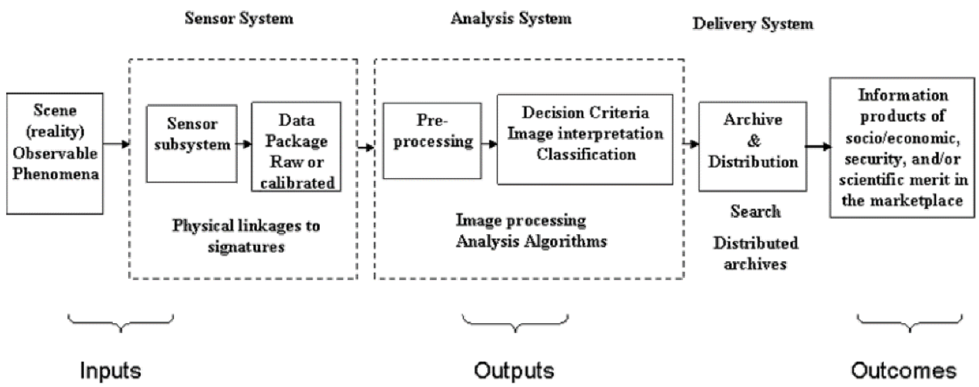


Figure 7. Model of the remote sensing end-to-end information channel [50].

2.5 SATELLITE REMOTE SENSING IN DISASTER RESPONSE

Despite the challenges with rigorous assessment of use cases for remote sensing in emergency management, it has long been evident that imagery is immensely valuable during disasters [50, 45]. TABLE 6 summarizes several benefits noted in literature. In addition, numerous reports in the latter half of the 20th century pointed toward optimistic future applications of satellite remote sensing in disasters in particular [51, 24, 52, 27, 26, 53]. These sources postulate that satellite remote sensing can support emergency activities that include real-time data acquisition, locating damage to infrastructure and homes, search and rescue, identifying debris, assessing requirements for food, water, and medical supplies, assessing damage broadly, forecasting disaster impacts, evacuation planning, selecting sites for relief centers, and allocating resources.

TABLE 6

Benefits of Remote Sensing in Disaster Applications

	Benefits
Access/Area	Acquiring data over inaccessible regions, where field operations are not possible [25] Shows spatial extent of the disaster and geographic distribution of impact [13]
Timeliness	Provide near real-time information [51]
Effort	Avoid duplication [13] Reduce the manpower required to collect information. For example, it would take 1000 volunteers 2–3 weeks to survey damage in a city the size of Houston after a disaster, and 3–5 Red Cross nurses would need 3–4 days to estimate the number of ill and injured patients; these tasks can presumably be completed much more quickly with imagery [13]
Accuracy and Safety	Remote sensing can enable better, faster damage assessments, diminish the number of disaster-related causalities, and reduce hazards for disaster personnel and survivors
Record Keeping	Photographs provide a permanent record of damage
Planning	Pre- and post-disaster images can be used together for future incident planning [53] Modeling based on image analysis can be used to predict disaster onset [27]

This section briefly reviews the types of assets currently used to collect imagery in disasters, presents the unique strengths of satellite remote sensing, and discusses the current state of the space industry that renders an analysis of requirements for satellite remote sensing in disasters timely.

2.5.1 Remote Sensing Platforms

Sensors are mounted onto platforms, which provide propulsion and direction for image collections. Sensing platforms include UAVs0., fixed-wing manned aircraft, rotor-wing manned aircraft (helicopters), satellites, dirigibles (blimps, airships), scientific balloons, sounding rockets, and medium-altitude and high-altitude long-endurance aircraft. Each type of platform offers unique advantages for remote sensing in disaster response. Although a robust trade study across platforms is beyond the scope of this work, Figure 8 summarizes key characteristics of several. UAVs, fixed-wing manned aircraft, and satellites warrant some discussion as they are increasingly used in disaster response. Figure 9 and TABLE 7 provide generalized comparisons of these asset classes.

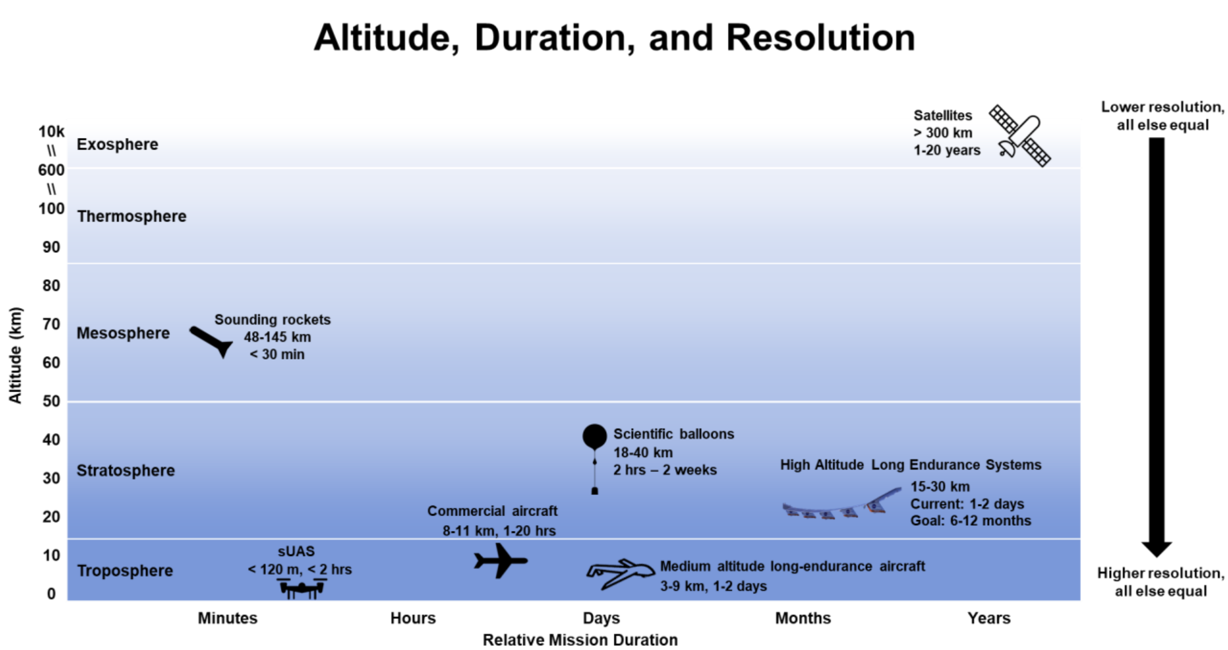


Figure 8. A comparison of the relative mission duration, operating altitude, and spatial resolution of data products across assets commonly used to collect remotely sensed data.

UAVs are easy to deploy and widely available but have limited area coverage. UAVs are inexpensive, and wide variety are commercially available. Imagery collected with UAVs is often posted to the internet by news agencies and individuals within hours of a disaster, but is not designed or intended to be a shared resource providing actionable information for emergency managers. As open-source data, these resources can be useful, but remain decentralized, non-uniform, and uncoordinated. Standards for image collection and processing, and centralized data storage, would significantly advance the use of UAVs in disasters.

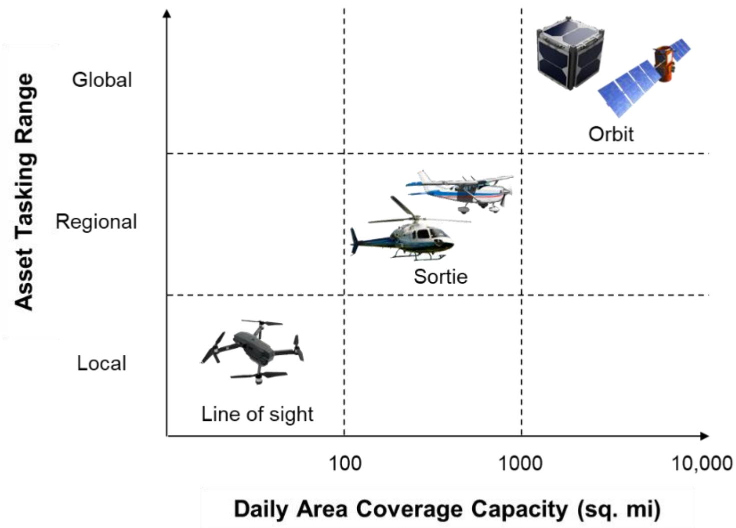
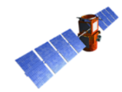


Figure 9. Comparison of UAVs, manned aircraft, and satellites. Satellites have the greatest daily area coverage capacity and the most versatile tasking range, with the potential for global collections.

Fixed-wing aircraft (airplanes) are widely used, and both sensors for manned aircraft and aerial collection services are commercially available. Using aerial imagery effectively during disasters is an area of great interest across government, industry, and academia. The cost of aerial collections is affected by the number and duration of *sorties*, or flights, the type of cameras and, historically, film, the extent of the area covered, and the desired resolution or detail of information needed [13]. Aerial imagery acquisition is limited by weather and time required to mobilize assets. Collections may continue for multiple days after a disaster, sometimes taking a week or more to collect images of priority targets over the impacted area.

TABLE 7

Comparison of Drone, Aerial, and Satellite Remote Sensing Capabilities, Based on the Authors' Experience

	Unmanned aerial systems (UAS) 	Manned aircraft 	Satellites 
Max. spatial resolution	< 3 cm	5–10 cm	25 cm
Daily area coverage per asset order of magnitude	10s km^2	100s km^2	100,000s km^2
Asset purchase and annual maintenance cost order of magnitude	2 ($100)	5 ($100k)	7–8 ($10M–100M)
Cost to deploy and collect 100 km^2 (a medium-size city) order of magnitude	2–3 (100s–1000s)	4 (10,000s)	2–3 (100s–1000s)
Global distribution	Highly localized, though many assets exist globally	Trained teams and assets must be mobilized	Global coverage
Min. time from tasking to collection	<24 hrs	24 hrs	<1 hr
Typical dissemination approach for EM	Limited, often user-only or shared with local team	Wide dissemination through web	Wide dissemination through web
Product consistency	Highly varied according to use	Menu of options, some standard products	High consistency once workflows are established
Repeat collection potential	Frequent, limited by operator availability	Infrequent due to cost and operator availability	Option for frequent revisit
Access to impacted area	Limited when damage is catastrophic	Possible if airports are operational	Unrestricted

2.5.2 Value Proposition for Satellites

Though more expensive to create, launch, and operate than UAVs or aerial sensors, satellites appear to be better poised for rapid collections, automated analysis, and centralized data storage and sharing. Satellite remote sensing is a core capability with four primary strengths: imaging inaccessible areas, timeliness and temporal resolution, delivering consistent products, and providing imagery for all incidents. This section presents a discussion on how satellite remote sensing provides—or appears able to provide—value in these ways. Further analysis of these value propositions is presented in this report.

2.5.2.1 Imaging Inaccessible Areas

Satellites can provide information at scale during catastrophic and non-permissive incidents where field crews lack access. Though all remote sensing assets pose this benefit, satellites are able to rapidly image over large areas and those with restricted airspace use. For example, satellite imagery was used extensively in 2022 to support the Earthquake in Turkey and humanitarian missions in Ukraine. Wide-area imaging can also support "tip-and-queue" architectures for identifying areas that should be imaged with higher resolution assets when weather conditions allow.

2.5.2.2 Timeliness and Temporal Resolution

As persistent assets, satellites appear to be available for near-real time tasking and data delivery. Commercial providers advertise as low as six-hour tasking turnaround times, which is far faster than pilots and assets can be deployed. Even for U.S. tropical storm incidents, which regularly warrant a national-level response and coordinated remote sensing collections, aerial imagery is never collected within the first 24 hours due to inclement weather conditions and mobilization.

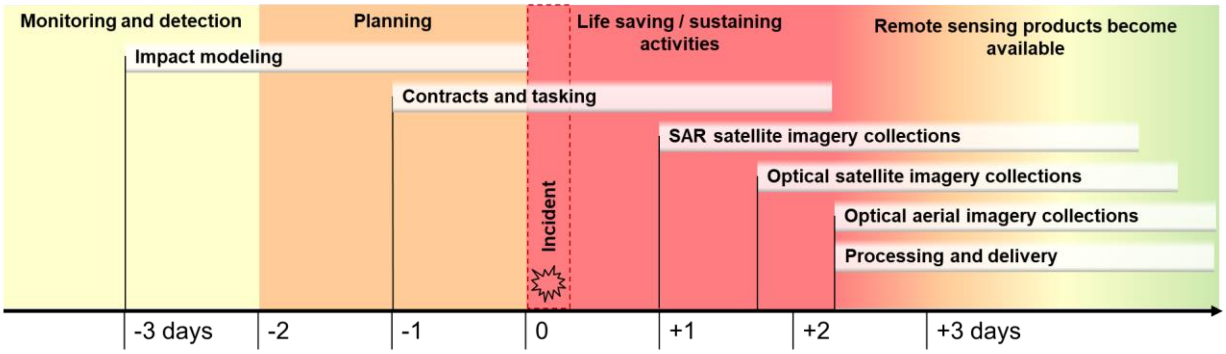


Figure 10. Typical timeline for remote sensing operations during national-level incidents in the U.S.

Figure 10 shows a best-case scenario timeline for well-coordinated remote sensing collections orchestrated by FEMA. With proactive tasking and pre-existing contracts, satellite imagery is often now available within 48–72 hours of severe and catastrophic incidents. If tasking were automated and more resources were dedicated to disaster imaging, industry standard turnaround times imply that this timeline could be further reduced.

In addition, satellites are theoretically persistently available for frequent repeat passes. Repeat collections are useful for tracking the progression of flood, fires, and other incidents that unfold over a period of time. They can be used to monitor debris removal and recovery operations. Though needed temporal frequency varies across use cases, satellites promise to streamline repeat collections.

2.5.2.3 Delivering Consistent Products

Processing, analysis, and dissemination of satellite imagery-based products can be streamlined and automated, ensuring that data products are delivered in the same format through the same channels every time. Automated processing and analysis can reduce the level of effort—and subsequently, cost and time—needed to develop useful information products from satellite imagery.

Product consistency enables wider adoption among users who have little background in working with remotely sensed data. Tools like Google Maps, Waze, and other navigation apps with satellite base layers are now used widely. They set a precedent for satellite imagery products that are orthorectified, tiled, fast-loading, and intuitive to navigate. Emergency managers always fall back on training and experience. While image processing for basemaps takes months, if disaster imagery can be delivered in a consistent format through the same channels for every incident, it will become a reliable, invaluable resource, rather than a nice-to-have bonus.

2.5.2.4 Imagery for All Incidents

Finally, satellites can more readily provide sensing for low-impact, wide-area, and slow-moving disasters, such as rural floods, that are expensive and taxing to observe with aerial assets. At this time, aerial imagery and satellite imagery are leveraged for severe and catastrophic incidents, but rarely for incidents that garner less attention on the national and international stage. When something really bad happens, everyone wants to help, but not so for slow-moving and rural incidents that still cost millions of dollars in economic loss and recovery.

The National Incident Management System (NIMS) defines five levels of *disaster complexity* as a proxy for the severity of an incident, the area affected, the number of organizations involved in response, time to stabilize the incident and begin recovery, and total impact to a community [54]. Figure 11 provides a qualitative assessment of the relative value satellite remote sensing might provide for disasters of different NIMS types.

Type 5 incidents, the least severe, can be remedied in a day by local first responders, with no enduring impacts. These might be small medical emergencies or fires. Even if it were tasked, processed satellite imagery would not be available during the incident timeframe for Type 5 incidents.

On the other hand, Type 1 incidents are catastrophic. They impact large areas and require the combined resources of state, federal, voluntary, and sometimes international emergency management organizations. The impacts of these incidents endure for months and years, with long-tailed recovery. Examples include Hurricane Katrina in 2005, the 2010 Haiti Earthquake, and Hurricane Maria in 2018. For catastrophic incidents, all available imaging assets are typically deployed, regardless of cost. Therefore, while satellites can provide essential early information, other resources are also available.

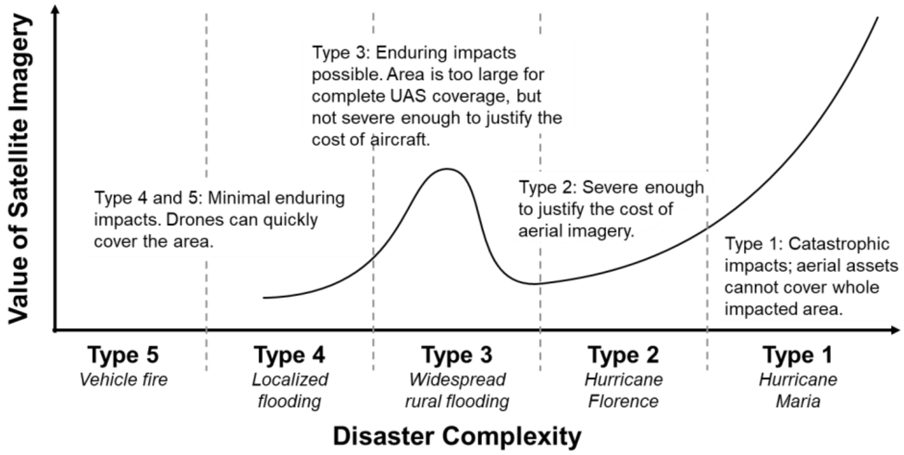


Figure 11. Qualitative visualization of how valuable satellite remote sensing is for different types of disaster incidents.

We posit that Type 3 incidents, such as a regional flood, snow storm, or EF2 tornado, have the most to gain from satellite remote sensing. These incidents tax local and regional resources and may warrant financial support or other resources from state or federal programs. These incidents may take weeks to months to recover from, simply because the incident is not severe enough to draw national attention or resources, but typically pose manageable threats to lives as they are happening. In other words, they are bad, but not *so* bad that all resources are deployed. As persistent assets, satellites could be used to collect imagery for these incidents that provides invaluable information to emergency managers when other imaging assets are too expensive (aircraft) or have limited area coverage (UAVs). For these incidents, overhead imagery could change the way emergency managers respond. To have this impact, imagery would need to be reliably available for every disaster, such that it would be incorporated into training materials and standard operating procedures at the state and local level.

2.5.3 Current State of the Space Sector and Satellite Sensing During Disasters

The space sector is rapidly expanding, availing high-resolution satellite remote sensing for new public and civil applications at an unprecedented scale. In the past, though widely available for military applications, satellite remote sensing was seen as too expensive, too advanced, unreliably accessible, and an overall poor allocation of scarce resources [55].

Today, the commercial space industry is worth over $350 billion [56]. In 2022, high-resolution satellites cost ~$3 million to procure, three orders of magnitude less than the estimated ~$1 billion (CPI adjusted) spent on high-resolution assets in 2016. Commercial launches now occur multiple times a month. Commercial off-the-shelf (COTS) components for small satellite technology are increasingly available at low cost. Access to space promises a near future where consistent and systematic use of satellite remote sensing becomes the norm in disaster response and recovery, regardless of the severity of the incident.

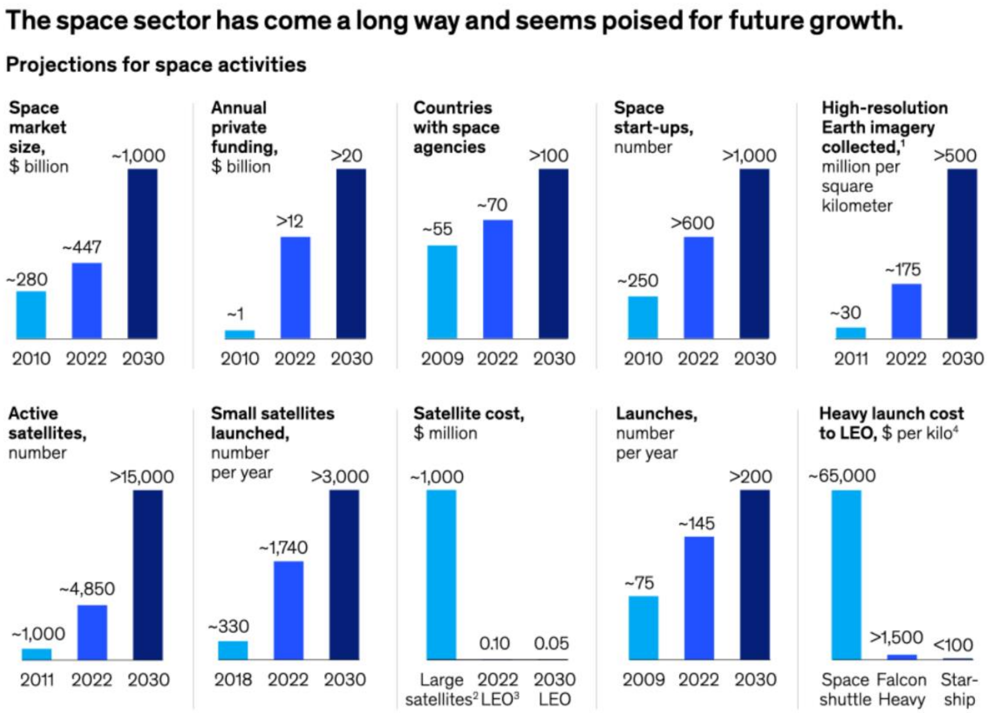


Figure 12. Trends in the space industry [57].

Satellites are also becoming much more economical, with great improvements in size, weight, power, and cost to achieve commensurate resolution. In an in-house survey of current Earth-observing systems, we collected data on the cost and mass of existing assets (Figure 13). In the last 10 years, several new commercial constellations are achieving high spatial resolution optical and SAR imagery with low-cost small satellites. The trend toward small, sharp, and cheap Earth observation systems continues and illustrates that this capability is now widely available to sectors like emergency management that previously lacked access to this kind of tool.

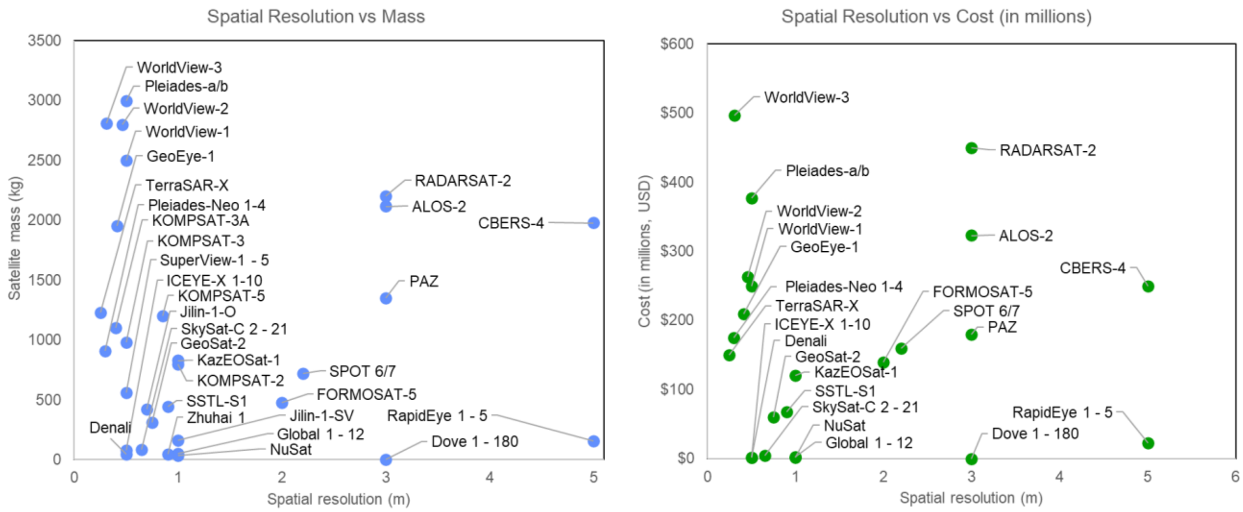


Figure 13. Mass and cost of current Earth-observing satellites compared to the spatial resolution of data products.

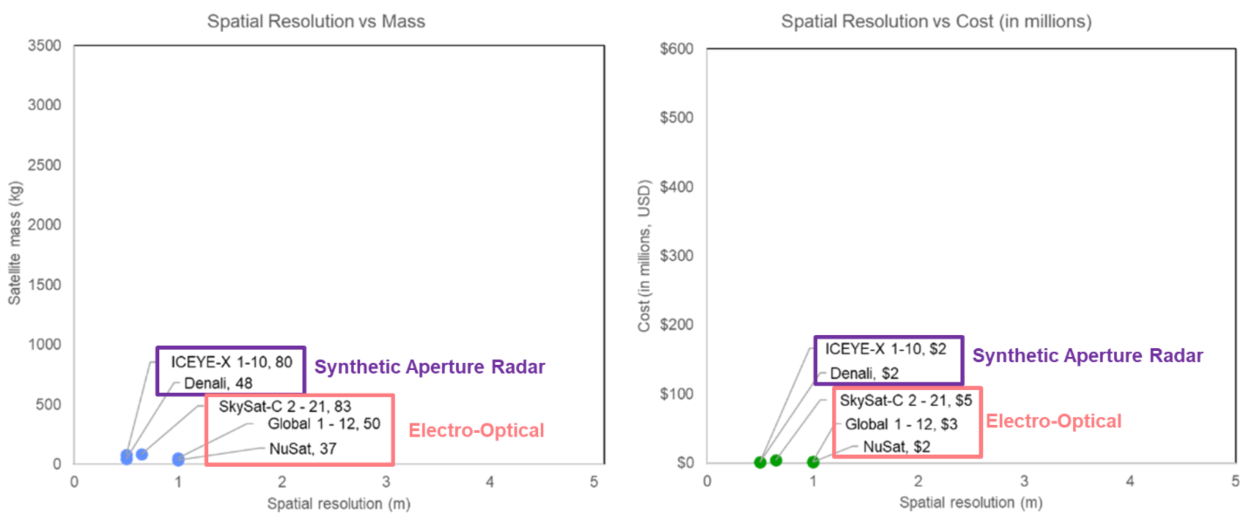


Figure 14. Commercial satellites that achieve spatial resolution of 1 m or less, have a mass of 100 kg or less, and cost $10M or less.

Since 2020, the U.S. emergency management enterprise has made significant advances in the use of remotely sensed data during disasters. The COVID19 pandemic precipitated a shift in federal policy toward the use of remote sensing. Previously FEMA and other responding agencies used imagery ad hoc, evading discussions on privacy, data management, and accuracy, relying on field reports. As natural disasters occurred in the midst of COVID, sending staff into the field became unsafe. Agencies sought imagery and other geospatial technologies to fill the information gap.

Currently, at the federal level, FEMA coordinates remote sensing activities during disasters that require federal support. In advance of and during incidents, FEMA's remote sensing coordinator, or in some cases a regional remote sensing or geospatial coordinator, holds daily calls with a wide range of stakeholders to discuss tasking requirements, operational status, and available products [17]. FEMA disseminates remote sensing products through its Geospatial Resource Center, a website built on Esri's Hub platform that allows approved users to view and access data through web-hosted REST services. This allows the federal government to easily share imagery data and analyses with other official response partners, including SLTT emergency managers, search and rescue teams, and voluntary agencies active in disasters (VOADs). TABLE 8 lists domestic and international programs through which government agencies can request or access satellite imagery-based products to support disaster response.

TABLE 9 notes assets that are frequently leveraged for disaster applications. Information is presented from a U.S.-centric perspective since domestic disaster response is the focus of this report.

TABLE 8

Programs That Provide Satellite Imagery and Derived Products to Support Disaster Response

Provider	Products	Process	Challenges
National Geospatial Intelligence Agency (NGA)	High-resolution commercial satellite imagery	FEMA's remote sensing coordinator may submit a formal request to NGA to task private sector assets in accordance with federal contracts	Tasking subject to right of first refusal; opaque process; data sharing is highly restricted
NASA Disasters Program	Blackmarble nighttime lights data; ARIA damage proxy, flood proxy, and land deformation products; Landsat imagery; commercial pre- and post-incident imagery	The NASA Disasters Program self-activates and curates a wide set of imagery and geospatial products related to ongoing incidents on their Disaster Mapping Portal; they use data from NASA satellites and through agreements with private sector partners	These products often provide situational awareness, but are not high enough resolution to shed light on the status of buildings or infrastructure
Copernicus Disaster Response	Public GIS and information products from Sentinel 1 and 2 and commercial data	The European Space Agency's Copernicus program may activate at the request of USG partners	Focused on the European Union; typically, only requested for catastrophic incidents in the U.S.

International Disaster Charter	Imagery data from commercial or government providers	Agreement among public and private satellite operators worldwide to provide free imagery data to official organizations responding to disasters; must be requested by an agency	As of September 2023, has not been requested by FEMA since Hurricane Dorian in 2019
UNOSat	Imagery data and analysis products from commercial or government providers	Respond at the request of United Nations partners; limited to lower- and middle-income countries	Unavailable in the US and Europe; must be requested
Commercial	Imagery data and analysis products	Public-benefit data programs	Limited data, usually not the highest quality

TABLE 9

Notable Satellite Remote Sensing Assets

Operator	Asset Name(s)	Primary Sensor Type	Operator Type
ESA	Sentinel	Optical (10 m) and SAR (<10 m)	Public
NASA	Landsat	Optical (30 m)	Public
Maxar	WorldView 1, 2, 3, and GeoEye	Optical (<1 m)	Commercial
Airbus	Pleaides	Optical (<1 m)	Commercial
Planet	Dove	Optical (3 m)	Commercial
Planet	SkySat	Optical (<1 m)	Commercial
Satellogic	NuSat	Optical (<1 m)	Commercial
Iceye	Iceye	SAR (<1 m)	Commercial
Umbra	Umbra	SAR (<1 m)	Commercial

2.5.4 Systemic Challenges and Barriers to Adoption

Despite the availability of resources and value proposition, satellite imagery is not used effectively during the response phase of most incidents. Resources are only leveraged for the most severe disasters, and data products are rarely available within the first 24 hours of an incident (e.g., Figure 10). This gap—the messiness and ad hoc nature of using satellite remote sensing operationally—stems from a number of barriers [16, 28].

- **Baseline data:** Pre-incident imagery and foundational GIS data must be available to determine impacts caused by an incident.

- **Asset availability:** Satellite tasking is always in response to a request, task order, or contract, which causes delays; if assets were tasked proactively in response to every disaster, timelines would be accelerated.

- **Visibility**: Clouds (e.g., floods, tropical storms, atmospheric rivers), smoke (fires), and other aerosols (e.g., volcanic activity) limit the collection of optical imagery.

- **Data management**: Imagery data is large, especially high-resolution satellite images. Downloading, processing, and hosting images requires sufficient bandwidth, processing power, storage space, and cloud services. This can be costly and time consuming. Processes and systems must be established outside of incidents.

- **Data sharing**: Sharing information is a core tenet of emergency management. Most satellite imagery providers restrict data sharing in their license agreements. Consequently, in addition, this requirement precludes the use of classified assets and data.

- **Economics**: Imagery is expensive, and commercial providers are unable to financially sustain pro-bono operations at the frequency of disaster incidents; partnerships with insurance companies may help defray costs, but are difficult to arrange with numerous potential beneficiaries.

- **Training**: Most emergency management agencies have only a few GIS professionals on staff, if any. Fewer still are remote-sensing experts who can manipulate image data.

- **Decentralization**: Emergency management is not a hierarchical enterprise; federal agencies, voluntary agencies, state, local, tribal, and territorial governments, and the private sector are sovereign and independent actors, meaning that decisions—including the procurement of imagery and use of new technologies—are made by consensus or by each organization independently.

- **Trust**: Lay users distrust derived products when the source data or processing steps are not transparent.

2.6 THE NEED FOR AN ENGINEERED SYSTEM

In summary, satellite remote sensing is enticing. It promises to fill important information gaps in the early days after disasters. The technology exists and is increasingly available to the emergency management community. However, actionable information derived from satellite imagery is underutilized and frustratingly elusive in the most crucial moments. This dichotomy between the possible and the accomplished, the tension between what we currently do and the better future we imagine could exist today, beseeches a thorough treatment of the engineering systems that underlie and enable satellite remote sensing in disasters.

3. RESEARCH QUESTIONS, APPROACH, AND OBJECTIVES

Satellite remote sensing in disasters can fill an essential gap. High-resolution imagery on the first day could enable better, faster decision making and allocation of resources, informed field operations, and improved coordination across agencies and organizations. Can we have Google Earth but with near real-time imagery of the impacted area? It seems like it should be easy, and that emergency managers are missing out, behind the times. What would it take to meet requirements? What *are* the requirements? Could we build a "DisasterSat" constellation specifically to provide operational information to emergency managers? What architectures could support this mission?

These questions motivated our team to explore use cases, requirements, and concepts for a possible DisasterSat mission, and to evaluate the conditions under which such a mission might be achieved. Throughout, the idea of DisasterSat has come to represent a complex system of space-based remote sensing assets, optimized tasking, coordinated processing and analysis, and broad dissemination that provides useful information to emergency managers in the first day after a disaster.

The goal of this two-year effort was to understand the conditions under which satellite remote sensing can provide useful information to emergency managers during disasters and to propose concepts for "DisasterSat" systems. The team has approached this objective through system engineering, prototyping, and quantitative modeling.

3.1 SYSTEM ENGINEERING

System engineering is a process for designing and managing complex systems to fulfill desired functions or outcomes. In the scoping phases of a project, system engineers aim to define stakeholders and their needs, understand the complexity of a problem, document use cases, develop requirements, and explore architectural decision trades. We sought to answer the following questions.

- Who are the stakeholders and intended users for satellite remote sensing in disasters?
- What are their specific use cases for satellite imagery?
- What data and imagery products could fulfill these use cases?
- What are the requirements and acceptable specifications for these products?
- What architectures and concepts of operation can yield data products that meet requirements?

We combined methods from social science research [58], system analysis [59], and space system engineering [60] to conduct this study. The first iteration of this analysis was completed between October 2021 and April 2022.

3.2 PROTOTYPING

From April to October 2022, we developed a prototype end-to-end satellite tasking and image pipeline to demonstrate the DisasterSat concept of operations using the Lincoln Laboratory Agile MicroSat (AMS), which launched in May 2022. This rapid prototyping effort and outcomes are described in Section 6.6. Specific goals included the following.

1. Develop an optimization model to prioritize satellite tasking during disasters

2. Develop a prototype image processing, change detection analysis, and dissemination pipeline for AMS images

3. Demonstrate end-to-end satellite tasking to product dissemination capability with AMS during the 2022 U.S. Atlantic hurricane season

3.3 MODELING AND QUANTITATIVE ANALYSIS

Throughout the program, modeling and quantitative analysis were used to better understand constraints. The team used quantitative methods to evaluate the following.

- Requirements for resolution based on stated needs

- The likelihood that cloud cover impedes optical imagery collections

- The orbital trade space for the DisasterSat concept

- Change detection model performance

The specific methods used and results of these analyses are presented throughout this report.

4. USE CASES FOR SATELLITE REMOTE SENSING IN EMERGENCY MANAGEMENT

If emergency managers had imagery, reliably, for every disaster, what would they do with it? What difference would it make? Answers to these questions are elusive for two reasons. First, imagery alone is usually insufficient for decision making. Baseline data, status updates, training, and experience all influence decisions and actions. Second, stakeholder use cases vary widely and are poorly codified.

This chapter aims to articulate a selection of decisions and actions emergency managers would like to support with remotely sensed data and document these use cases. First, building on the literature review in Section 2.4, we present a framework that links stakeholder use cases with data products and sensors. Subsequently, we identify relevant stakeholders, the decisions they make, and several essential elements of information that support those decisions. Finally, we describe four imagery and imagery-based data products that provide these essential elements of information. Chapter 5 then assesses requirements for a satellite sensing and data analysis pipeline that could deliver these products.

4.1 USE CASE ANALYSIS

This section describes the approach taken to identify key use cases for remote sensing in disaster response and recovery, summarized and visualized in Figure 15. Each selected use case is described in detail in the sections that follow.

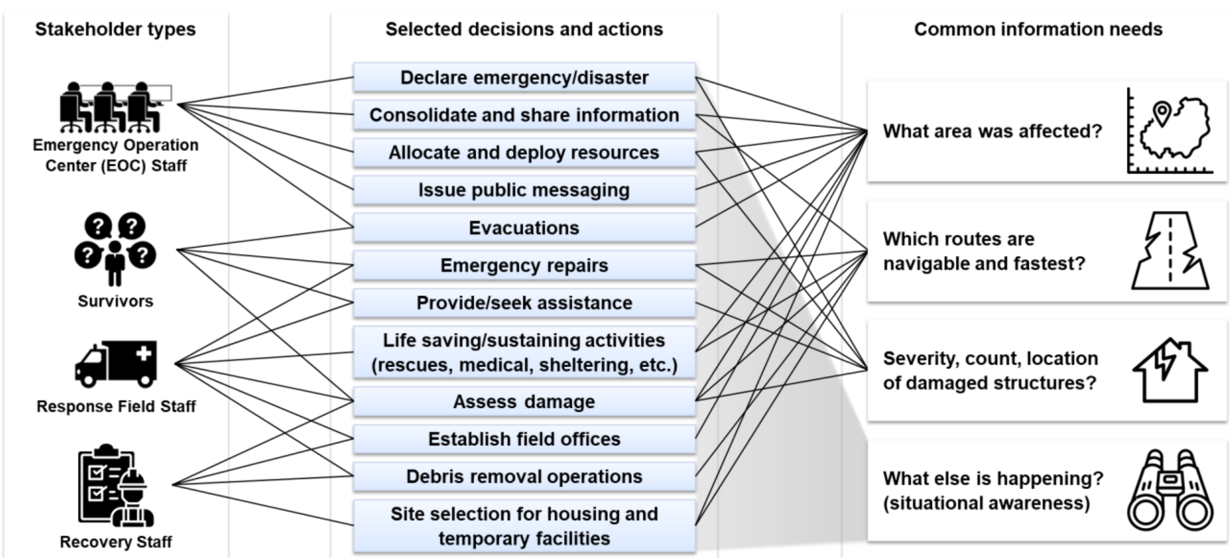


Figure 15. Visual summary of stakeholders, selected decisions, and information needs.

4.1.1 Approach

This section presents a framework for analyzing how specific remote sensing assets can provide products that inform specific operational decisions and actions. The *operational use case framework*, Figure 16, adapts the TCPED process to an emergency management decision making context. It allows system engineers to anticipate the steps required to leverage data from a given sensing asset for a specific purpose.

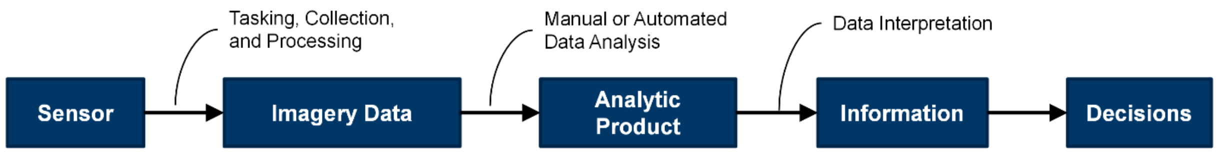


Figure 16. Operational use case framework. This flowchart captures the primary outputs and main process steps for using sensors to inform decisions. Reversing this process, we identify sensors that can provide useful information to fulfill stakeholder use cases.

Borrowing graphic convention from the field of system dynamics, the boxes in this framework are stocks, or state variables, and the arrows are flows, or rate variables that describe how one stock is converted to the next. The first three items (sensor, imagery data, analytic product) are physical stocks and the last two (information, decisions) are information stocks.

TABLE 10

Descriptions of Variables in the Operational Use Cases Framework

Variable Name	Variable Type	Description
Sensor	Asset	A specific sensing asset and the platform on which it is collected
Tasking, Collection, and Processing	Process	Through tasking, collection, and processing, sensors yield imagery data
Imagery Data	Product	L1, L2, and L3 image tiles and layers, including orthoimage mosaics hosted by web services. The required image processing and final product is different for data from each sensor; imagery data can be used for situational awareness, documentation, and validation
Analysis	Process	Manual or automated analysis, including machine learning
Analytic Product	Product	GIS data layers, annotations, or data points; analysis products can stand alone and need not be delivered with the imagery data from which they are derived
Interpretation	Process	Translating data into information
Information	Non-tangible output	Actionable data, or data that have been summarized and formatted to convey specific facts about disaster conditions,

		organizations, the position of resources, etc.; provides context for and can influence decisions and actions. Information might come in the form of a dashboard, situation report, briefing, or infographic that summarizes and presents data derived through analysis; can be quantitative or qualitative
Synthesis	Process	Combining imagery-derived information with other pieces of information to inform decisions and actions
Decisions and Actions	Non-tangible output	Conclusion, resolution, and subsequent activities based on understanding numerous pieces of information

Although presented linearly, there is not only one solution for using a sensor to provide useful information. Rather, for example, the same piece of information could be derived from multiple different data sources, or the same sensor can be used to create a variety of data products. To capture some of this complexity, we also conceptualized this framework as a relational database. As we developed use cases, we tracked each of these variables in a Microsoft Access database following this structure.

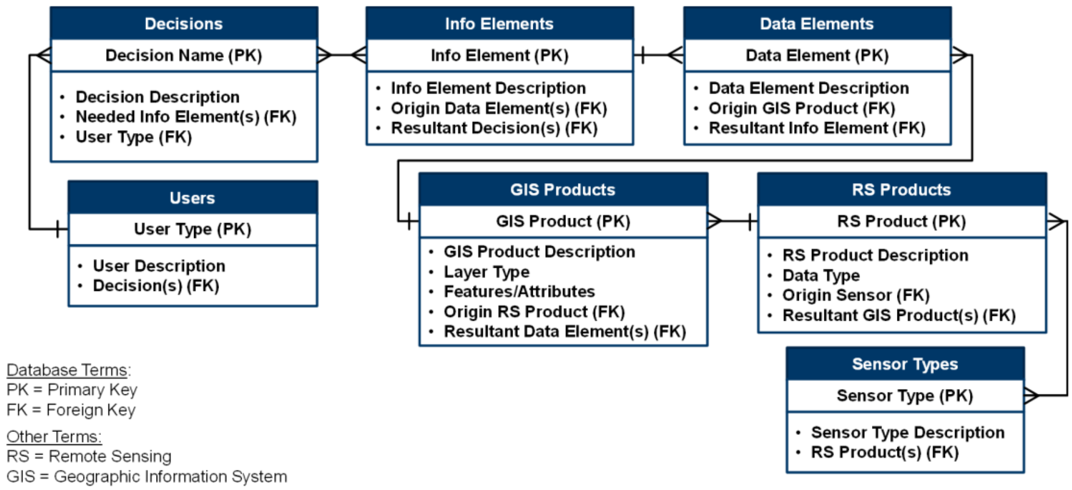


Figure 17. Representation of the operational use case framework as a relational database.

We combined first-hand experience and observations from recent disasters with a review of relevant literature on the use of imagery in disaster response and emergency management doctrine. We created a record of stakeholders, decisions they frequently make, and specific pieces of information often used in decision making. The following documents were used in this review.

- IA Geospatial Damage Assessment Guidelines [47]
- FEMA PDA Guide [48]

- Post-Disaster Damage Assessments at FEMA and The ARC [49]
- Max Assistance IHP memo FR [61]
- Huyck, C. et al. (2013). Remote Sensing for Emergency Response and Recovery. FEMA [16]
- Imagery use cases and system requirements [42]
- FEMA Public Assistance Program and Policy Guide [62]
- FEMA. (2016). NRF Emergency Support Function #1 – Transportation Annex. [63]
- FEMA. (2016). National Response Framework. [64]
- FEMA. (2020). Public Assistance Program and Policy Guide. [62]
- FEMA. (2015). Geospatial Framework. Response Geospatial Office. [35]
- FEMA (2014). Post-Disaster Damage Assessment at FEMA and the ARC Draft. [49]
- FEMA. (2020). Preliminary Damage Assessment Guide. [48]
- FEMA (2021). Individual Assistance Program and Policy Guide. [65]

We limited this review to decisions and information that has both physical and geographic relevance, to things that can be sensed. In addition, rather than simply recording the multitude of possible use cases noted in Section 2.4, we selected several common use cases for known stakeholders.

4.1.2 Stakeholders

We considered four main types of stakeholders: those in emergency operations centers (EOCs) who collect information and coordinate operations, field staff who carry out operations, the individuals and communities impacted by disasters, and staff involved in recovery operations. TABLE 11 lists specific stakeholders within each category, selected roles these stakeholders assume during disasters, and several of their key activities.

TABLE 11

Selected Stakeholderes, Roles, and Actions

Category	**Selected Organizations**	**Selected Roles**	**Selected Key Actions**
Emergency Operations Centers (EOCs)	• FEMA National Response Coordination Center (NRCC) • FEMA Regional Response Coordination Centers (RRCCs) • Joint Field Offices (JFOs) • State/Local/Tribal/Territorial (SLTT) EOCs • Voluntary Agency EOCs • Other Federal Agency (OFA) EOCs • FEMA Incident Management Assistance Teams (IMAT)	• Situational Awareness Section/ Geospatial Information Unit (GIU) • Remote-Sensing Coordinator • Response Coordination Staff Chief • Resource Support Section Chief	• Allocate, disburse, and deploy resources • Coordinate and direct field operations • Consolidate and synthesize information • Share information among partners • Public messaging
Response Field Actors	• First responders (firefighters, police, emergency medical services) • Urban Search and Rescue (USAR) • Voluntary Agency disaster assistance teams (e.g., American Red Cross) • FEMA Disaster Survivor Assistance • Commercial partners (e.g., Walmart)	• Technical Information Specialist (TIS) • Planning Team Manager (PTM) • Preliminary Damage Assessment (PDA) teams	• Lifesaving and life sustaining activities (e.g., rescues, medical services) • Delivery of emergency goods and services (e.g., food, water, medical) • Sheltering operations • Emergency repairs (e.g., tarps) and lifeline restoration (e.g., generators, road repairs, emergency communications) • Register survivors for programs and assistance • Damage assessments • Establish field offices
Survivors	• Community Based Organizations • Individuals, Families, Households	N/A	• Evacuations • Repairs • Seeking and requesting assistance • Regular patterns of life

Recovery Program Staff	• FEMA HQ/Regional/JFO Individual Assistance staff • FEMA HQ/Regional/JFO Public Assistance staff • SLTT Emergency Management Agency staff • Debris removal contractors • Insurance companies	• Program Delivery Managers • Site Inspectors • Claims adjusters • Contractors	• Damage assessments • Develop, approve, execute plans for repair and reconstruction • Oversee and monitor debris removal operations • Identify sites for temporary housing and other facilities

4.1.3 Decisions and Information Needs

Attributes of decision making in emergency management include the following.

- Timing
- Location
- Type
- Quantity
- Availability
- System capacity

We identified three themes common to many users: identifying hazard boundaries, understanding the status of and navigating road networks, and assessing structural damage to infrastructure and residences. Since residential damage assessments are slightly more standardized than assessing damage to infrastructure, we elected to focus on residential damage assessments only at this time. Emergency managers also frequently wish to have a visual picture of impacts to provide situational awareness.

TABLE 12

Common Decisions and Information Needs that Meet Needs for Many Stakeholders

Common Decisions	**Common Information Needs**	**Suggested Information Products**
• Issue disaster declarations • Allocate and distribute resources (staff, supplies, equipment) • Navigate in the field • Prioritize activities (rescue, repairs) • Provide funding, financial assistance	• What is the affected area? • What is the severity, count, and location of damaged structures? • Which routes are navigable and what is the best way to enter the impacted area? • Situational awareness	• Disaster extent/boundary • Structural damage assessments • Road network status layer • Visual imagery

Selected use cases that tie stakeholders to data products are listed in TABLE 13 and summarized in Figure 15. We translated these needs into four information products frequently requested during disasters: disaster extent/boundary, structural damage assessments, road network status, and visual imagery. Each product is described in more detail below. For each category, we developed user stories for a number of these stakeholders to more clearly articulate known needs and desired uses for overhead imagery. User stories are based on literature, observation, and personal experience of the research team. For each information need, we link specific user stories, information needs, and decisions.

TABLE 13

Use Cases for Imagery-Based Data Products

	Organization	**Decision/Action**	**Essential Element of Information**	**Data Product**
EOC	ESF 6, ARC Response	Determine what resources to deploy, quantity, and where to send them	Geographic locations of greatest damage	Hazard boundaries
Field	ESF 6, ARC Response	Determine optimum routes for service provision	Location and severity of road damage	Road navigability
Recovery	FEMA Recovery	Activate Transitional Sheltering Assistance (TSA) program	Number of homes destroyed	Structure-level damage assessments
Recovery	FEMA Recovery	Authorize rental assistance rate increases	Damage assessment summary figures	Structure-level damage assessments

Recovery	FEMA Recovery	Activate crisis counseling	Severity and concentration of damage	Road navigability
Recovery	ARC Recovery	Level of assistance provided to each survivor	Residential damage assessments by structure	Structure-level damage assessments
EOC	ARC Response, ARC Recovery	Direct fundraising and staffing decisions	Estimated scale and budget of disaster operations	Hazard boundaries
EOC	ESF 9	Allocate search and rescue resources	Geographic locations of greatest damage, number of people affected	Hazard boundaries
Field	ESF 9	Conduct search and rescue operations	Locations of hazards and navigable roads	Road navigability
Field	ESF 1	Conduct emergency repairs of roads and transportation systems	Locations of road and transportation system damage	Road navigability
EOC	Remote-Sensing Coordinator	Task remote sensing assets, manage data	Regions likely to sustain greatest damage	Hazard boundaries
EOC	Response Coordination Staff Chief	Coordinate and direct field operations	Regions of greatest damage	Hazard boundaries
EOC	Resource Support Section Chief	Determine what resources to deploy, quantity, and where to send them	Geographic locations of greatest damage	Hazard boundaries
Field	US&R Planning Team Manager/Technical Information Specialist (TIS)	Determine US&R search perimeters	Geographic locations of greatest damage	Hazard boundaries
Field	Preliminary Damage Assessment (PDA) teams	Recommend or request presidential disaster declarations by county	Total estimated cost of assistance for uninsured homes and personal property losses, Total estimated cost of repairs to public	Structure-level damage assessments

			infrastructure, by category	
Survivors	Community-based organizations	Prioritize and request assistance for repairs	Locations and severity of damaged homes and infrastructure	Structure-level damage assessments
Recovery	Public Assistance Program Delivery Managers	Complete and submit grants for applicants	Determine whether damage was caused by the incident	Structure-level damage assessments
Recovery	Public Assistance Site Inspectors	Document damage caused by incident	Descriptions and dimensions of damage sustained to infrastructure	Structure-level damage assessments
Recovery	Individual Assistance Individuals and Household Programs Staff			
Recovery	Recovery GIS Analysts	Support decisions for housing grants and program services	Residential damage assessments by structure	Structure-level damage assessments
Private Sector	Insurance Adjusters	Issue payouts against claims	Assessment of cost damage for each insured structure	Structure-level damage assessments
EOC	State Governor	List evacuation orders	Active hazard has passed and conditions are suitable to return	Visual imagery
Survivors	Families and individuals	Return after evacuating	Status of home and roads	Structure-level damage assessments

4.1.4 Private Sector Needs Assessment

To complement the information needs assessment for public sector emergency managers, we also briefly interviewed and synthesized results from private sector actors through the MIT Lincoln Laboratory iCorps program. In March and April 2022, we conducted eight unstructured interviews. We found that information products valuable to emergency managers also would fill important information gaps in the private sector.

We identified four potential markets for rapid satellite imagery and information products, summarized in TABLE 14.

TABLE 14

Private Sector Use Cases for Remote Sensing in Disasters

Customer Segment	Value Proposition
Business Continuity for Consumer Goods	Rapid remote asset status
Logistics/Transportation	Confident routing during disasters
Insurance	Rapid payouts, property protection, and reduced fraud risk
Emergency Management Consultants	Enable emergency managers to use 21st century geospatial technology

Other key findings from private sector interviews are as follows.

- Timely and accurate information related to disaster extent is extremely valuable
- For insurance companies
    - Field teams deploy to policy holder homes and could leverage more timely information (wildfires)
    - Non-disaster risk assessments would benefit from imagery
    - Insurers already consume imagery, but it isn't always timely enough or of high enough quality (clouds)
- For business continuity, logistics, and transportation providers
    - Dynamic situation after disasters challenges interstate logistics
    - Even basic assessments (e.g., is a parking lot flooded?) is useful, when timely
    - Post-disaster routing is key to movement of people and supplies
- For emergency management consulting groups
    - Automated home damage assessments would support equitable recovery outcomes
    - Hard to measure the effect of mitigation and resilience efforts
    - We treat no news as good news, but it isn’t always so.
    - Having immediate information is helpful

4.2 DISASTER EXTENT AND HAZARD BOUNDARIES

Knowledge of the *extent of the hazard* or *hazard boundaries* is a key piece of information, especially early after a disaster happens. Hazard boundaries on their own are used to triage field activities and, later on, for documenting the nature of the incident. More importantly, when combined with geospatial data on facilities, critical infrastructures, and demographics, hazard boundary data can provide critical information on possible impacts.

4.2.1 User Stories for Hazard Boundary Products

Identifying hazard boundaries from imagery is well established in literature and practice. TABLE 15 lists several specific stakeholders and decisions they make that can be informed by knowing hazard boundaries.

TABLE 15

Decisions and Information Needs Related to Hazard Boundary Products

Stakeholder	Decision/Action	Information
Search and Rescue	Triage search and rescue operations	Extent of the impact area and search area; known locations of floods, fires
Response Leadership	Early decisions about declarations, resource requirements, allocations	Extent and severity of impacts
Remote-Sensing Coordinators	Locations to collect high-resolution aerial imagery	Which areas should be prioritized for additional imagery collection?
State and FEMA Recovery Staff	Determine eligibility for assistance based on hazard exposure	Was a facility located within the hazard boundaries?

The following user stories illustrate how knowing the location of ongoing hazards and the extent of damage informs decisions and actions.

- As the FEMA NRCC RGO, I need to acquire the disaster extent as a spatial dataset that can be used to support numerous analyses on a local machine and be redistributable via AGOL to OFA.
- As the RRCC GIU, I need to acquire the disaster extent as a spatial dataset that can be used to support numerous analyses on a local machine and be redistributable via AGOL to SLTT.
- As the FEMA JFO GIU, I need to acquire the disaster extent as a spatial dataset that can be used to support numerous analyses on a local machine and be redistributable via AGOL to OFA, SLTT, and the public

- As the FEMA JFO GIU, I need to update the disaster extent as new spatial datasets are created with a more precise measurement of the extent.

- As a local emergency management GIS analyst in an intermittent, low-comms environment, I need to the disaster extent so that I can perform analysis to support numerous decisions.

- As a USAR TIS/PTM, I need to know the boundaries of the disaster, relative to concentrations of housing, to focus SAR efforts, and I need to be able to work with this data locally, acquired when communications are available.

- As a survivor I need to know how the impact area correlates to my home and services required for living (e.g., grocery)

4.2.2 Product Descriptions and Requirements for Hazard Boundary Products

The following types of hazard boundaries provide essential information to emergency managers.

- **Flood extents and depth grids** – polygons of flood extents, spatial grids indicating the maximum flood depth. Traditionally flood grids are produced days to weeks after a flooding incident. Trained crews, often from the U.S. Geological Survey, go into the field and observe indications of flood edges, such as water marks on buildings and deposited sediment. Observations are combined with digital elevation models to produce a map of flood boundaries. Flood extents can be derived from multispectral imagery and synthetic aperture radar using known automated approaches or manual annotation.

- **Debris field, wind field, and damaged area** – line and polygon data indicating the extent and centerline of storm tracks (e.g., tornadoes, hurricanes) or damage caused by other incidents. Traditionally, damage assessment teams from the National Oceanic and Atmospheric Administration (NOAA) develop wind and storm track data by observing the location and nature of damage.

- **Shake maps** – topographic maps indicating the magnitude of seismic activity. These are produced from ground sensors managed by the U.S. Geological Survey and are extremely timely already. Satellite remote sensing is not needed to produce shake maps.

- **Ground deformation maps** – raster data or topographical maps indicating land lift or subsidence following seismic incidents. These maps can be produced using synthetic aperture radar and are frequently made using Sentinel 1 SAR.

- **Landslide movement maps** – polygon and raster data indicating where land has shifted (red/blue).

- **Active fire and fire perimeter products** – point locations for fire starts and polygon perimeters updated in near-real time.

- **Burned area and scorch mark boundaries** – polygons.

TABLE 16 below lists key observables for detecting hazard boundaries and requirements for hazard boundary data products.

TABLE 16

Observables and Requirements for Hazard Boundary Products

Relevant Observables	Key Data Product Requirements
• Ground deformation • Active fire • Scorch marks • Shoreline recognition • Open water • Debris field • Ground scarring	• Must detect a larger area than is actually impacted in order to confidently differentiate the impacted area • Should have pre-incident imagery • Should combine with foundational data layers. • Should be delivered through web-hosted feature services and applications

4.2.3 Examples

Hazard boundary products are frequently created and disseminated by NASA Disasters, Copernicus ERS, the International Charter, and other data providers. Although often based on fairly coarse resolution imagery, these products provide valuable information in days-to-weeks following major incidents. An example is NASA's ARIA program, which generates damage proxy, flood proxy (Figure 18), and land deformation products.

Figure 18. JPL ARIA, Flood Proxy Map, Flooding in Midland, Michigan 2020.

4.3 NAVIGATION AND ROAD DAMAGE

Knowing the location of road damage and whether roads are passible informs field operations and triage. The envisioned road navigation product would be a GIS layer that shows the locations of flood, debris, and road washouts that impede passage. This section includes user stories, a product description, and documented methods for road damage detection.

4.3.1 User Stories for Road Damage Products

Identifying hazard boundaries from imagery is well established in literature and practice. TABLE 17 lists several specific stakeholders and decisions they make that can be informed by knowing hazard boundaries.

TABLE 17

Decisions and Information Needs Related to Road Navigation Products

Stakeholder	Decision/Action	Information/Data Element
Search and Rescue	Routes to take for USAR operations	Which roads are navigable? What is the optimal route to priority locations?
ESF 1: Transportation (DOT)	Identifies temporary transportation solutions; coordinates long-term repairs	Locations and severity of damage to transit systems and roads
ESF 6: Mass Care	Distribution of emergency supplies; provides critical transportation services	Transportation infrastructure damage
State and Federal Recovery Staff	Describe and document road damage and repairs	Location, date of damage, date of repairs

The following user stories illustrate how knowing the location of road damage and whether roads are passable informs decisions and actions.

- As the FEMA NRCC RGO, I need to support other federal agencies with transportation system status, including major disruptions. To support their routing analyses, this data needs to be available for offline and online integration into network routing tools.
- As the FEMA JFO GIU, I need to be able to track road network status and update as road conditions improve
- As a USAR TIS/PTM, I need to know what roads are passable to enable ingress/egress planning.

- As a survivor I need to know how the transportation network has been impacted so I can determine: Can I get home, evacuate, get to services such as hospital, doctor, pharmacy, shelter, grocery store?

4.3.2 Product Descriptions, Key Observables, and Requirements for Road Damage Products

An ideal road navigability product will indicate the current state of roads, the nature of damage, and whether a vehicle can transverse damaged road segments. Four categories of navigability include: fully passable, partially obstructed, limited access, no access. The product should be delivered as an edge and node road network that can be optimized for routing. Damage points should be indicated as point or line features and should link to source imagery for additional situational awareness. The product should be lightweight for mobile access in low-connectivity environments. Figure 19 shows a mockup of what this product might look like.

Figure 19. Mockup of a road navigability product.

TABLE 18 below lists key observables for detecting hazard boundaries and requirements for hazard boundary data products.

TABLE 18

Observables and Requirements for Road Navigability Products

Relevant Observables	Key Data Product Requirements
• Pavement recognition • Pavement obstruction • Pavement damage • Inundation • Vegetation • Miscellaneous debris	• Available within 24 hrs, refreshed daily • Must be able to detect obstructions or damage as small as 1.2 m at least • Ideally can differentiate between debris, pavement damage, and water • Can identify routes of entrance and egress to affected areas • Needs to show actual roads, not only road network data

In addition, Figure 20 includes specifications for detecting different levels of road damage. Roads may be impeded by pavement damage and washouts, debris (usually vegetation), and flood. If severe, any of these modes of road damage might render a particular road inaccessible. Therefore, it is important that road damage products treat roads as polygons extracted from the image. Damage attributes can then be used to enrich road network data, either from foundational data layers or also extracted from imagery. Since foundational data do not exist for all regions, both feature extraction and classification are needed to determine whether a road is passable, the nature of the damage, and the extent of needed repairs.

Passable Category	Damage Width	Damage Distribution	Debris Obstruction	Water Inundation
Fully Passable	<10% of road width (0.6m)	< 5 damage sites per km	< 10% of road width (0.6m)	< 2 inches
Partially Obstructed	<20% of road width (1.2m)	< 10 damage sites per km	< 20% of road width (1.2m)	< 4 inches
Limited Access	<40% of road width (2.4m)	< 10 damage sites per 0.5km	< 40% of road width (2.4m)	< 6 inches
No Access	>60% of road width (3.6m)	>10 damage sites per 0.5km	> 60% of road width (3.6m)	> 6 inches

Figure 20. Road navigability depicted by impedance type [66].

4.3.3 Current Approaches for Automated Road Damage Products

Although road damage images can be manually exploited, automated analysis approaches can enable rapid product development and dissemination. Automated analysis is essential for delivering products during the period when it is most useful. This section briefly mentions notable tools and approaches.

Academia has produced numerous approaches to evaluating road damage with computer vision techniques. Overhead imagery paired with road network data provides a basis for rule-based processes for damage detection and classification. Algorithmic workflows may include georegistration of pre- and post-incident images, masking the analysis area to features of interest, detecting road edges, detecting other line features that define roads, identifying road segments that have not been damaged, and detecting damage based on spectral and radiometric features [67].

Recently, machine-learning approaches have been widely tested for detecting road damage. A notable example from researchers at William and Mary used crowdsourced road quality observations and satellite imagery to compare transfer learning performance across a number of neural networks pre-trained on ImageNet data, including ResNet50, ResNet152V2, Inceptionv3, VGG16, DenseNet201, InceptionResNetV2, and Xception. Each model was pre-trained on ImageNet [68]. Trained models were able to achieve 94% accuracy in determining quality of roads in Nigeria.

In addition, companies are beginning to develop products for road damage analysis. SeerAI[2] (an ESRI partner) used aerial imagery collected by NOAA after Hurricane Ian for to demonstrate a capability that uses a U-net neural network to identify and classify road damage and identify traversable routes [69]. They developed a road obstruction deep-learning model, trained by their data scientists on tens of thousands of human-annotated training samples, to accurately classify drivable surfaces, road debris, flooded roads, and damaged roads at the pixel level on images with a resolution from 30–50 cm.

Item 10 (road damage using edge detection) indicates that having good pre-disaster reference data makes solving the disaster needs possible with relatively simple techniques. Perhaps more energy should be spent developing and applying techniques for automating the generation of pre-disaster reference data, and perhaps that is an easier problem to solve post disaster.

Although any of these approaches can be used to deliver a road damage and network product, selected solutions will likely need to be adapted to anticipated data sources and sensors used in standard operations.

4.4 DAMAGE TO RESIDENTIAL STRUCTURES

Structural damage assessments inform field operations and decisions on providing assistance. This section documents use cases and user stories for imagery-derived damage assessment data products, explanations of several national-level damage assessment processes, and descriptions of useful products. Although "damage assessment" refers to a broad array of activities, spanning assessment of damage to agricultural land and forests, public infrastructure, businesses, and cultural assets, we have focused the discussion on damage to residential structures, which include houses, condominiums, apartment buildings, and trailer parks.

[2] https://seer.ai

4.4.1 User Stories for Residential Damage Assessments

Conducting structural damage assessments with imagery, sometimes called "geospatial damage assessments" is increasingly common. The count and severity of damage to homes, in particular, is a key piece of information early on in response and recovery. TABLE 19 lists several specific stakeholders and decisions they make that can be informed by imagery-based structure-level damage assessments.

TABLE 19

Stakeholders and Decisions They Make Using Information on Residential Damage

Stakeholders	Decisions/Actions	Information/Data Elements
Search and Rescue	Type and quantity of resources to deploy; priority search areas	Building damage level; search areas
American Red Cross	Logistics decisions, routing	Geographic locations of greatest damage
American Red Cross	Level of assistance to provide to survivors	Geographic locations of greatest damage; damage level to individual homes
Federal and State Response Leadership	Request, recommend, or approve housing assistance programs for jurisdictions	Damage assessment summary figures
Federal and State Recovery Staff	Validate and document damage for housing assistance grants	Damage level to individual homes

In addition, the following user stories shed light on how this information is used.

- As the FEMA NRCC RGO, I need a spatial dataset to support rapid, virtual damage assessments. To do this, the data must report damage using the FEMA PDA damage scale and be spatially accurate enough to spatially correlate with financial/parcel data to estimate damage costs on a per county/per capita basis.
- As the FEMA JFO GIU, I need to be able to reconcile initial PDA observations with site inspection data.
- As a USAR TIS/PTM, I need to know the clusters of structural damage, and be able to acquire these data for local analytical use when communications are available.
- As a survivor, I need to know if my home has been damaged, and if so, how badly. This helps me determine whether it is safe to return if I've evacuated or have an idea of what to expect when applying for FEMA assistance.

Two national-level damage assessment processes deserve more detailed treatment: Preliminary Damage Assessments (PDAs) and geospatial damage assessments for FEMA's Individual Assistance (IA) program.

PDAs are early damage assessments conducted by local, state, and federal emergency managers in the immediate aftermath of an incident. During PDAs, which may be conducted jointly or sequentially by staff at each organizational level, staff typically go into the field to document the estimated cost to repair damage to homes and infrastructure [48]. For residential structures, the cost is estimated based on the severity of damage to structures, typically categorized as no damage, affected, minor damage, major damage, or destroyed. These statistics are used to substantiate requests for financial assistance at the state and federal levels.

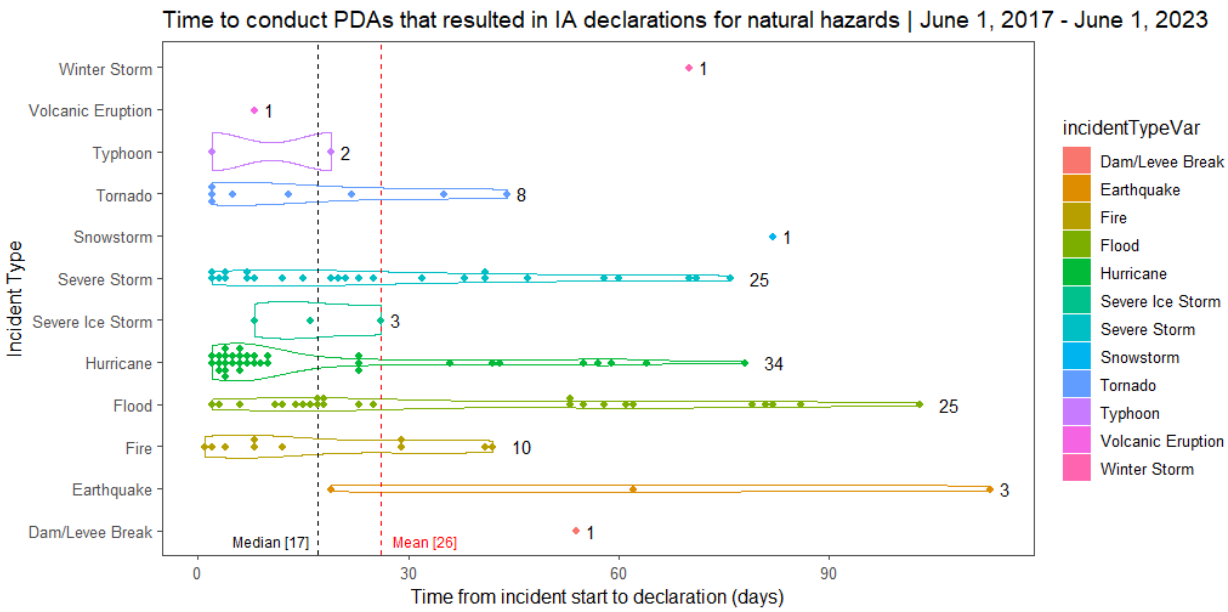


Figure 21. Preliminary damage assessments that result in declarations authorizing Individual Assistance grants take weeks to finalize for many incidents. On average, between 1 June 2017 and 1 June 2023, PDAs that resulted in federal declarations authoizing IA took an average of 26 days and a maximum of 113 days. Data are aggregated to the state level, reflecting the time to the last IA declaration for a given incident.

At the federal level, assistance is authorized through Presidential Disaster Declarations, which are issued on a per-county basis. Declarations may approve the use of federal funds for housing grants and other assistance to individuals and families through the Individual Assistance program, administered by FEMA. The Public Assistance program analogously provides federal funding to restore public infrastructure. Other agencies also provide grants for disaster recovery, though these are not discussed at length here.

PDAs are typically a lengthy process of verification. Damage assessments must be performed by official parties and counts of damaged structures must be agreed upon by local, state, and federal authorities. In an analysis of FEMA’s declaration data published on FEMA.gov, we found that between 1 June 2017, the beginning of the 2017 hurricane season, and 1 June 2023, FEMA authorized the IA Individual and Households Program for 1290 counties across 114 disaster declarations, visualized in Figure 21. For 50% of incidents, declarations took 17 days. On average, 26 days elapsed before all counties were declared (see Figure 21 and Appendix E for more details).

Once a declaration has been issued, making a county eligible to receive individual assistance, FEMA program staff and contractors conduct structure-level damage assessments, following a similar affected/minor/major/destroyed scale. Typically, these assessments are conducted in the field with paper forms or tablets. The results of the inspection, along with information provided by an applicant when applying for assistance, are used to determine the amount of funding an applicant is eligible to receive.

Recently, both PDA and IA staff have begun using overhead imagery to conduct early damage assessments, thereby expediting decisions to issue declarations and assistance grants, in accordance with FEMA’s 2020 Preliminary Damage Assessment Guide [48]. The process for geospatial damage assessment to decision is summarized in Figure 22. Currently, damage assessments are conducted through visual analysis, where staff view imagery in a GIS application and annotate editable feature services with the damage level. Program staff at the federal level are also aligning the criteria they use to determine the level of damage (affected/minor/major/destroyed) to reduce duplication of effort. With visual imagery as a foundation for these assessments, the damage determination for each home can be verified independently by staff across program areas.

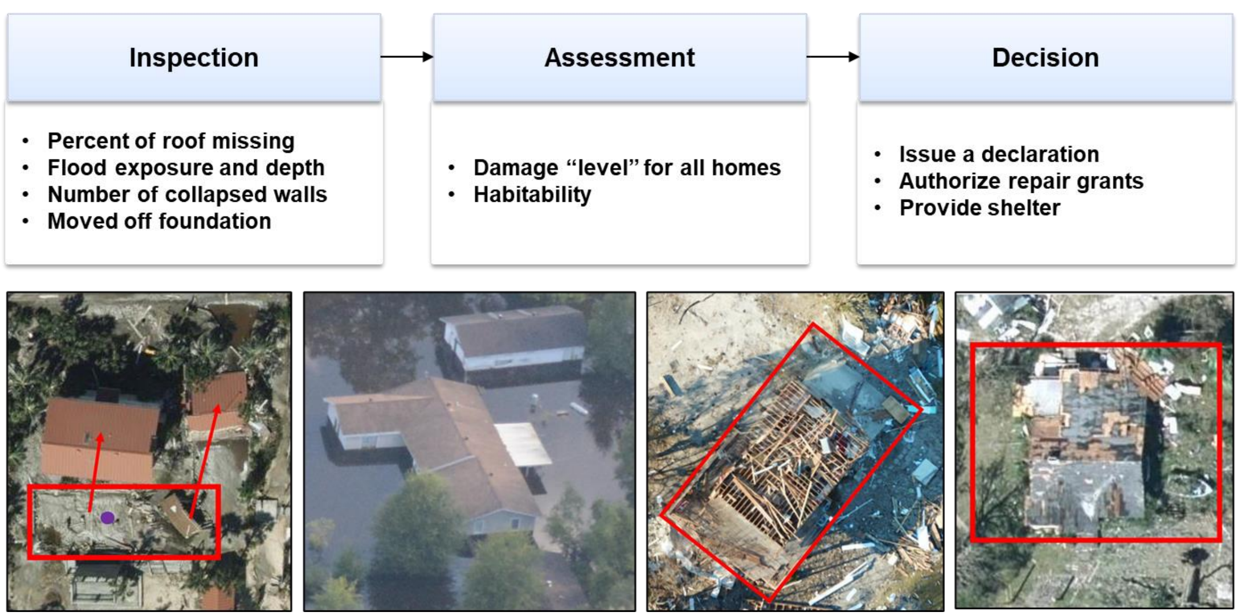


Figure 22. Summary of damage assessment process for PDAs and IA, with examples of homes that have sustained damage in different ways that can be evaluated with optical imagery. From left to right, homes can be moved from their foundation, inundated, have collapsed walls, or sustain roof damage [47].

4.4.2 Description, Key Observables, and Requirements for Residential Damage Assessment Products

An ideal residential building damage assessment product for the above use cases includes an imagery layer that can be visually analyzed by lay users and a point or polygon layer that indicates the level of damage to all residential structures of interest following the PDA damage assessment scale. Figure 23 presents an example produced by the Civil Air Patrol (CAP) in 2020 with annotated and colorized building outlines.

Figure 23. Example of a residential damage assessment product. The underlying images were collected by CAP, and structure level damage assessments produced by a subcontractor for FEMA after a tornado in in Jonesboro, AR 2020. The color scale is as follows: purple is destroyed, red is major damage, orange is minor damage, yellow is affected, and green is unaffected.

Key observables of interest include roofs, blue tarps on roofs, walls and rubble, debris, building foundations, flood extent and depth, burned debris, lava flows, and the presence of hazards in the vicinity of the house. TABLE 20 provides a summary of required observations for many of these observables based on documents shared by FEMA staff. In addition, residential damage assessment products benefit from meeting the following qualitative requirements.

- Enable an easy determination of the number and severity of damaged homes and other summary statistics of demographics
- Timing: product is most useful when delivered within the response timeframe
- Resolution: must be sufficient to count collapsed walls, determine the percent of roof missing, evaluate the depth of water, and view whether other hazards have affected the structure
- Area: must cover all populated areas of affected counties to provide damage counts that support declaration requests

TABLE 20

Common Indicators of Building Damage Level [47]

Damage Level	Roof	Walls	Foundation	Interior	Water
No Damage	No change to roof	No evidence of damage to walls or exterior structures	No damage	Not exposed	No water surrounding structure
Affected	Blue tarp or missing shingles	Cosmetic damage only: siding, gutters, screens	No damage	Not exposed	Standing water: in, or was in
Minor	Up to 1/3 has substantial damage, including visible holes	Damage to windows, doors, or siding, but not collapsed	No damage	Not exposed	Standing water: in, or was in
Major	2/3 or more of roof is missing or collapsed	More than 1 wall collapsed or major holes in more than 1 wall	Structure moved off	Some exposed	Evidence of flooding
Destroyed	Entire roof is missing or collapsed	All walls collapsed	Compromised	All exposed	Up to roof

4.4.3 Current Approaches for Automated Residential Damage Assessments

At this time, damage assessments are largely done manually. Groups of trained analysts look at available images of houses and contribute to a shared feature service of damage assessment annotations. Automated approaches are becoming more and more widely available as well.

However, imagery-based structure damage AI/ML algorithms are rapidly developing and being adopted. Assessing structural damage from fires is more accurate than floods. Location plays a significant role in the performance of AI/ML algorithms since geographies and geologies vary widely along with architectural trends and construction materials. This section presents several examples of current efforts to use AI and machine learning for structural damage assessments.

Damage assessments are often broken up into two tasks, building detection and damage classification [70, 71]. Examples from both industry and academic literature are now exploring the ability to fine-tun pre-trained models using limited labeled examples [71, 72]. In addition to emergency management, the insurance industry is driving the need for rapid post-disaster damage assessments.

A key dataset in the open development of damage assessment models is the xBD dataset developed by the Defense Innovation Unit (DIU). In 2019, DIU ran a prize challenge called Xview2 to crowdsource damage assessment models that perform well on the xBD dataset [73]. Solutions have been demonstrated in many disasters, and are starting to be used operationally as an input to expedite manual damage annotations.

4.5 SITUATIONAL AWARENESS ORTHOIMAGERY

Situational awareness is a broad term use to describe making sense of complex situations where neither the decision points or information needs are known a priori. Imagery is a powerful tool for providing information that decision makers did not know they needed by communicating a large amount of information visually. Though difficult to quantify, visuals are frequently requested and highly valued, especially in the early hours or days after a disaster when little information is available. This section briefly summarizes user stories and requirements for imagery products that provide situational awareness.

User stories are as follows.

- As the FEMA NRCC RGO, I need to enable general situational awareness for all federal partners in the NRCC. To visualize the impact of a disaster, I need the boundaries as a spatial dataset that can be redistributed via AGOL. Any visuals available such as imagery, must also be available for efficient sharing via AGOL products.

- As a local emergency management GIS analyst in an intermittent, low-comms environment, I need to be able to pull down imagery once, while we have connection, and use that to generate paper products to support decision making.

- As a USAR TIS/PTM in an intermittent, low-comms environment, I need to be able to pull down imagery once, while we have connection, and use that to generate paper products to support decision making.

- As a survivor, understanding what the disaster looks like can help me understand and process all of the information I receive from various sources.

Optical imagery processed into orthomosaic tile layers or photogrammetrically generated 3D models are currently the technology best suited to provide situational awareness at scale. These imagery products can be delivered through image tile services and displayed in web maps for easy interactivity. Key requirements for products that provide situational awareness include the following.

- Available within the first 12–24 hours of an incident

- Can easily be accessed and interacted with by a non-technical user

- Can easily be interpreted by a non-technical user

- Delivered in a lightweight format for field deployments

Spatial accuracy and delivery timing is an important trade-off with respect to orthoimagery. High-precision, high-accuracy processing can take considerable time. High spatial accuracy is more important with regard to automated analysis when an algorithm may leverage spatial data from several co-registered datasets to derive outcomes. However, for simple viewing, less accuracy is required. Further analysis of requirements for spatial accuracy is out of the scope of this report.

5. REQUIREMENTS ANALYSIS

Current efforts to employ satellite remote sensing in disasters, and those documented in literature tend to follow a trial-and-error approach. A disaster happens, emergency managers acknowledge the present information gap, and any resources that are physically and bureaucratically available are tasked to collect imagery. Domestically, success stories focus on catastrophic disasters. As discussed in Section 0, this function is critical not only in the most severe disasters, but equally for disasters that cause billions of dollars in damage and lead to loss of life and property without making the national or international news.

In this section, based on the use cases described in Section 4.1, we have proposed a set of requirements for satellite remote sensing-based data and information products. This section specifically focuses on requirements for products, not for satellites themselves. This requirements analysis seeks to balance needs and desires with what is currently physically and operationally feasible. Therefore, the analysis presented here considers both technical and operational constraints, including considerations of sensor design, platform design, operating procedures, and policy. Physical performance constraints include spatial, spectral, radiometric, and temporal resolution, sensor duty cycle limits, data transfer rates and storage capacity, and internet services. Operational constraints include tasking and scheduling limits on sensor time, resources, end user license agreements, and standard operating procedures.

Requirements were evaluated through literature review, experience and observation, informal interviews and conversations with practitioners, and quantitative analysis. For each of the following categories—timeliness, area coverage, and resolution—we discuss minimum, acceptable, and ideal data product specifications.

5.1 TIMELINESS AND TEMPORAL RESOLUTION

One of satellite imagery's main value propositions is that it could be available more quickly than imagery collected with aerial assets, and that repeat collections can be easily coordinated. But how soon is soon enough? Is there a time period that is "too soon" to collect imagery? To answer these questions, we first identified three different types of collections for which timeliness matters: pre-incident imagery, immediate post-incident imagery (response), and post-incident repeat collections (recovery).

Across each time period, the duration of peril is a common factor that affects the ideal timeliness of satellite imagery. Some incident types continue to cause damage over an extended period of time. For tornadoes and Earthquakes, damage typically occurs within a few hours (pending aftershocks, liquefaction, ongoing severe weather). For these incidents, capturing imagery within several hours of incident onset is ideal. Hurricanes may impart damage over the length of a day or more. Continued cloud cover poses obstacles for optical imagery collection from any assets, and continued strong wind and rain prevent aerial assets from flying. For hurricanes, the optimal collection period is several hours after the skies have cleared, which may be 24 hours or more after incident onset.

Floods, wildfires, and volcanic incidents continue to evolve and cause new damage over an extended period. Two pieces of information are crucial: the real time extent of the hazard and the maximum extent of the hazard. Wildfire burned area and lava flows are detectable after the hazard has subsided, but detecting the maximum extent and depth of a flood is tricky since flood boundaries change continuously as water moves. Traditionally, high water marks are observed and marked in the field by experts. For these incidents, timeseries data collected at regular and frequent intervals can provide real-time and post-hoc situational awareness.

5.1.1 Pre-Incident Imagery

Pre-incident imagery is essential for post-incident analyses [16, 42, 47] and is used for the following.

- Identify changes visually or algorithmically
- Determine whether damage was caused by the current incident, caused by a different incident, or pre-existing
- Geolocate features in images if damage is severe enough to be unrecognizable
- Run some feature classification models

Ideally, pre-incident imagery would be collected as close as possible to disaster onset. Several models have been suggested for capturing useful pre-incident imagery.

- Collect imagery over the entire country once a year
- Collect imagery over high-risk areas 3–4 times a year
- For hurricanes, collect imagery over urban settings within a storm's projected impact area 2–3 days in advance of landfall; in recent years, several partners have adopted this model with varying degrees of success

Based on recent incidents, pre-incident imagery collected within the last 3–6 months seems to be adequate for completing visual damage assessments and need not come from the same sensor. The creation, destruction, and modification of structures and natural features are the greatest confounders for imagery taken prior to this period. If multiple incidents occur within a few months of each other—for example, Hurricanes Laura and Delta, which both affected Louisiana in 2020—imagery collected in between the co-located incidents is essential for determining which incident caused what damage post-hoc.

5.1.2 Immediate Post-Incident Imagery

Although some sources report that imagery is most useful for response decision making within the first 100 hours after an incident [5], surveys of state and local emergency managers in the U.S. have indicated that imagery-derived information on building damage, critical infrastructure damage, and transportation damage is most useful within 24 hours of an incident and becomes only moderately useful after 72 hours [32]. Case study analysis has implied that imagery available the next day can be used to assess damage, support a declaration, and gauge resource requirements [16]. Figure 24 and Figure 25 present findings from studies conducted at the University of South Carolina to gather evidence on the timeliness required for imagery to be useful.

If imagery is collected too late, field teams have already evaluated the situation and assessed damage manually. Although imagery maintains its value for documenting damage, there is a zero-sum game where its value is reduced when information is provided by other means. However, if imagery is collected too early, the imagery could show only part of the damage that the incident will ultimately cause. Cascading impacts may also lead to ongoing damage. Depending on the type of natural hazard and imaging modality, collecting too early might yield images obscured by clouds or smoke.

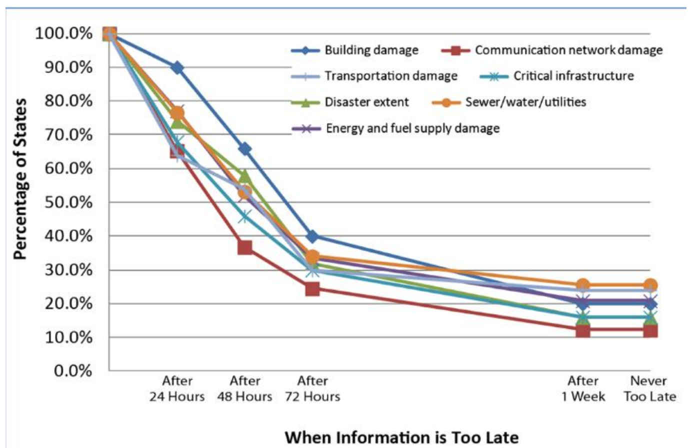


Figure 24. Empirical curve derived from state responses for when post-disaster imagery information is too late for the emergency response phase, reproduced from [41].

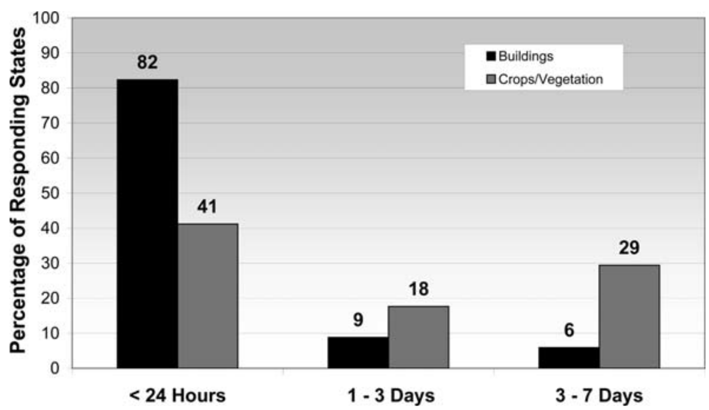


Figure 25. Information regarding damage to buildings or crops/vegetation needed within a specified time period after a disaster incident, reproduced from [33].

Therefore, there exists a disaster-specific time window in which the first imagery collections are most useful. The window of maximum utility varies according to several incident-specific factors.

- **The spatial extent of damage [**Direct relationship]. Emergency managers need to know where disaster impacts occurred *and* what areas were unaffected. No news is not necessarily good news, and thus the entire extent of the potentially impacted area needs to be observed. Damage that is concentrated in a fairly small area can easily be captured in aerial images with a few overhead flights. Damage that is spread out over multiple states requires more resources. Because it would take longer to collect imagery over the whole area with other types of assets, the window of maximum utility for satellite imagery is longer if the spatial extent of damage is wider.

- **Availability of other imaging resources** [Inverse relationship]. In some regions, such as the U.S. Territories, aerial imaging resources are less available than in states frequently affected by disasters. In these cases, the window of maximum utility for satellite imagery is longer because it would take longer to deploy sufficient aerial resources to these locations.

- **Field team access and other information sources** [Inverse, complex relationship]. As the quantity and mobility of field teams and other information sources increases, they obviate the need for rapid information from remote sensing. Interestingly, remote sensing can also obviate the need for field operations if reliable.

- **Operational tempo** [Direct relationship]. Rapidly unfolding incidents have an operational period of 6–8 hours, which typically ends with a briefing or meeting to convey the most up to date information. Some incidents have longer operational periods of 12–24 hours. Under current processes, the operational period indicates the shortest time within which imagery is useful. If a 12-hour period is established, having imagery within 12 hours is most useful, since insights can then be shared at the end of the operational period.

- **Incident period** [Direct relationship]. For disasters that continue to unfold over the course of days or weeks, an extended incident period may be declared that simplifies later administrative processes. Imagery collected at the end of the incident period is useful for capturing the final state of damage, even if intermittent images are captured as well.

In summary, satellite imagery is most valuable when it is delivered before aerial imagery, before field crews observe damage directly, as soon after the incident as possible, and, for extended-duration incidents, as frequently as possible and/or at the end of the incident period.

Based on our experience and observation of recent unfolding disasters, we suggest that the window of maximum utility for information derived from satellite imagery is typically 12–24 hours after incident onset. After two days, aerial or UAS imagery is frequently widely available and field crews are assessing damage. For our mathematical approach to optimizing across different timeliness criteria, see Section 6.6.1.

5.1.3 Post-Incident Repeat Collections

After an incident occurs, time must elapse before a second collection yields useful insight. During the first week of an incident, or during the incident period, daily collections offer useful insights for the following information needs.

- Near-real time extent of flood, fire, or other ongoing incidents
- Estimates of the number of damaged homes and the severity of damage
- Road damage and emergency repairs; routing options
- Debris volume estimation
- Site selection for temporary facilities and relief centers

Over time, the utility of frequent repeat passes is reduced. During the first 2–3 months after a Type 1 or Type 2 incident has stabilized, weekly updates may be useful for observing the construction of temporary housing facilities, monitoring debris removal operations, and documenting repairs. Monthly updates for an additional 6–9 months may be useful for monitoring recovery. For Type 3 incidents, monthly repeat passes for 4–6 months may be sufficient.

5.1.4 Recommended Timeliness Requirement

The constraining requirement for timeliness is rapid post-incident tasking. Ideally, satellite imagery-based data products would be delivered for each incident within 12–24 hours for all Type 1, 2, and 3 incidents. Pre-incident imagery collected within days of an incident, and repeat collections for several months are also useful.

5.2 AREA COVERAGE

Disaster declarations are made by county, based on a federally determined per-capita estimated damage cost indicator. If the estimated cost of damage, averaged out over the county population, exceeds a certain threshold, published annually in the U.S. Federal Register, the county becomes eligible to receive various types of federal disaster assistance. Though the cost of damage in a major urban area readily exceeds the per-capita indicator, sometimes damage is spread over a wide area and it takes weeks or months to demonstrate that the county is eligible, delaying recovery and incurring administrative costs. Ironically, due to a risk-averse and bureaucratic emergency management culture, the disasters that are least severe—and therefore more frequent—demand the highest administrative burden up front, thereby delaying recovery, occupying personnel, and consuming resources.

5.2.1 Collecting Sufficiently Large Area

Satellite remote sensing, capable of collecting imagery over large areas in a small timeframe, offers the potential to expedite recovery by providing improved awareness of damage across counties. From an image analysis and data management perspective, the efficient solution collects imagery only over the areas where damage occurred. However, since the locations of damage are not certain until days after the incident, a larger area must be collected—ideally entire counties for completeness. If delivered within 24 hours, satellite imagery could be used to direct more efficient aerial imagery collections through a tip-and-cue architecture. Similarly, SAR data could be used to tip and cue the collection of high-resolution optical imagery from space. To determine minimum area collection requirements, we analyzed the size of counties in the U.S. and the frequency with which they experience disasters.

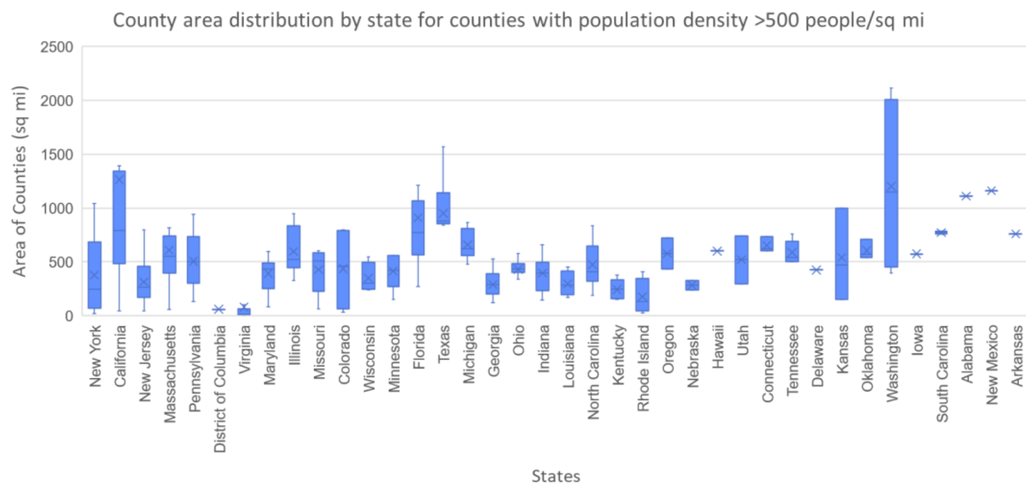


Figure 26. Distribution of the size of U.S. counties, in square miles, bucketed by state based on data from the 2010 U.S. Census.

Figure 26 shows the area size distribution of counties in each state. Since the U.S. has a large number of counties with very low population density, these data are filtered to show counties that have an average population density greater than 500 people per square mile (266 out of 3142 counties) for visualization purposes. Population density indicates the presence of urban and suburban developments; when natural disasters occur here, they require a more coordinated response than incidents in rural areas since more people are affected and more property subject to damage[3]. The average size of all counties in the U.S. is 1124 square miles, and the average size of these 266 densely populated counties is 482 square miles. Area data and population are based on the 2010 census[4].

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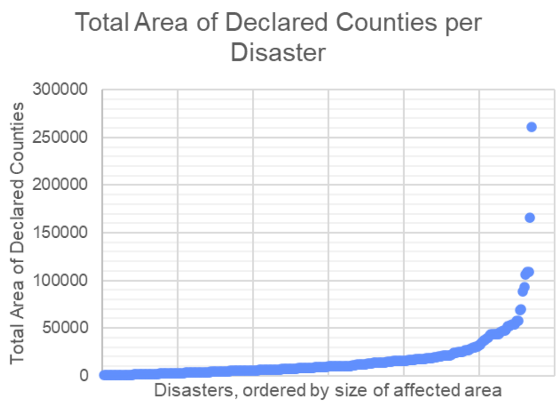
[3] Although agricultural incidents, which occur in rural areas, are equally concerning and severe, managing incidents that threaten life and property requires coordination among a larger group of actors and are the focus of this study.

[4] County area and population were downloaded on 6/6/2023 from https://www.openintro.org/data/?data=county_complete.

Merging this county area data with FEMA's data on disaster declarations[5], we calculated the total area declared for disasters that occurred between 1 January 2017 and 7 June 2023. Ordering disasters by total area impacted gives us a visual representation of the distribution of county areas. Below, we have included summary statistics and plotted these data on both linear and logarithmic scales to provide a sense of the spread across four orders of magnitude.

Ideally, the entire impacted area would be collected on the first day to provide wide-area situational awareness. We see that for 50% of disasters that have occurred in the last six years, 3,900 to 17,800 square miles is ultimately declared. The average area declared is approximately double the mean, indicative of a skewed distribution where a small number of disasters have very large areas declared. Although these values have a large variance, they indicate that having the ability to collect **20,000 square miles** of imagery would provide full coverage of the impacted area for more than 75% of incidents.



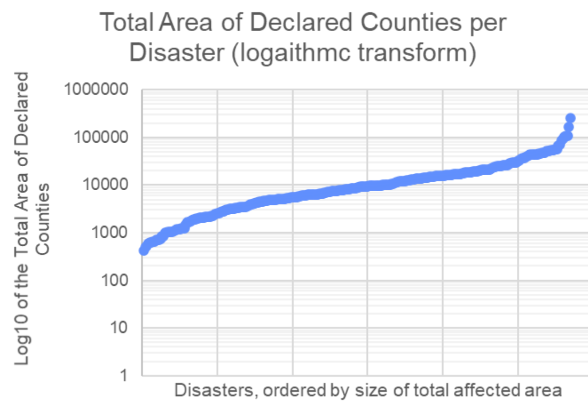


Figure 27. Total area of declared counties for incidents that occurred 1 January 2017 to 7 June 2023 (available data at the time of analysis). County size data are from the 2010 U.S. Census, and disaster declaration data are from FEMA's open data portal.

One limitation of this analysis is that area was determined on a per-declaration basis, not a per-incident basis. Even if an incident affects multiple states, each state receives a unique disaster declaration number. For accounting purposes, federal disaster declarations have a unique number for each state. Future analyses could explore the total area impacted per incident by correlating incident start dates and types of peril.

[5] https://www.fema.gov/api/open/v2/DisasterDeclarationsSummaries.json

TABLE 21

Distribution Statistics of the Total Area Declared, by Disaster Number

Total Declared Area (sq. mi)	
Minimum	426.3
First Quartile	3964.7
Median	8826.7
Mean	16166.8
Third Quartile	17876.2
Maximum	261231.8

5.2.2 Collecting the Right Area

A secondary challenge is to identify which counties are likely to sustain damage. Currently, satellite imagery tasking requests are made based on forecasts and predicted impacts. FEMA has developed a tool called the Prioritization and Operations Support Tool (POST), which has recently been incorporated into a web-hosted model called TEMPO[6]. These tools combine forecast weather and hazard impact data with the social vulnerability index and other foundational infrastructure data layers to indicate populations or other assets that are likely to be impacted. Though these resources are still evolving, they are becoming a valuable resource for prioritizing remote sensing tasking based on near-real time data and forecasts.

5.3 SPATIAL RESOLUTION

Spatial resolution of images is quantified as *ground resolved distance* (GRD), *ground sample distance* (GSD), pixels per meter, or pixel size, which, though different, all relate to the size of features that can be resolved. Required spatial resolution for disaster imagery has been a topic of much debate.

We have approached the question of resolution is needed by articulating the operational value gained from increased resolution. In this section, we present evidence from various sources that supports the expected utility of imagery at 0.25 m GSD, 0.5 m GSD, and 1 m GSD. Sources generally agree that above 1.5 m GSD, the utility of imagery for providing operationally relevant response information is greatly reduced.

5.3.1 Literature on Spatial Resolution

Several reports indicate that 0.25 m GSD imagery or better is required for emergency management use cases [18, 30]. A 2011 report commissioned by FEMA explored uses of remotely sensed data to conduct damage assessments after tornadoes in Joplin, MO; Tuscaloosa, AL; and Birmingham, AL. They describe three levels of damage assessment: determining the geographic extent of visible damage, profiling the

[6] https://tempo.nltmso.com/

severity of damage by square kilometer, and conducting structure-level damage assessments [30]. For the latter, they found that 25 cm aerial imagery was ideal for determining the level of damage to buildings. Conversations with and observations of users support the claim that 0.25–0.3 m GSD imagery is good enough, but still subject to criticism.

The proliferation of commercial and public high-resolution overhead imagery tools (e.g., Google Earth) raises suspicions that spatial resolution requirements, in particular, are subject to *monotonicity of preference*. This economic principle says that an increase or improvement in a good or bundle of goods is always preferred. Given the choice, emergency managers would always choose the higher-resolution imagery, and as members of society, emergency managers are quite aware that it is possible to collect and widely disseminate high-resolution overhead imagery. Online mapping platforms leverage a combination of carefully processed satellite and aerial imagery from multiple platforms to produce high-resolution image maps. These activities take many months and are not feasible to complete within the disaster response timeframe. However, since commercial and public satellites currently achieve a maximum spatial resolution of 0.25 m GSD, which are occasionally delivered within or close to the disaster response timeframe, it comes as little surprise that this is the preferred resolution for satellite imagery.

Other sources support that 1–1.5 m spatial resolution is good enough and that the main operational benefit is increased perceived confidence and the ability to detect minute damage. A 2012 cognitive study conducted at the University of South Carolina found that, for panchromatic imagery, resolutions finer than 1 m GSD did not improve interpretability in a statistically significant way, and that 1.5 m GSD was the threshold for acceptable resolution [31].

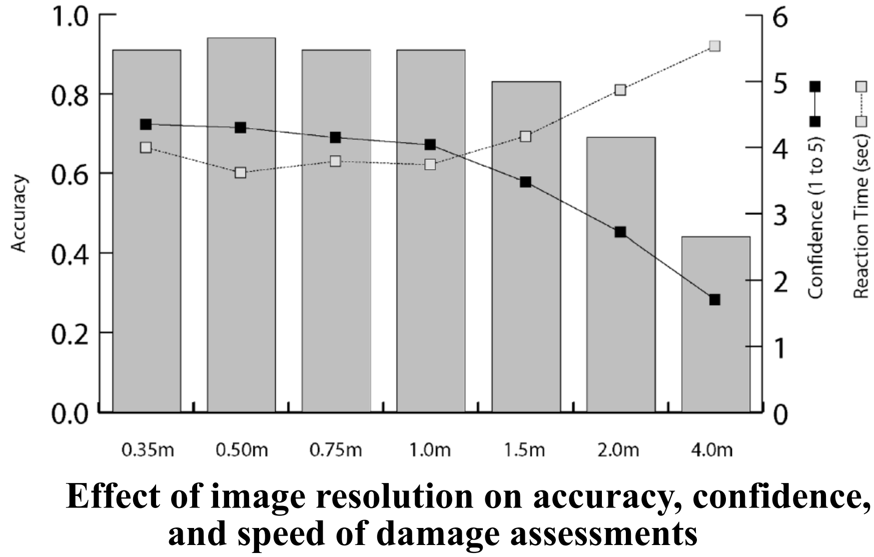


Figure 28. Relationship between image resolution and accuracy, reaction time, and confidence aggregated across experience levels, from [31].

The literature is inconclusive. Since few objective studies exist and we can presume that higher-resolution is always preferred, the focus of this requirements analysis shifts from what resolution is needed to what resolution is achievable.

5.3.2 Qualitative Resolution Analysis

From Chapter 4, we have a qualitative list of requirements for spatial resolution. Users must be able to perform the following actions.

- Detect the extent of hazard boundaries
- Detect and recognize roads obstructions
- Identify the nature and size of road obstructions
- Recognize damaged residential structures
- Identify the level of damage to residential structures
- Visually scan images to recognize facilities of interest and the status of those facilities

Several standards exist that relate resolution to image interpretation. The National Image Interpretability Rating Scale (NIIRS)[7] was developed by the U.S. intelligence community to describe the quality of images and imaging systems based on the ability to detect, distinguish between, and identify[8] objects or features of different sizes. NIIRS defines nine levels of interpretability and ascribes resolution ranges to each, according to what types of features can be identified. Levels 5, 6, and 7 all contain examples of features relevant to emergency management, reproduced in TABLE 22. NIIRS offers qualitative guidance on the marginal benefits of improved resolution for applications in emergency management.

TABLE 22

NIIRS Resolutions Associated with Observables Related to Emergency Management Use Cases

Level 5: 0.75–1.2 m GRD	Level 6: 0.40–0.75 m GRD	Level 7: 0.20–0.40 m GRD
• Identify individual lines painted on paved roads, aprons, parking lots (NIIRS 5.1) • Identify individual telephone/electric poles in residential neighborhoods (NIIRS 5.4) • Identify fallen utility poles (NIIRS 5.5)	• Identify pole-mounted electrical transformers in residential neighborhoods (NIIRS 6.4) • Detect small road signs (e.g., stop, yield, speed limit) in an urban area (NIIRS 6.6) • Identify building materials of urban structures (e.g., brick, wood, concrete, stucco, tile, adobe) (NIIRS 6.8)	• Identify individual above ground utility lines in a residential neighborhood (NIIRS 7.1) • Identify a manhole cover (NIIRS 7.1) • Identify a fire hydrant (NIIRS 7.2) • Identify individual asphalt shingles on a residential roof (NIIRS 7.9)

5.3.3 Quantitative Resolution Analysis

This section presents an alternative approach to calculating the maximum viable pixel resolution based on the size of objects we wish to resolve.

[7] https://irp.fas.org/imint/niirs_c/app2.htm

[8] Another approach, sometimes called the probabilistic determination approach, defines three levels of interpretability: detection, recognition, and identification (DRI). This approach considers the probability of either detecting that a feature is a target of interest, recognizing the type of target (e.g., a building), and identifying the specific class of that type (e.g., house, commercial, municipal, or damage level). These terms are defined differently than they are used in NIIRS. An extension of the DRI model is the Detection, Observation, Recognition, and Identification (DORI) standard, defined in the IEC EN62676-4: 2015 International Standard, was not considered here, but could provide direction for future analysis.

Based on the Nyquist–Shannon sampling theorem, which states that a sample rate is sufficient if it is at least twice the frequency of a signal, and its adapted use in microscopy, at least two pixels are needed to resolve an object. Hengel and McBratney [74] suggest that for Earth observation applications, the same principle can be applied to determine a minimum pixel resolution sufficient to distinguish between objects or land areas of a known size. They suggest that a minimum of two pixels are needed to identify long observables, and that a 2×2 grid (4 pixels) is needed to detect observables with more equal proportions.

In cartography, the minimum legible delineation (MLD) is smallest area that can be mapped, traditionally limited by cartographic tools and visual acuity. For Earth observation applications, pixel size and MLD can be related mathematically [74]. Where a is the area of the smallest object, r is the radius of a circle with the same area, w is the width of the narrowest object, S is the shape complexity index, and P is the perimeter of a polygon, pixel size p can be calculated as

$$r = \sqrt{\frac{a}{\pi}}$$

$$S = \frac{P}{2\pi r}$$

$$p \leq \begin{cases} \sqrt{\frac{a_{MLD}}{4}} \; if \; S < 3 \\ \frac{w_{MLD}}{2} \; if \; S > 3 \end{cases}$$

From the use case analysis in Chapter 4, roof damage and pavement damage are two of the smallest observables identified. Pavement damage is critical when it impedes access, though determining precise dimensions is also useful in recovery. For residential damage assessments, determining whether a building has been "affected" or not requires identifying whether shingles have been damaged.

For simplicity, we used width MLD to calculate ideal pixel size for road damage and area MLD to calculate ideal pixel size for homes, summarized in TABLE 23. We estimated that individual shingles are 12 inches by 36 inches[9] and that roof fractions are based on the average size of a home in the U.S., which several roof repair websites quote as 1700 sq ft[10][11].

The results shed light on the added value of increased spatial resolution. When damage is severe, 1 m spatial resolution or coarser is sufficient to capture multiple pixels of the observable. This is sufficient for most operational response applications. However, sub-meter resolution is required for informing decisions

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[9] https://austinroofingandwaterdamage.com/what-are-asphalt-roofing-shingle-sizes/

[10] https://www.prestigeroofinglv.com/how-much-does-a-new-roof-cost

[11] https://roofkeen.com/how-many-square-feet-is-the-average-house-roof/

that require more detailed analysis of individual structures, such as structure-level damage assessments for affected homes or grants for minor road repairs that remain costly, even if less urgent.

TABLE 23

Maximum Viable Pixel Size to Detect Observables of Interest

Category	**Observable**	**MLD Dimension**	**Pixel Size (ft)**	**Pixel Size (m)**
Road Damage	Fully passable	<0.6 m	0.98	0.30
	Partially obstructed	0.6–1.2 m	1.97	0.60
	Limited access	1.2–2.4 m	3.94	1.20
	No access	2.4–3.6 m	5.91	1.80
Residential Damage Assessments	Individual shingles	3 sq ft	0.87	0.26
	1/3 roof	566 sq ft	11.90	3.63
	2/3 roof	1133 sq ft	16.83	5.13
	Total collapse	1700 sq ft	20.62	6.28

The drawback of this analysis is that in practice, more than four pixels are generally needed for an analyst to evaluate the level of damage to a home. However, the results give credence to empirical findings that 1 m GSD is sufficient for assessing the level of structural damage to homes [44]. Although there is no one correct answer, these results provide a sense of the added benefit of higher-resolution data—the higher the resolution, the more useful the data in non-catastrophic, but still impactful incidents.

5.4 SENSING MODALITY SUITABILITY COMPARISON

The following characteristics of sensing modalities are useful during disasters.

- Can distinguish proximate objects or materials (e.g., through spectral or radiometric sensing)
- Achieves high spatial resolution from space
- Can sense through adverse atmospheric conditions or smoke
- Can sense at night
- Is late-TRL such that automated processing and analysis tools exist

Numerous sensing modalities are now available in space. TABLE 24 provides a high-level comparison of the state of the art in space-based multispectral, hyperspectral, synthetic aperture radar, and lidar capabilities. These four sensing modalities are generally accepted as well-suited to providing actionable information to emergency managers during disasters.

TABLE 24

Sensing Modality Comparison

	MSI	**HSI**	**SAR**	**Lidar**
Highest Current Spatial Resolution	0.25 m GSD (e.g., Maxar)	30 m GSD (EnMap)	0.25 m GSD (e.g., Iceye)	25 m GSD (GEDI)
Night Capability	Nighttime lights	Nighttime lights	Full imaging	Full imaging
Clouds/Weather	Impeded	Impeded	Full imaging	Impeded
Smoke Capability	Some capability in IR spectrum	Some capability in IR spectrum	Full imaging	Impeded
Power Required	Low	Medium	High	High
Existing Automated Analysis Methods	In use	Immature	Mature, occasional use	Immature
Visual Interpretability	Intuitive	Spectral data may be reduced	Requires trained analyst	Requires some training

Multispectral imaging and synthetic aperture radar (SAR) are currently used to collect post-disaster information and generate data and information products relevant to emergency managers. Though not yet standard practice or executed efficiently, precedent shows that both are capable of providing actionable information.

HSI systems are not yet able to achieve high enough spatial resolution from space, since the increase in spectral resolution corresponds with a decrease in spatial resolution using current technology. Lidar requires significant power draw and compute resources, which are not yet available in small space systems. In addition, the optical wavelengths typically used are subject to atmospheric interreference.

In general, active sensing modalities enable sensing at night, though passive sensors may also shed light on the severity of disaster conditions through nighttime lights analysis. SAR, as a microwave sensing modality, has the added benefit of penetrating clouds and adverse atmospheric conditions as well. Appendix D provides an analysis of the likelihood that cloud cover precludes capturing clear satellite images within three days of an incident.

In summary, SAR and multispectral optical imagery are the two capabilities most readily available and applicable to emergency management use cases. Together, they provide both intuitive image products and rapid sensing in the immediate aftermath of an incident, even when inclement weather conditions persist.

5.5 HUMAN FACTORS REQUIREMENTS

Across case studies and experience, three main categories of human factor issues frequently prevent imagery satellite imagery from being used effectively and efficiently during disasters: delivery format, data use policies, and cost.

5.5.1 Delivery Format

Although new tools are increasingly available for working with GIS and remote sensing data, the number of people who have expertise in both remote-sensing processing and analysis and in emergency management is woefully small. In an EOC or in the field, data and imagery products need to be delivered in a format that is intuitive, familiar, and use-friendly. Important requirements are listed here.

- REST services: use OGC-compliant REST services
- Low bandwidth: deliver through web apps and applications developed for low-connectivity environments
- Intuitive: deliver data through easy-to-use applications that require minimal training
- Consistent: data are delivered through a familiar platform and users know where to look for it
- Analysis ready: data should be prepared for subsequent analysis, especially when image pairs are available

Ideally, data products are delivered through REST services or other APIs, allowing end users to stream data directly into web maps, applications, and dashboards for visualization and subsequent analysis. Data products should be formatted as OGC-compliant vector data feature service supporting points, lines, and polygons with export support. Raster data products, such as imagery and depth grids, should be delivered as WMTS services.

Services and applications should allow imagery to be downloaded for areas of interest for including in reports and access in low-connectivity environments. Data products should be delivered as phone- and computer-consumable visualizations of boundaries, damage assessments, road status, and raster imagery with address lookup capability. Road status products should enable routing that accounts for road network blockages.

Since most emergency managers are not experts in remote sensing, delivering products in a format that is intuitive and requires little training is essential. For example, traditional tile-based ordering and download platforms require that users know how to open and interact with image files and have sufficient bandwidth to download large imagery files.

Data need to be delivered through a consistent pathway or system. Ideally, new imagery would be easy to find through a search engine. Data-sharing portals like FEMA’s Geospatial Resource Center and the NASA disasters mapping portal are examples of systems that emergency managers can rely on for identifying and accessing new data, at least for severe incidents. Many data providers now offer paid user access through proprietary image-viewing systems. Since emergency managers rely on experience and training when making decisions under pressure and with incomplete information, delivering data products through a consistent venue is essential to enabling their use as a standard part of operations.

Finally, data need to be delivered analysis-ready for cases where subsequent analysis is anticipated. For example, image pairs should be co-registered, orthorectified, and with complete band information. When these data are stripped or image pairs are poorly correlated, additional analysis is not possible.

5.5.2 Data Use Policies/Access

Liberal data-sharing policies are essential for effectively using imagery for disaster response and recovery. Data sharing is extremely important during disaster response [41, 28, 75]. Emergency management is not a hierarchical enterprise. Successful responses require coordination across a large number of independent actors and organizations, including state, local, and federal agencies, voluntary organizations, and the private sector. Decisions are made through consensus, funding, and delegated authority. Sharing information is not only a core activity in emergency management, but it essential to having a well-coordinated response with minimal delay and duplication of effort. Frequently, effective use of satellite remote-sensing products is thwarted by data access and sharing policies. The main requirements are as follows.

- Authentication: no authentication required, or tokenized authentication available
- EULAs: liberal end-user license agreements enable data sharing across a wide number of partners

Authentication issues that limit usefulness come in two forms. First, the need to create an account, remember a password, and manage login credentials is deterring for many users. Second, access may be limited to specific user groups. Both design decisions limit the ability for new users to easily access data and incorporate them into operations. Since location-specific groups of stakeholders are involved in response, it is important that new users are easily and quickly able to locate and access data.

System policies aside, contractual language from data providers often limits data sharing. End User License Agreements (EULAs) issued to an organization that purchases data (often expected to be the federal government during national-level incidents [41]) often prohibit sharing imagery data and derived products within the purchasing organization, let alone with responding partners. If the data cannot be shared, they bear little value to responding agencies. Some data-sharing policies limit sharing to a 60- or 90-day window, which precludes the use of these products in recovery and future planning.

In short, to maximize the utility of satellite-based remotely sensed data and derived products, license agreements must enable broad data sharing and data delivery must be streamlined.

5.5.3 Cost Model

A challenge with offering liberal data-sharing agreements is that private sector organizations' business models are tailored to providing data directly to paying customers. Both tasked data and archival data have value. Operating satellites (and aircraft as well) is an expensive business, and private companies are beholden to investors to maximize profit. Unfortunately, a dissertation on the ethics of profiting from withholding information that can support life-saving and life-sustaining services and accelerate the restoration of stable society is beyond the scope of this study.

However, one of the reasons satellite imagery is only used for the most severe disasters is that high-resolution data must be purchased, and the resources to purchase these data are typically only available when the federal government is involved or when an incident is so severe that companies make data available pro bono through various data-for-good programs.

Natural disasters are, by definition, market failures. The demand for services far exceeds available supply for everything from safety and security to debris removal to construction materials. Looking at disasters through an economic lens, government funding remedies these market failures by creating a monopsonist system where essentially all emergency goods and services are ultimately paid for from federal accounts through procurements and grants. Fraud and price gouging are perennial concerns among the emergency management community.

As with other goods and services (e.g., mass care, medical services, feeding programs) that are offered by voluntary agencies, the only cost model that ethically and financially makes sense in disaster contexts is a non-profit or benefit-corporation model, where products may be given freely to those in need once the base costs are covered. In other words, once one entity has paid for disaster data, those data should be available at no-cost to the rest of the community.

Several aerial imagery providers have piloted this approach. Notably, CAP, which operates as a non-profit organization when supporting state needs, collects imagery at cost and makes all data available to the public through FEMA's ImageEvents[12] server. The National Insurance Crime Bureau for a time offered complementary gray-sky imagery to official response partners if collected at the request of paying customers from the insurance industry. This is a model that commercial satellite imagery providers should seek to emulate if their data are to provide the desired and advertised social benefit.

5.6 SUMMARY OF RECOMMENDED SYSTEM-LEVEL REQUIREMENTS

In summary, this chapter discussed requirements for satellite imagery-based data products that may meet the needs of emergency managers regarding the use cases described in Chapter 4. TABLE 25 summarizes these requirements and presents suggested acceptable and unacceptable ranges. An observation throughout is that more precise requirements enable satellite imagery products to be used for a wider range

[12] http://fema-cap-imagery.s3-website-us-east-1.amazonaws.com/

of incident types. Current practices provide some useful information during the most catastrophic incidents, but many moderate incidents are neglected all together.

TABLE 25

Summary of Requirements and Acceptable Ranges for Satellite Imagery-Based Data and Information Products

Category	Desired	Acceptable	Minimum	Unacceptable
Resolution	≤0.25 m GSD	1 m GSD	1.5 m GSD	3 m GSD <
Daily Area Coverage Capacity	20,000 sq mi ≤	10,000 sq mi	3,000 sq mi	<100 sq mi
Time from Incident to Deliver First Product	≤12 hrs	24 hrs	48 hrs	>72 hrs
Delivery Method	User-friendly interactive web interface	REST service	Data download, annotated PDF	Screenshots, L1 or L2 image data
Data Access	Shared with the public	Shared with partners	Shared within requesting organization	Cannot be shared at all, classified
Cost Model	Proactive tasking, free to all or most end users	Task orders on a per-incident basis under indefinite delivery vehicle, free to all or most end users	Task orders on a per-incident basis under indefinite delivery vehicle, paid access for each user	Separate procurement for each incident and each organization

To fully meet needs of the emergency management community and make satellite imagery a standard tool, high-resolution data must be available for every incident that requires coordinated response (i.e., Type 3 and above). The next chapter discusses a concept of operations and architecture to achieve this vision.

6. CONCEPT OF OPERATIONS AND SYSTEM ARCHITECTURE

In order for satellite imagery to be useful within the incident period, tasking, collection, data transfer, processing, analysis, and dissemination must all take place efficiently. This section presents a concept of operations for satellite remote sensing in disasters, followed by a discussion of the architectural elements needed to carry out these tasks, visualized in Figure 29. This section also describes a prototype data pipeline developed at MIT LL that leveraged the MIT LL AgileMicroSat (AMS) to demonstrate the DisasterSat architecture and concept of operations.

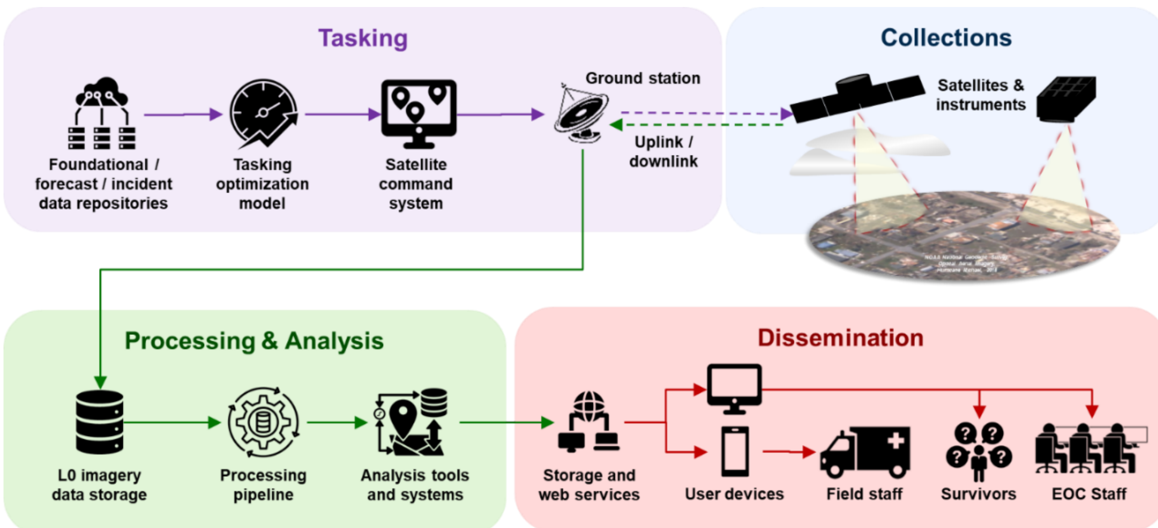


Figure 29. Visualization of core architectural components in the TCPED concept of operations for satellite remote sensing in disasters.

Satellite remote sensing during disasters requires more than the sensor and sensing platform. The assets must be tasked according to known priorities, data must be transferred, manipulated, and stored, and finished products must be delivered to end users. A key contribution from this analysis highlights the socio-technical components of this complex system, visualized in Figure 30.

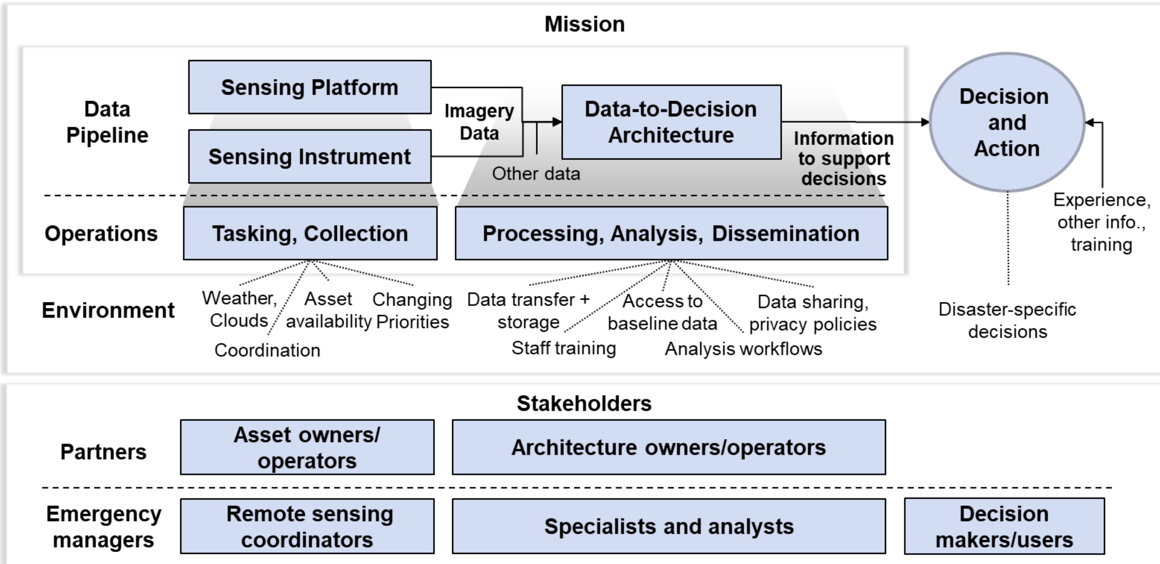


Figure 30. Socio-technical system map of key components and stakeholders involved in satellite remote sensing in disasters.

This section summarizes key architectural components that enable the concept of operations described above. Architecture includes hardware, signals, software, and data and the relationships between components. Although some components must be custom built, such as the tasking and collection management platform, existing services can provide many of the others, such as satellite ground infrastructure.

TABLE 26

Overview of the Concept of Operations and Architecture to Enable Effective Satellite Remote Sensing in Disaster Response

CONOPS Steps	**Associated Architectural Elements**
Tasking • Recognize hazard • Identify priorities • Optimize collections • Generate and push commands	Tasking tool • Foundational data • Hazard data and warnings • AOI management interface • Tasking optimization model Satellite command system
Collections • Uplink • Onboard command • Payload operations • Onboard processing • Downlink	Ground station network Communication links Space vehicle(s) • Payload(s) • Onboard computer and memory • Wiring and subsystems
Processing • Noise and pixel calibration • Atmospheric correction • Georegistration • Orthorectification (if appropriate)	Cloud or server-based system • Storage • Compute nodes • Data processing scripts • Webhosting services
Analysis • Manual analysis • Automated analysis • Spatial analysis • Interpretation	Analysis tools and systems • Storage • Compute notes • Analysis software or web apps • Automated analysis scripts • Geospatial product pipeline
Production and dissemination • Curate products • Publicize • Decide and act	Web mapping data portal • Hosted services and REST APIs • Intuitive web maps and applications End user devices • Apps or browsers

6.1 TASKING

Tasking should take place in the days preceding an incident and/or immediately following a no-notice incident. The goal of tasking is to direct assets to collect relevant imagery. This is notoriously difficult during disasters because of the decentralized nature of disaster decision making, the large number of independent stakeholders involved, and a large number of potential targets spread over a large geographic region. Four main steps are involved.

Step	Current Stakeholder	Relevant Inputs	Relevant Outputs
Recognize Hazard	Emergency managers	Meteorologic and geologic data, news reports	Warnings, initiate process
Identify Priority Collection Areas	EM remote sensing coordinators	Hazard forecast data, demographic and vulnerability data, foundational data	Prioritized points and areas of interest
Optimize Collections	Satellite operators	TLEs, prioritized collection points	Tasking locations and times
Generate and Push Commands	Satellite operators	Tasking locations and times	Commands ready for uplink

6.1.1 Hazard Recognition and Tasking Initiation

Currently, tasking is initiated ad hoc, where emergency managers communicate priorities to satellite operators. For no-notice incidents and technological disasters, news outlets and social media may also indicate the need for imagery. Due to the cost of commercial satellite imagery, FEMA or other federal agencies issue tasking requests for imagery, typically only for incidents that warrant federal support.

When possible, natural hazard severity thresholds should be used to initialize tasking. Although evaluating and recommending thresholds was outside the scope of this study, several federal services already provide alerts on the likelihood and severity of natural hazards.

- Earthquakes 4.0 or greater https://www.usgs.gov/media/images/alert-thresholds-shakealert
- NOAA warnings for non-precipitation incidents https://www.nws.noaa.gov/directives/sym/pd01005015curr.pdf
- NWS storm surge warnings https://www.nhc.noaa.gov/surge/warning/
- NOAA flood https://www.weather.gov/safety/flood-watch-warning

Future work should evaluate thresholds by comparing historic alert data with disaster declaration data. Ideally, the use of tasking thresholds ensures that data are collected for all incidents, not only the ones where an explicit request is made.

6.1.2 Tasking Prioritization

Currently, tasking priorities are identified based on a number of inputs.

- Field reports and situation reports
- Forecast data and impact models

- Foundational data layers/locations of critical infrastructure
- Demographic data and the Social Vulnerability Index
- Points of interest requested from leadership and field teams

Over the last five years, FEMA and New Light Technologies have developed the Tool for Emergency Management Prioritization and Operations (TEMPO)[13], which draws on numerous natural hazard datasets, foundational data, and demographic data to provide hazard risk monitoring. This tool indicates what areas are most likely to experience impacts from natural hazard incidents and attributes priority to 1 m U.S. National Grid squares. At this time, the tool must be manually initiated, but it could be automated in the future.

6.1.3 Collection Optimization

Tasking should optimize collecting priority targets as quickly as possible. There are a number of criteria that need to be considered when optimizing collections.

- Collection windows when a capable satellite will be overhead
- Type of incident
- Time since incident onset
- Priority level of targets based on exposure and demographics
- Time since last collection

We have designed a tasking model, discussed in Section 6.1, that optimizes collections based on the *utility* of a given image, where utility is a function of the factors above.

Once tasking commands are generated, they must be pushed to a satellite command system for uplink to the spacecraft. Tasking commands accompany commands for other spacecraft operations, including computer operations, thruster operations, and attitude control.

6.1.4 Tasking and Collection Management Platform

Tasking and collections should be centralized in a single system. For example, FEMA recently began using an ArcGIS Online web map to track remote sensing tasking priorities as a web-hosted GIS layer that can be shared with partners. Areas of interest are indicated with point and polygon data manually added by FEMA's remote-sensing coordinator during severe incidents.

[13] https://tempo.nltmso.com/

The tasking and collection management platform should allow emergency managers and satellite operators to jointly view tasking requests, windows of opportunity for collections, scheduled collections, and delivered data.

6.2 COLLECTIONS

6.2.1 Uplink, Downlink, and Ground Components

Commands are transmitted to the satellite through a ground station or ground station network. Several companies now offer global ground station links, including Ksat, Globalstar, and Amazon. Communications links from ground to space typically use S, X, Ku, or Ka band frequencies.

In a constellation, intersatellite links can reduce tasking delays by passing signals through satellites with a clearer view of the ground station. Relay architectures can also leverage services like NASA's Near-Space Network and the Tracking and Data Relay Satellite (TDRS) system.

Antenna design, modulation encoding, signal processing, and relay design were not considered in this study since a 24-hour or less tasking turnaround is now the industry standard. However, these aspects play a significant role in reducing latency and improving timeliness.

6.2.2 Satellite Constellation and Onboard Processing

In contrast to aerial assets, spacecraft carry out collections autonomously after receiving commands. Several key actions are essential for the spacecraft's onboard computer system to handle.

- Uplink: receive commands from the ground station
- Payload operations: instrument timing, look angle, duration, and other sensor parameters
- Attitude determination and control: stabilize spacecraft to enable payload operations
- Data management: image pre-processing and temporary storage
- Downlink: send data to the ground

Once received at the ground, the raw data must be transferred to a repository.

6.2.3 Alternative Concept

An alternative mission concept could leverage edge computing to process and analyze imagery onboard the spacecraft. Local networks could be established for transmitting data directly from a satellite to users. Although this architecture is desirable for disasters where communications networks are affected and for rapidly delivering insights to users who have user terminals, we chose not to analyze this option further at this time since disseminating data widely is a goal of the mission. The majority of disasters do not experience widespread communications outages. Data links and user terminals would need to be incorporated in community and state-level pre-disaster planning. This approach would require significant upfront product design that would be completed onboard the spacecraft. Transmitting directly to users is possible, but not easy. Use of the system would need to be incorporated into emergency management trainings, plans, and programs.

6.3 PROCESSING

Though necessary processing steps vary by sensing modality and according to specific sensors, there are several key processing steps generally required for all imagery data types.

- GeoTIFF parsing
- Pixel stretching
- Radiometric calibration
- Noise reduction for white noise, black noise, and dead pixels
- Atmospheric correction
- Orthorectification and mosaic processing
- Georegistration and co-registration

Synthetic aperture radar processing also often includes de-speckling and color channel selection. To make images interpretable for non-expert users, additional calibration and processing may be needed depending on the specific imager and data type.

Ideally, processing would happen automatically leveraging cloud hosting and compute services as data is downlinked. Data-processing pipelines require the availability and inclusion of foundational data and geodetic reference systems.

6.4 ANALYSIS

Like processing, analysis methods are highly specific to imagers and data products. However, there are four types of analysis relevant to this concept of operations, summarized in TABLE 27. Additional automated analysis approaches are discussed in Chapter 4.

TABLE 27

Analysis Types Relevant to Remote Sensing in Disasters

Analysis Type	**Description**
Manual Image Analysis	Ad hoc visual analysis for situational awareness, damage assessments, and answering specific questions about the status of facilities or operations Crowdsourcing may be used to expedite the annotation of imagery and creation of new datasets
Automated Image Analysis	Analysis scripts and machine learning models must be validated and integrated into workflows during non-disaster times; once established, these tools may be incorporated into an automated or semi-automated cloud-based or local data pipeline
Spatial Analysis	Combining imagery data with foundational data, forecast data, and other spatial data
Interpretation	Extracting useful information from imagery; these elements of information may be presented and disseminated in a number of formats, including situation reports, briefings, or through the dissemination platforms described below

Useful analysis combines imagery-derived information with foundational data and other geospatial response and recovery data. For example, understanding the impact to roads benefits from having road network and routing data. Understanding impacts to infrastructure and homes benefits from foundational data on the locations and nature of infrastructure and building footprints, respectively.

6.5 PRODUCTION AND DISSEMINATION

Three key steps for production and dissemination are as follows.

- Curate products
- Publicize
- Decide and act

Architectural elements include the following.

- Web mapping data portal
  - Hosted image and feature services delivered through REST APIs
  - Intuitive web maps and applications
  - Static information products where desired
- End user devices
  - Apps or browsers
  - Access and user management

Finished products may be displayed in EOCs, accessed on mobile devices in the field and at field offices, and distributed to disaster survivors. This is the most important step, where imagery and imagery-based products create real value for emergency managers.

Disseminated products can focus the area of interest for numerous subsequent activities, including field operations and damage assessments, and inform routing and resourcing decisions. Satellite-based products can also become part of a tip-and-cue architecture where results from low-resolution data can direct the collection of higher-resolution imagery with aerial assets.

6.6 DEMONSTRATION WITH MIT LINCOLN LABORATORY AGILE MICROSAT

Through this part of the program, we developed a prototype of the mission concept and proposed system architecture and completed several demonstrations with the MIT Lincoln Laboratory Agile MicroSat (AMS) during the 2022 hurricane season. The team built a tasking optimization tool for AMS, overcame challenges with data processing and georectification, developed a demonstration change detection script, and showed how resulting products could be used to produce operationally relevant information and delivered to users.

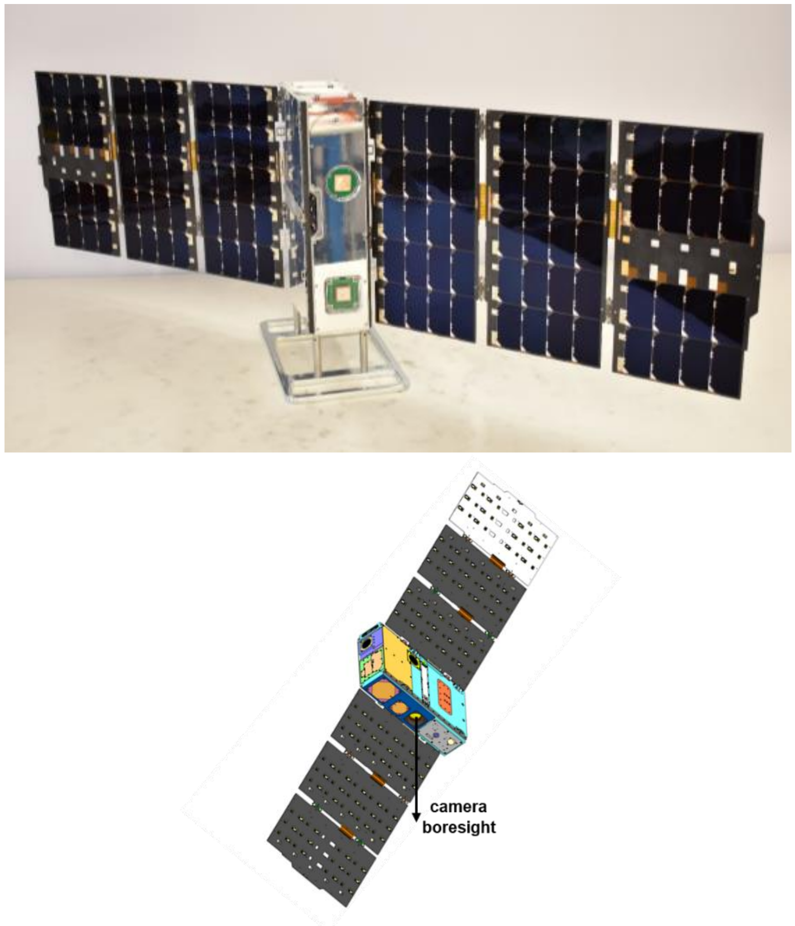


Figure 31. Photograph of the AMS pre-launch [76] and artistic rendering [77].

AMS was a 6U maneuverable cubesat launched on 25 May 2022. It initially orbited at an altitude of ~500 km, with a mission to descend over a period of months. One of the payloads on AMS was an optical camera sensing in the red, green, and blue bands at a resolution of ~25 m GSD from 500 km. Although AMS imagery was not have high enough resolution to provide specific insights on a disaster-affected area, the prototype workflow was proof of concept that centralized operations are essential for operating in disasters. Figure 32 and Figure 33 show the TCPED pipeline and system architecture developed to use AMS to demonstrate satellite operations in disasters.

The tasking model described in this section was integrated into the AMS tasking operations workflow and executed in three notable demonstrations: a Las Vegas blue skies demo, response to Hurricane Fiona, and response to Hurricane Ian. Images were also tasked and collected for Hurricane Nicole and the 2022 floods in Pakistan, but the tasking model was not used for those collections. Incoming raw images were processed into image products and cross-referenced with planned targets to associate the image file with the appropriate camera target. A change detection algorithm and image publication workflow were developed for using camera images to detect disaster damage. In demonstrations, image and change detection products were published as web-hosted tile services and feature services using Esri ArcGIS Online.

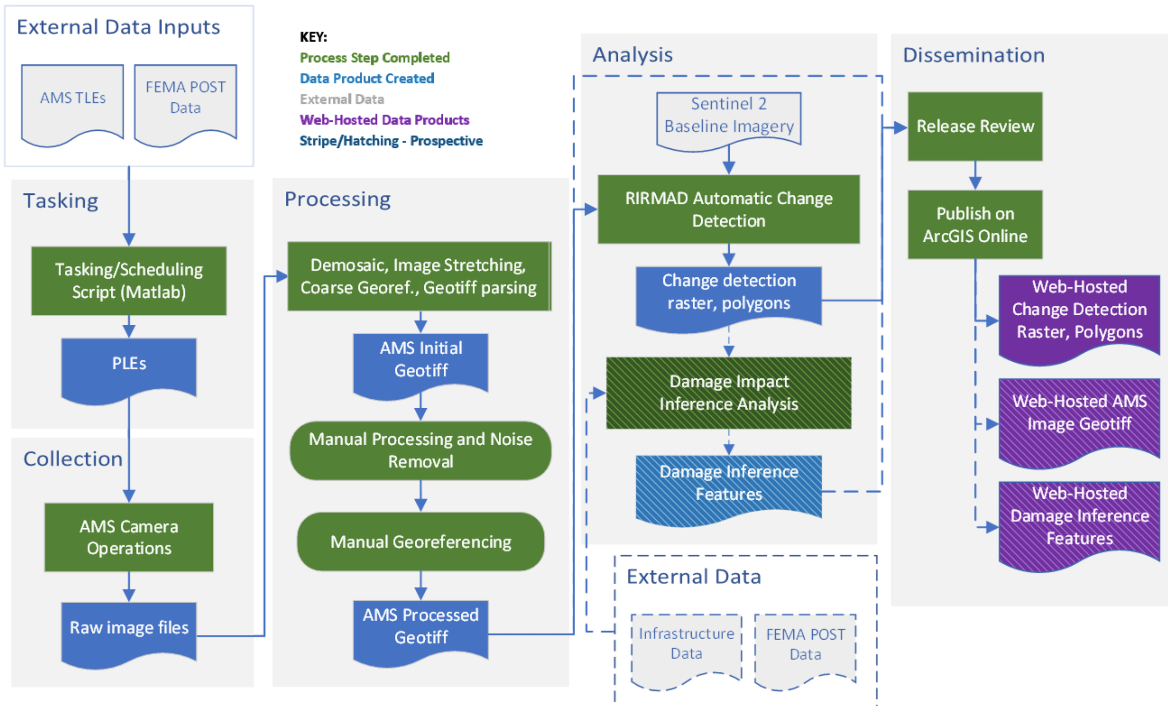


Figure 32. AMS imagery tasking, collection, processing, analysis, and dissemination pipeline.

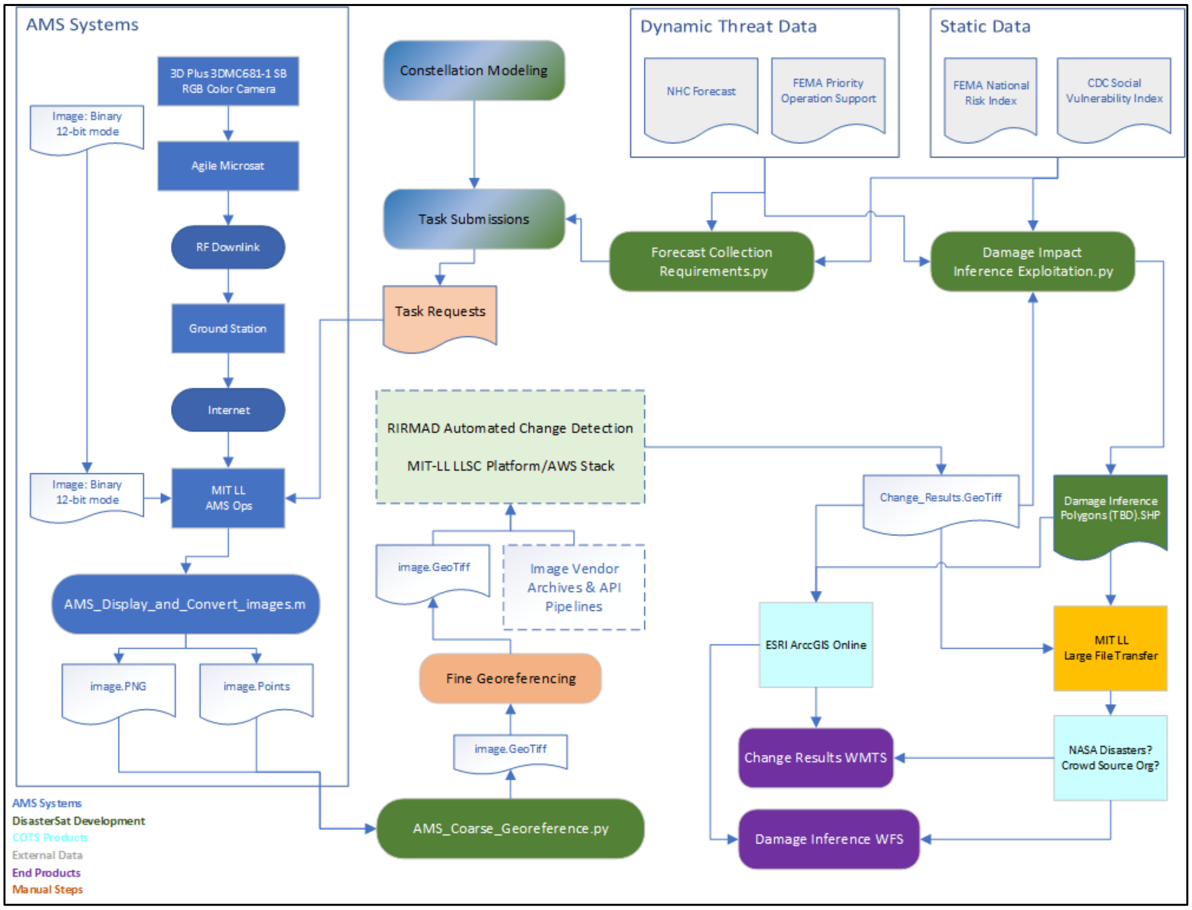


Figure 33. AMS architecture visualizing tangible and non-tangible assets.

6.6.1 Disaster-Tasking Optimization Model

During disasters, points of interest often span a wide area and are unknown at the time tasking requests must be made. Current practice is to task based on hazard forecasts, weather data, and initial damage reports. The tasking optimization model developed for AMS uses several data inputs to generate tasking commands that make efficient use of limited spacecraft capacity. The model uses target priority data, payload characteristics, and two-line elements (TLEs) to create a tasking plan that maximizes the collection of high-priority targets. The tasking planner then generates a command list, which is uploaded to the spacecraft. Content in this section was first presented at the 2023 Small Sat Conference [76].

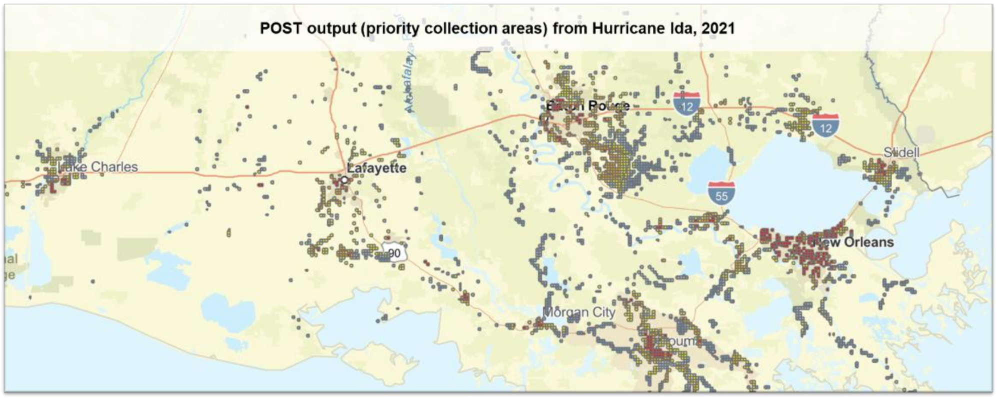


Figure 34. Image of POST data generated for Hurricane Ida in 2021. This image shows only a small segment of the POST model output and is zoomed in so colorized grid squares are visible. Data for the state of Louisiana were used to develop the tasking optimization tool.

During natural disasters, targets and points of interest change frequently, especially in the days preceding predictable incidents (e.g., tropical storms) and in the 24-48 hours following an incident. FEMA developed POST to inform remote-sensing tasking during disasters. It uses hazard models, the Social Vulnerability Index, and foundational geospatial infrastructure data to generate a 1 km×1 km grid indicating areas likely to sustain damage and require emergency services. In the output layer, each grid cell is prioritized on a scale of 1 to 5 (1 is currently the highest priority, but the scale has changed several times in the development of the tool). Highest-priority grid cells cover populated areas where heavy impacts are expected. Lower-priority grid cells cover areas where fewer people live or where impacts are expected to be less severe. We used POST data generated for Hurricane Ida in 2021 in developing the tasking optimization model (Figure 34).

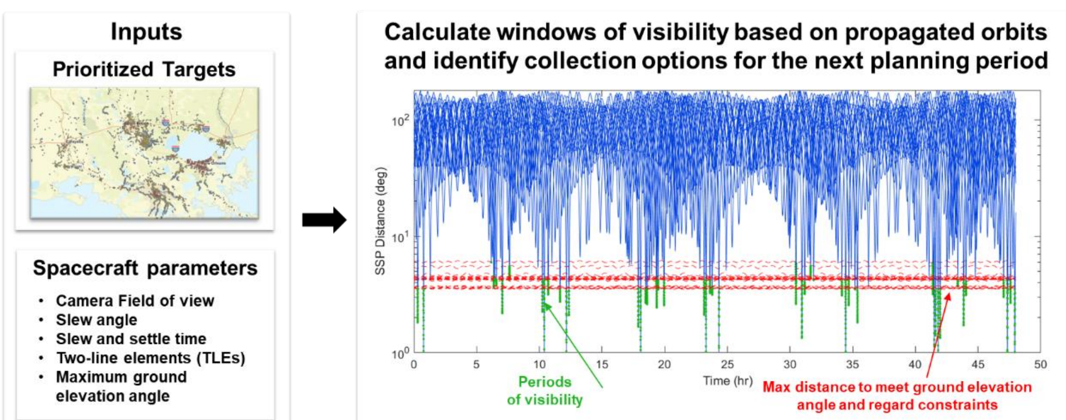


Figure 35. Optimization model inputs to calculate windows of opportunity for collecting images of priority targets.

Spacecraft parameters used in the tasking optimization model include orbital altitude, camera field of view, maximum slew angle, and bus slew and settle time. The model also considers a user-specified maximum acceptable ground elevation angle. TLEs, accessed through SpaceTrack.com, indicate the spacecraft's current state and trajectory. To identify windows of opportunity for collection (Figure 35), the spacecraft orbit is propagated over an operational planning period. Bus slew capability and settle time, minimum and maximum acceptable elevation angle, and camera field of view are used to generate a list of collection opportunities for each target.

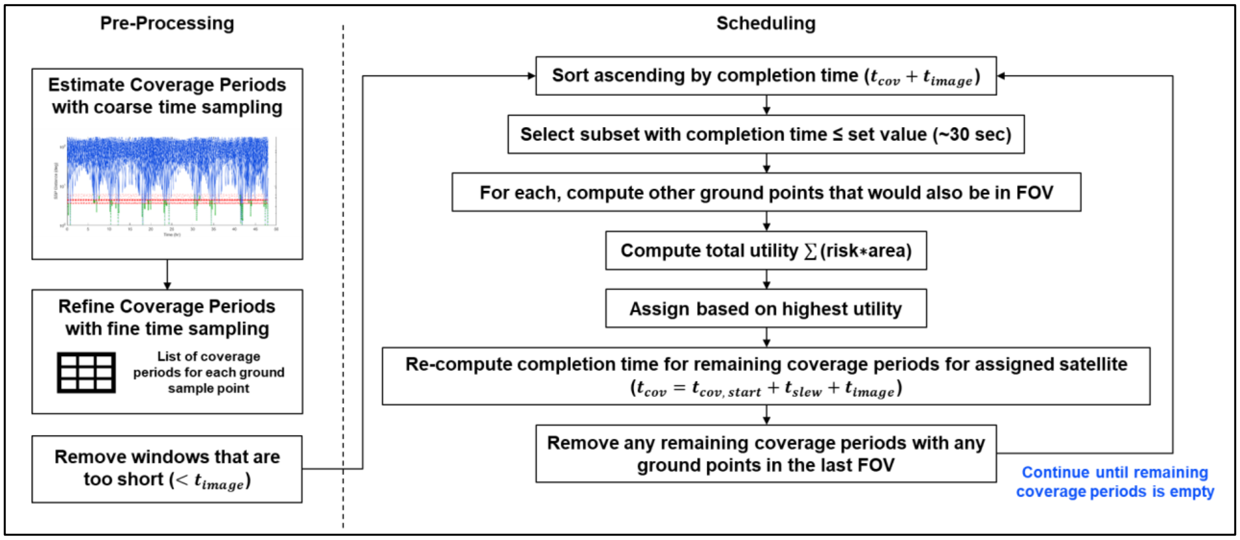


Figure 36. Tasking optimization process.

The optimizer uses a dimensionless utility index to schedule collections that capture as many grid points as possible given the constraints. Utility generated for any given collect is a function of the sum of the utilities for grid points that would be covered with the collect. The individual utility for each grid point is the product of the priority and the area that each grid point represents. Figure 36 summarizes the optimization process. In simulations, utility increases over time as targets are collected. The optimizer generates a collection schedule where the estimated image footprints maximize utility (Figure 37). For AMS, this model was integrated with the AMS planner to generate commands that maximize overall utility [76].

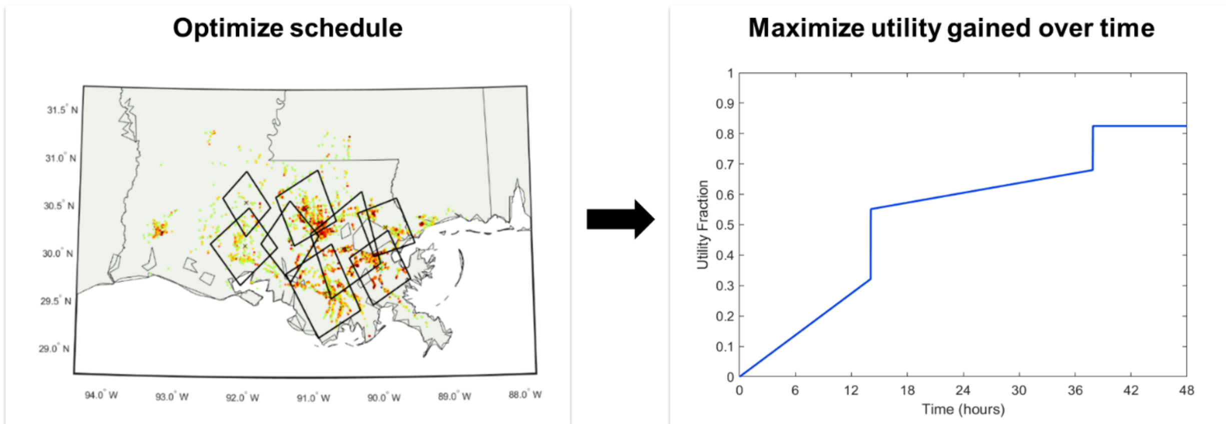


Figure 37. Utility is a function of the priority and number of targets captured in simulations.

Performance of the system over a fixed period of days is highly dependent on the satellite's starting state. For example, over a period of two days, and using the POST dataset from Hurricane Ida, AMS might achieve utility upward of 90% or utility as low as 40% depending on its starting position (Figure 38).

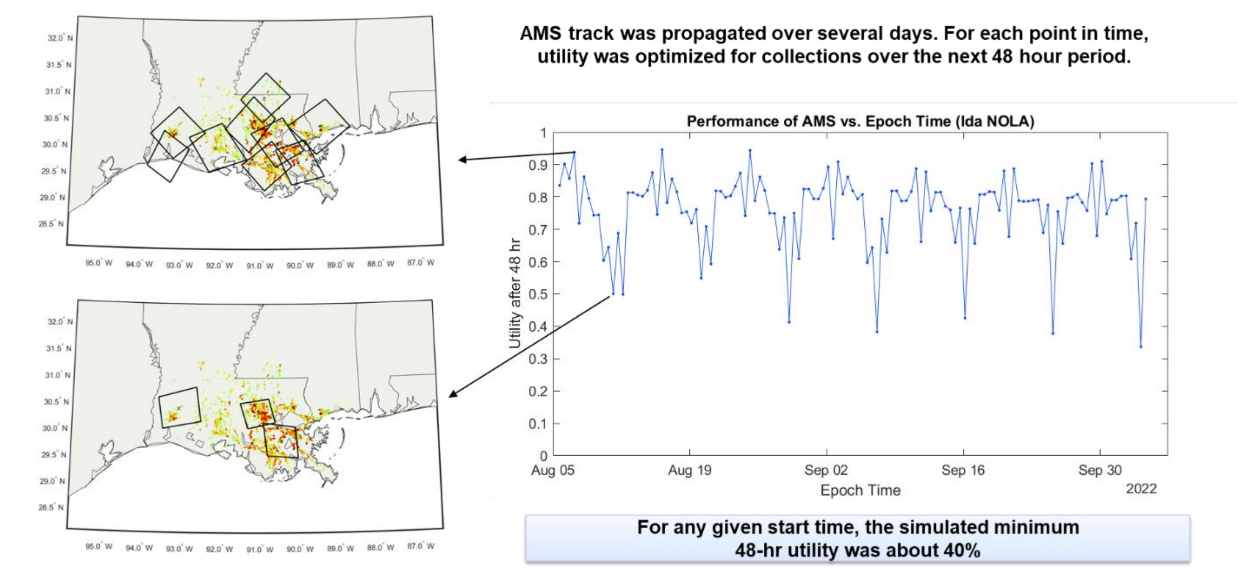


Figure 38. Performance variation with starting position (epoch).

By varying the length of time available to optimize collections, we were able to simulate how long it would take AMS to achieve different levels of utility. With the Ida POST dataset, AMS would achieve 80% utility within 2 days 50% of the time, and within 3 days 80% of the time (Figure 39).

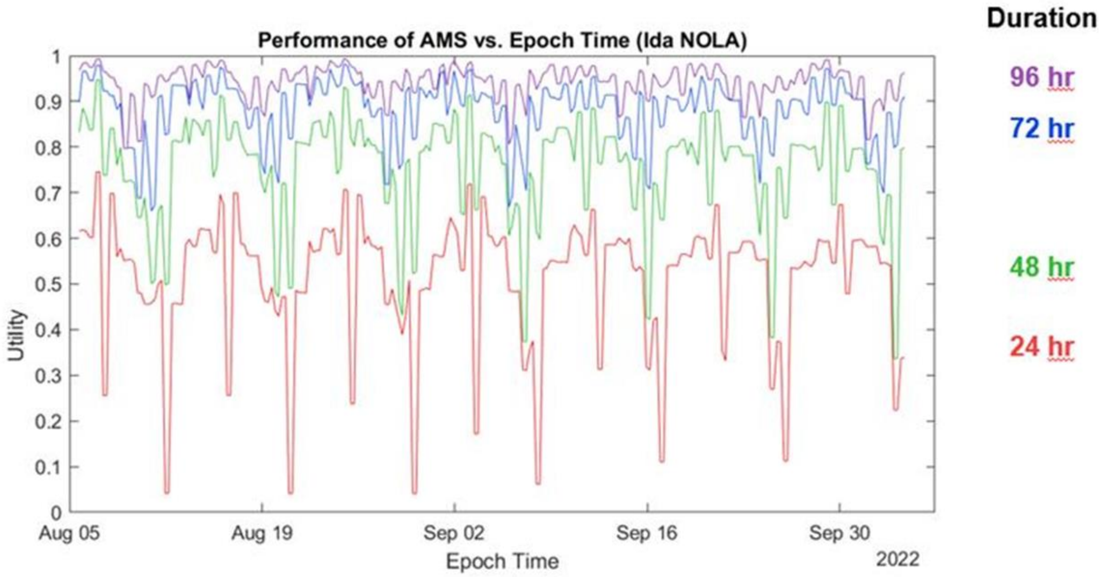


Figure 39. Simulated AMS utility achieved over different time durations, varied by starting state.

The tasking model was used to task AMS after several hurricanes in 2022, described below, and later expanded to model constellation configuration trades (report forthcoming).

6.6.2 Image Processing

In collaboration with the AMS team, we developed an image-processing pipeline that generates preview PNG images and georeferenced GeoTIFFs. The pipeline, depicted in Figure 40, included steps for GeoTIFF parsing, pixel stretch, demosaicing, radiometric calibration, and noise reduction.

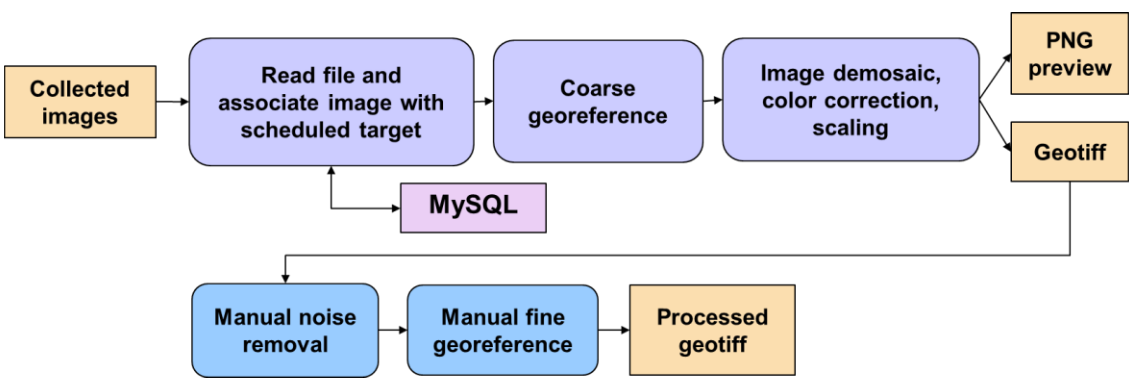


Figure 40. AMS image processing pipeline [76].

Two main challenges were with georegistration and overcoming metadata errors incurred in command processing. Ultimately, the team developed a coarse automated georeferencing script and followed with manual precise georegistration when needed.

6.6.3 Regularized Iteratively Reweighted Multivariate Alteration Detection (RIRMAD)

Section primary author: Sean Anklam

Image change detection is a process that analyzes two or more multi-temporal image observations acquired over the same geographical area in order to identify features and objects that have changed over the period of observation. Traditionally, image sets are annotated manually by a trained image analyst. Red annotations indicate the former locations structures or targets that have moved or disappeared and blue annotations indicate those that have appeared. However, these annotations fail to address the central problem with change detection, namely that not all changes matter to the end user.

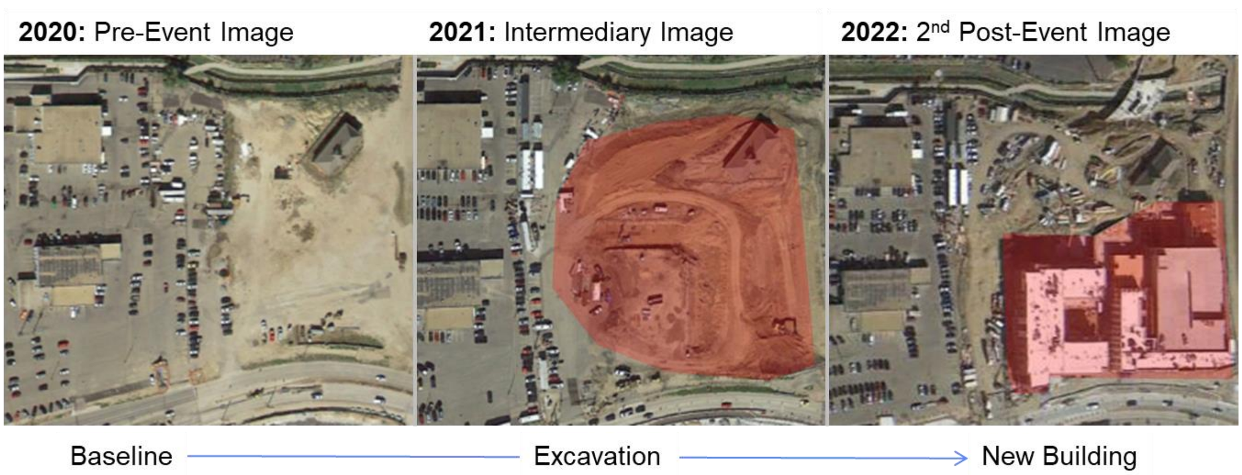


Figure 41. Illustration of change over time detected in overhead imagery.

Automating change detection is challenging. Human beings quantify change slower, but more intuitively and effectively, than a computer. Change detection is also too broadly defined for a machine learning system to determine which changes are significant and which are not. The result is a majority of pixels in an image pair can be flagged as “change”. Additional challenges are summarized in TABLE 28.

Some approaches to change detection reduce noise and minimize variance by compiling numerous historic images to develop a model for average pixel values. However, since disaster applications often search for minute changes that occur over short time intervals, identifying meaningful change between a single pair of images offers valuable insight.

TABLE 28

Challenges with Change Detection Analysis

Category	**Challenge Area**	**Description Or Variance**
Resolution Variance	Spatial	1 sq km–25 sq cm ground sample distance
	Spectral	1 discrete broad band to 100s of narrow contiguous bands spanning the blue to longwave-infrared optical window
	Radiometric	256 bits to 64,000 bits
	Temporal	Revisit rate varies from annual to monthly, to weekly, to daily, and now to hourly
Knowledge Gap	Interpretation	Literal visual interpretation of images and non-literal semantic analysis of pixels are worlds apart
	Context	Semantic information is not explicitly contained within an image, dependent on phenomenology expertise and context
	Scales	Lack of concordance between low-level information (automatically extracted from images) and high-level information (analyzed by phenomenology experts)
	Meaningful features	10? Road, vegetation, building, impervious surface, vehicle…. 50? Highway, secondary street, parking lot, sidewalk, tree, grass, white car, blue car, red roof, brown roof…
Spatiotemporal Data Characteristics	Data at rest	Exabytes of existing data to process; the majority of satellite images in archives have never been analyzed
	Data in motion	Streaming data require milliseconds to respond at scale
	Data forms	Structured, unstructured, and dynamic visual media
	Data in doubt	Unverified veracity, incompleteness, ambiguity, and deception
Automation-Specific Challenges	Radiometric noise	Sensors have various forms of random noise and imaging artifacts that a computer will erroneously flag as “change”
	Environmental noise	All optical sensors are sensitive to noise caused by atmospheric gases, water vapor, and particulates which will be erroneously flagged as change
	Image geometry	Differences in imaging geometry will cause parallax effects on 3D objections like buildings to be erroneously flagged as change
	Seasonality	At high and low latitudes, seasonal variations in vegetation, water, and weather will be flagged as change; although these changes are real, they are not significant
	Solar angle	Varying solar angles will cause shadows to change in size, shape, and direction which will be erroneously flagged as change
	Resolution disparities	Any disparity in any type of resolution within an image pair can cause erroneous change to be flagged

The Regularized Iteratively Reweighted Multivariate Alteration Detection (R-IR-MAD) model was developed to detect meaningful change between an image pair. RIRMAD ingests images from any platform and can detect change between images from different sensors.

Satellite images can arrive in a wide-variety of formats, data types, projections, processing levels, coverage extents, resolutions etc. Most satellite images also have an associated metadata file that describes these characteristics. Unfortunately, there is no agreed upon common metadata file format, structure, or content. For automated change detection to be effective, image pairs and their metadata must first be scanned by a "data adapter" which can then determine which pre-processing routines are needed to normalize the image pair and in which order they will be performed.

Data adaptors need to recognize sensor specific file name metadata formats in order to perform the correct normalization procedures. Pre-processing routines are not applied to image pairs equally. For example, for any disparities in resolution the higher resolution image will be down-sampled to the lower resolution image. If one image in the pair is atmospherically corrected and the other isn't, atmospheric correction will only be performed on the radiance image.

RIRMAD first scans metadata to determine if images require automated computer vision-based co-registration, resampling, data type conversions, reprojections, subsets, and other forms of normalization.

- **Radiometric Normalization**: Both images should be radiometrically calibrated to spectral radiance, spectral reflectance, or brightness temperature. The dynamic range in each image should be the same and solar angles should be as close as possible. Radiometric normalization can be achieved through a combination of dark object subtraction and flat fielding and radiometric resolution normalization can be achieved by down-sampling the higher radiometric resolution image to the bit depth of the lower radiometric resolution image.

- **Spectral Normalization**: Both images should have the same spectral resolution (# of channels, band designations, bandwidth, wavelength range). Spectral normalization can be achieved by down-sampling the higher spectral resolution image to the lower spectral resolution image.

- **Spatial Normalization**: Both images should occupy the same extent and have the same spatial resolution. Spatial normalization can be achieved by down-sampling the higher spatial resolution image to the lower spatial resolution and cropping the image covering a larger area to the boundaries of the image covering a smaller area.

- **Geometric Normalization**: Both images should share the same projection, datum, and have a similar look angle. Geometric normalization can be achieved by reprojecting one image to the match the projection of the other image. Geometric offsets in images can be normalized through automated co-registration.

- **Data Type Normalization**: Both images should have digital number formats stored as the same data type (e.g., float, integer, double, etc.).

- **Image Format Normalization**: Both images should be in the same raster format (e.g., GeoTIFF, HDF5, .dat, .img, JPEG2000, etc.).

If required, images are first normalized. If not, RIRMAD initiates the change detection process. RIRMAD can also be programmatically triggered to initialize anytime an image pair arrives in its input S3 bucket. TABLE 29 includes examples of pre-processing algorithms used by RIRMAD.

TABLE 29

Pre-Processing Steps for Images Used with RIRMAD

Pre-Processing Category	**Example Operations**
Data Adaptors	• Sensor\platform data modules (WV-3, S2a, AMS, L8, etc.) • Spectral response functions • Calibration coefficients • Rational polynomial coefficients • Metadata descriptions • Image handler instructions
Data Type	• Identify data type • Convert data type to match primary image
Radiometric Resolution	• Check bit depth and dynamic range • Down-sample higher radiometric resolution image to match bit depth and DNR of lower-resolution image • Perform radiometric calibration • Perform atmospheric correction • Perform brightness temperature correction
Spatial Resolution and Extent	• Identify pixel size in each image • Down-sample higher-resolution image to match lower-resolution image using bilinear-interpolation • Larger image cropped to match smaller image
Spatial Reference	• Identify projection, datum, and coordinate system • Transform and reproject images to match primary projected coordinate system
Masking	• Cloud mask • Water mask • Vegetation mask • Snow/ice mask • Shadow mask
Spectral Resolution	• Check # of bands, bandwidth, band designations, spectral wavelength range

	• Perform spectral down-sampling on higher-resolution image to match lower-resolution image
Data Format	• Identify image format • Convert image format to match primary image format
Geometric and Co-Alignment	• Check image geo/ortho-rectification • Perform SIFT image warping and tie-point generation • Perform RANSAC tie point selection • Co-register images based on homography

RIRMAD then generates a co-variance matrix for the image pair and scores it using canonical correlation analysis (CCA). This score is the baseline CCA score. RIRMAD then performs "n" number of image transformations on each image pair. Transformations are algebraic operations applied to each image pair, and examples are summarized in TABLE 30.

TABLE 30

Examples of Algebraic Transformations Applied to Image Pairs

Basic Operations	**Spatial/Morphology/Texture Operations**	**Dimensionality Reduction Operations**
• Adding, subtracting, multiplying, dividing • Squaring • Summation • Sine, cosine, tangent • Arc: asine, acosine, atangent • Hyperbolics: sinh, cosh, tanh • Relational and object operators • Exponent and natural exponent • Natural logarithm • Log base 10 • Integer rounding • Square root • Absolute value • Derivates • Integrals • Contrast enhancements • Cross-correlation • Color space transforms • Histogram transforms	• Hough transformation • Canny transformation • Sobel transformation • Roberts transform • Haralick texture • Pantext texture extraction • Occurrence measures • Data range • Mean • Entropy • Skewness • Dissimilarity • Second moment • Correlation • Bit error filters • Enhanced Frost filter • Enhanced Lee filter • Gamma filters • Kuan filters • Local sigma filters • Convolution filters • Morphology filters	• Principle components transform • Minimum noise fraction transform • Noise-adjusted principle components transform • Independent components transform • Maximum auto-correlation factor transform • Fast Fourier transform • Wavelet transform • Decorrelation transform

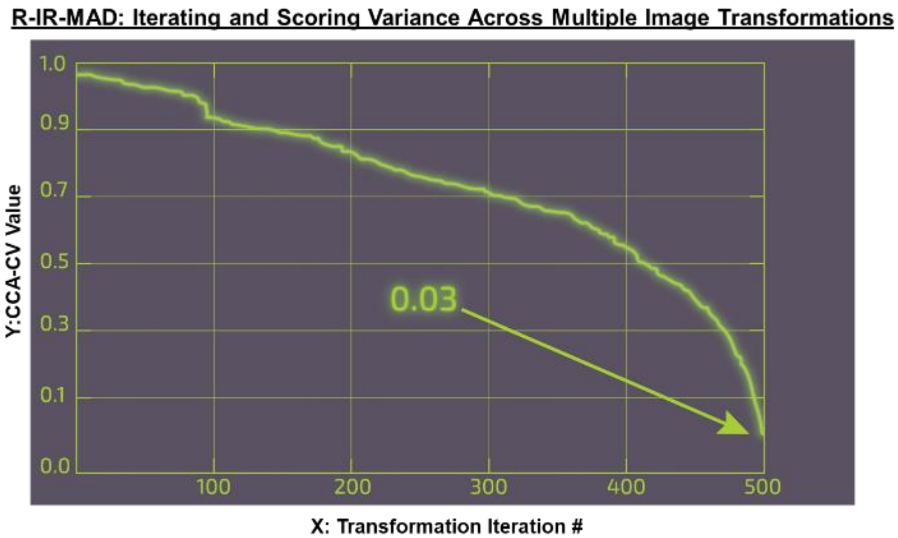


Figure 42. RIRMAD iterating and scoring variance across multiple image transforms.

The variance between each transformed pair of images is scored using CCA and compared to the baseline CCA. RIRMAD will iterate transformations until the best transformation that contains the least amount of variance between image pairs is discovered. This process is regulated and optimized by RIRMAD selecting transforms more likely to lower the CCA score based on previous transforms.

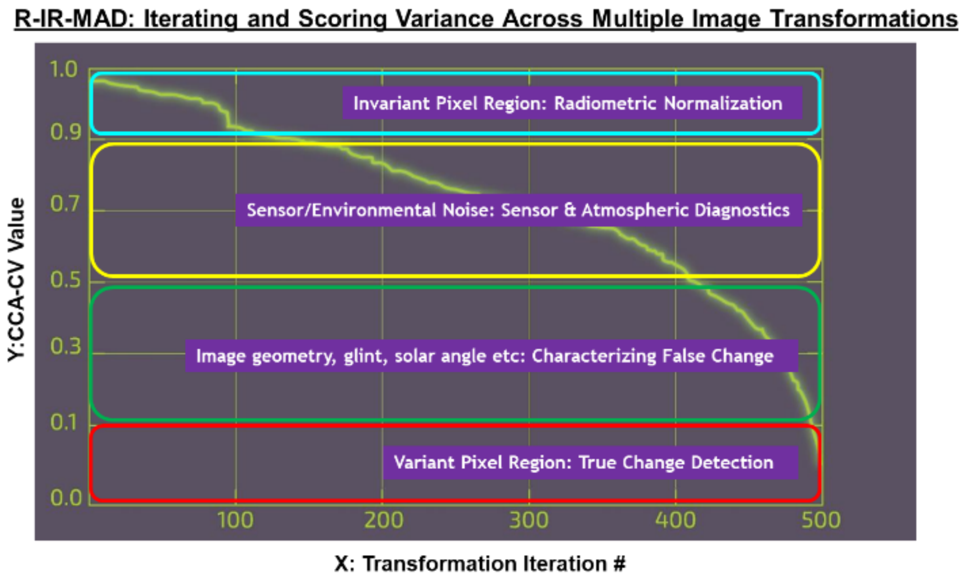


Figure 43. RIRMAD reduces variance to identify true change by accounting for confounders.

RIRMAD selects the best change detection variate using maximum auto-correlation analysis. Change detection is performed on the best variate transformation and change significance can be determined by a Chi-square test, Otsu's threshold, or similar method. Figure 44 compares the results of running RIRMAD on sample data from Landsat 8 to the outputs from other change detection approaches.

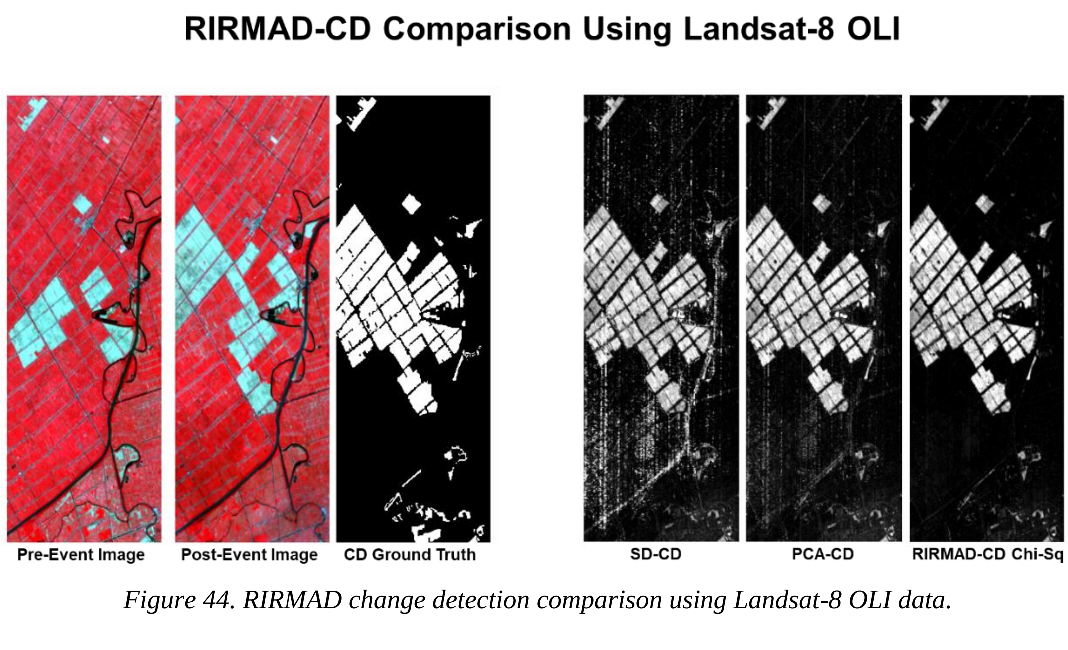


Figure 44. RIRMAD change detection comparison using Landsat-8 OLI data.

The advantages of this approach are that RIRMAD is impervious to sensor and environmental noise, though every effort should be made to minimize both in the input images through pre-processing. RIRMAD is also impervious to minor differences in both image look-angle and solar-angle. It can be effectively run on image pairs from different sensors, platforms, and resolutions and is extremely effective at isolating image pixels where real, physical change has occurred between observations. Detected change can be scored for “significance” in comparison to all other changes.

Several constraints illustrate the limits of RIRMAD as well. Input images have to at least contain partially overlapping coverage of the same area. One of the two input images needs to be spatially referenced unless the image pair comes from the exact same sensor with the identical imaging parameters in all respects (except for the date of collection).

RIRMAD is negatively affected by extreme differences in image look-angle and solar-angles. For example, the seasonality theta between a peak winter and peak summer image pair for Hawaii will not impact RIRMAD’s performance, but the effect of the seasonality theta between a peak winter and peak summer image pair for a city with both a northerly latitude and continental climate such as Buffalo, NY will be profound. Images can be de-seasonalized by masking materials that are highly susceptible to seasonal changes such as vegetation, water, snow\ice etc.

Clouds are an open-ended problem for all automated image processing. For RIRMAD, every effort should be made to mask clouds in the input image pairs during pre-processing and uniformly omit any pixels with a cloud mask label from any change detection results. Some data providers are good at estimating the cloud cover in their images, flagging cloud cover in their metadata, and providing a cloud mask for each image. Other data providers do some or none of the above. Automated cloud cover masking as a pre-processing routine is trivial for multispectral images with robust spectral resolution—especially if any bands are collected in the SWIR, MWIR, or LWIR. For panchromatic, true-color, or VNIR only multispectral images, blind cloud cover masking is extremely challenging.

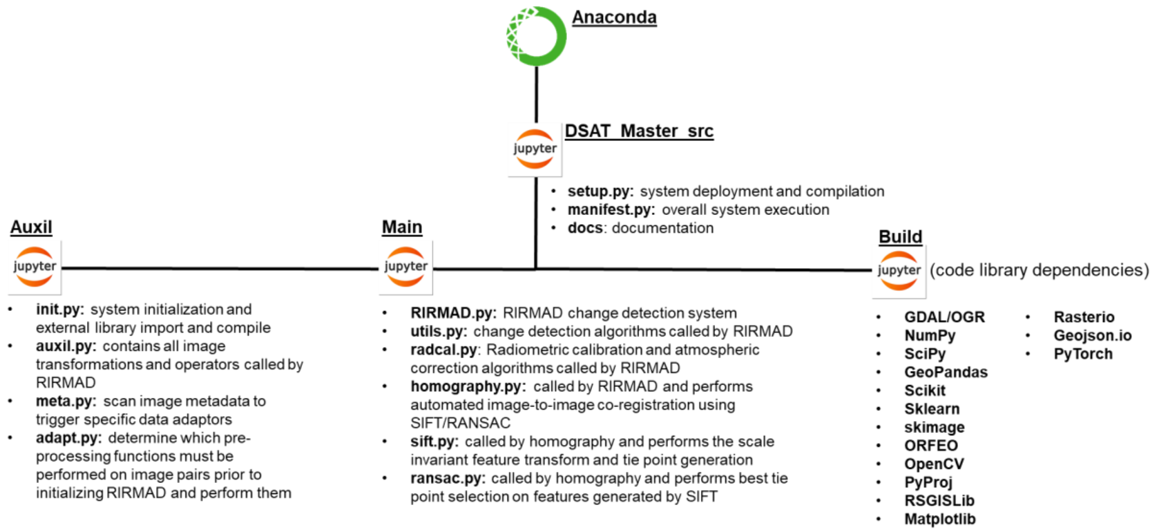


Figure 45. RIRMAD architecture for AMS demonstration.

To carry out the AMS demonstration, a prototype RIRMAD module was prepared to perform change detection on received images. The prototype architecture is presented in Figure 45. This module was converted to a package that can be loaded into QGIS to more easily integrate into disaster response workflows. In addition, we envisioned a cloud-based architecture where RIRMAD would run automatically on received images, shown in Figure 46.

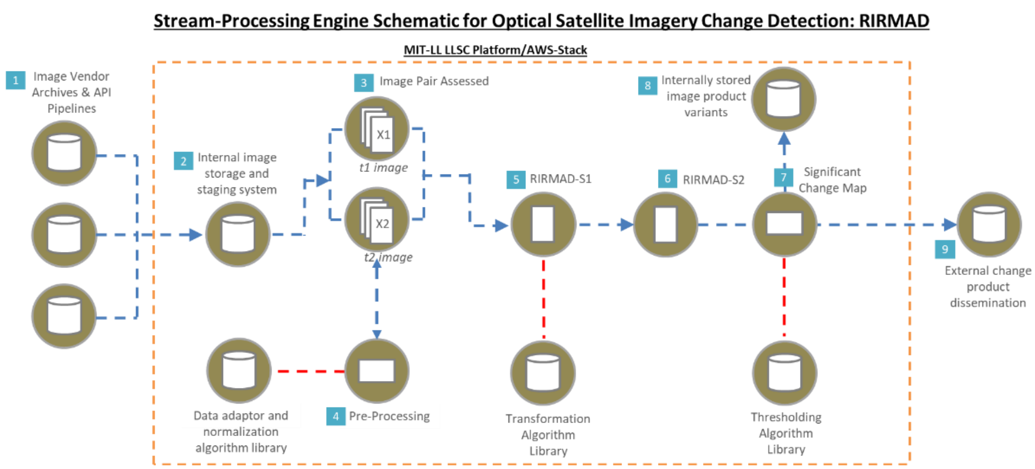


Figure 46. Stream-processing engine schematic for ideal optical satellite imagery change detection RIRMAD module.

6.6.4 Las Vegas Demo

The first demo was a "blue sky" collection over Las Vegas, conducted in steady state when no disaster was occurring. To test out model integration, we used the same POST data from Hurricane Ida. For the first test, we wanted to ensure clear photos would be captured. Figure 47 shows the average cloud cover in August based on historic data from GOES imagery. We selected Las Vegas as the test location since it is one of the least cloudy areas in the U.S. We translocated the POST dataset from New Orleans to the Las Vegas area for tasking.

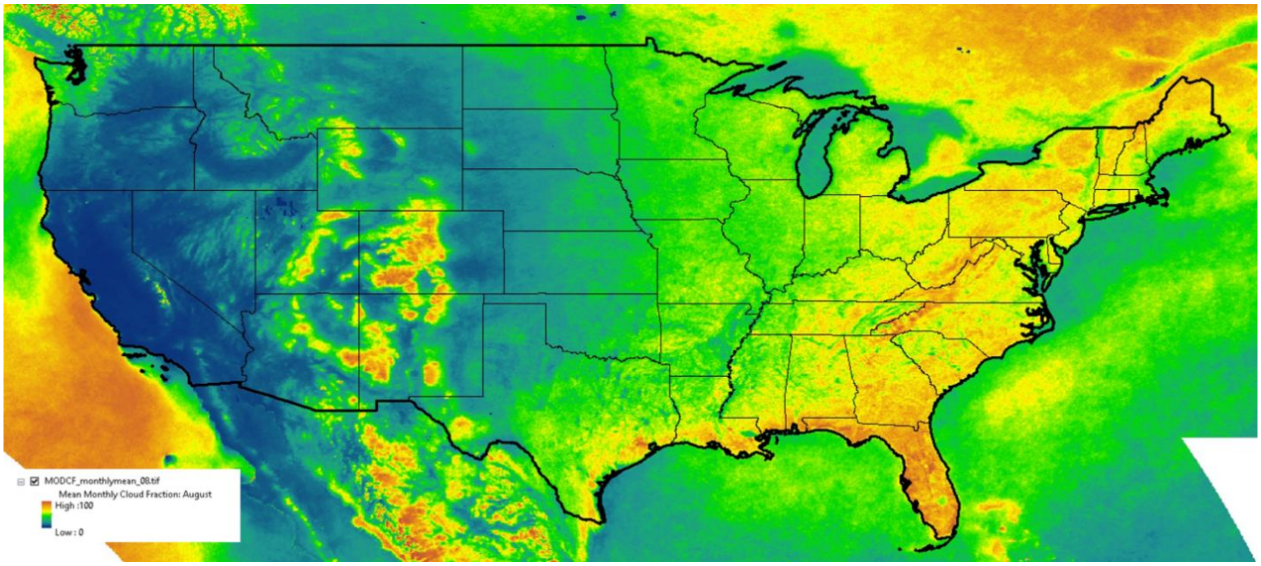


Figure 47. Average cloud cover in August, based on GOES data. Red areas are frequently cloudy and blue areas have little cloud cover.

Images were tasked using the DisasterSat tasking optimization model, collected the next day, and downloaded the third day. Following some troubleshooting, the processed images were ready on Day 5. RIRMAD change detection analysis was conducted later using a Sentinel 2 image collected in August 2021 as the pre-incident baseline image. Figure 48 and Figure 49 present the tasked areas and resulting image products from the blue-sky test. Even with accommodating issues in the data-processing pipeline, the change detection analysis was performed within five days of image tasking. A complete timeline is presented in Figure 50.

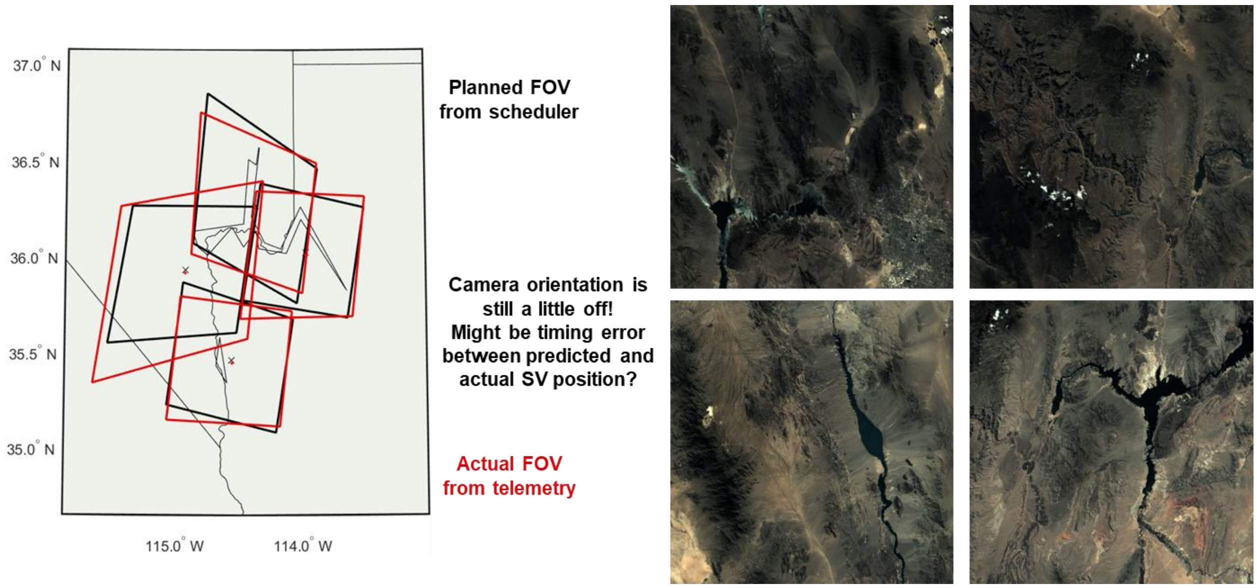


Figure 48. Tasked areas and images collected over Las Vegas during the blue-sky test.

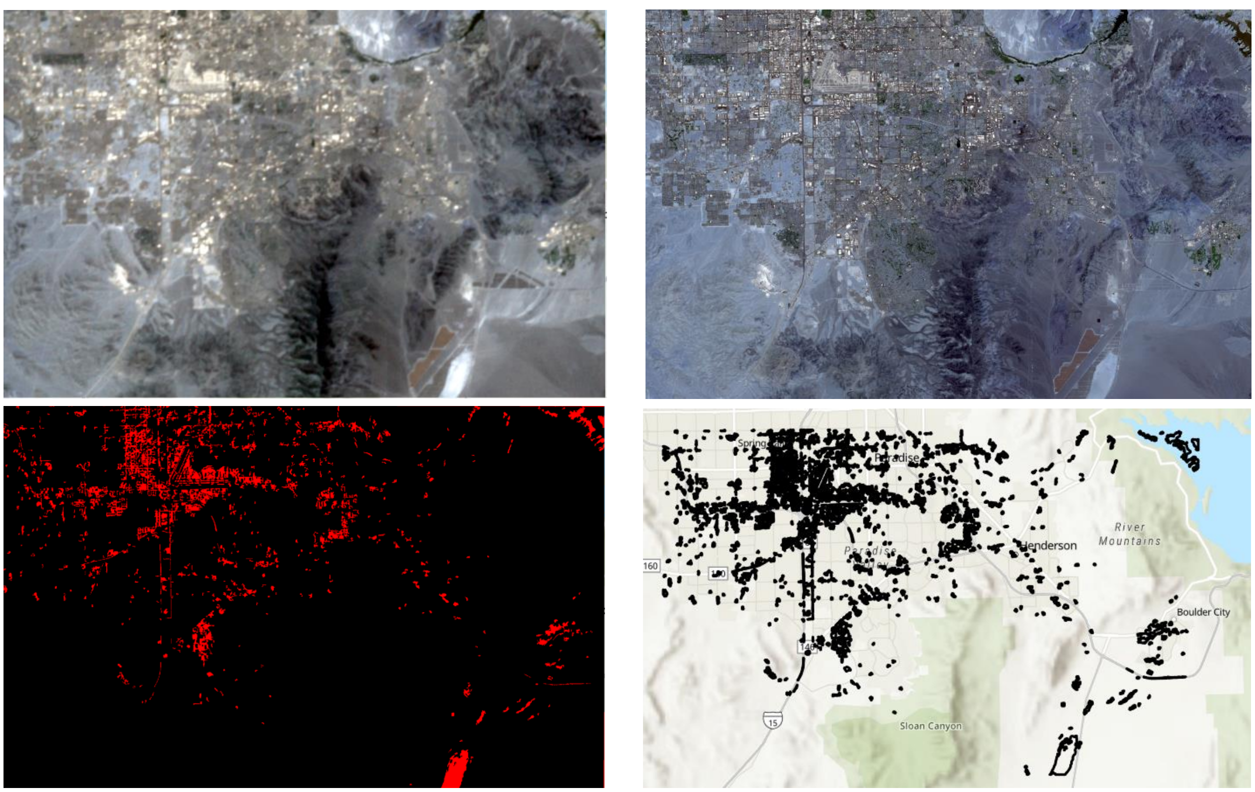


Figure 49. Upper left: orthomosaic AMS image from collections on 5 September 2022; upper right: Sentinel 2 image collected on 08/08/2021 used as a baseline for comparison; bottom left: RIRMAD change detection output; bottom right: extracted change detection polygons.

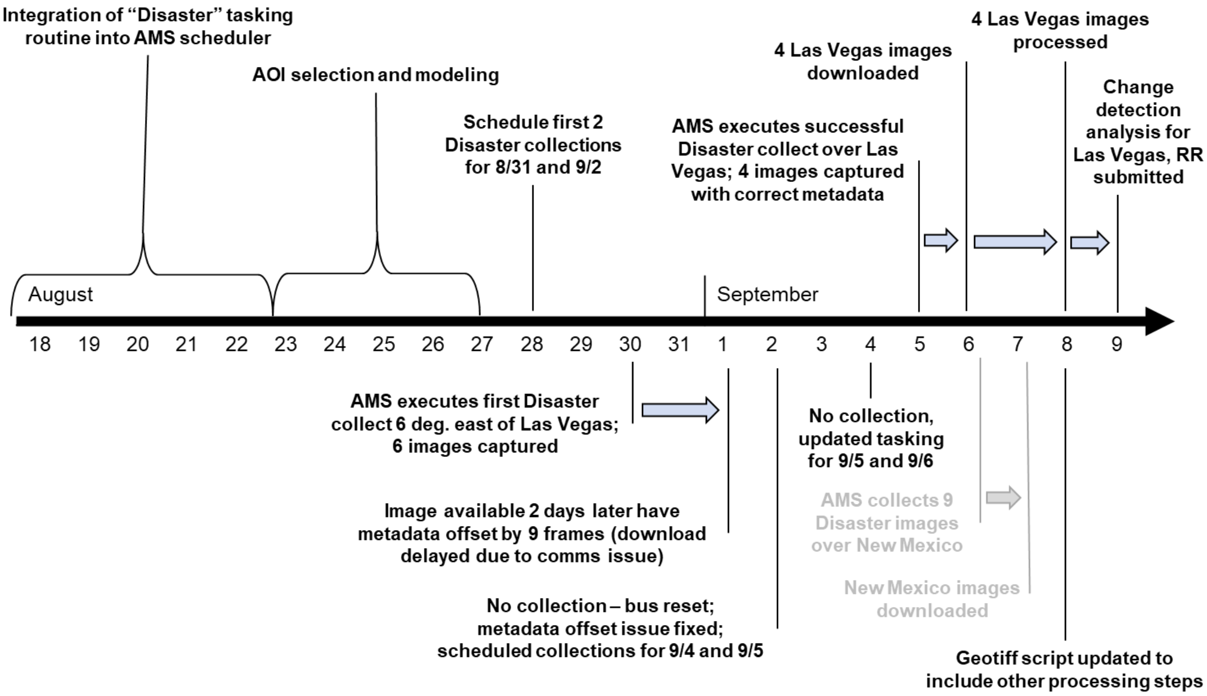


Figure 50. Timeline of main events for the Las Vegas blue-sky test.

Subsequently we were able to developed and demonstrate the final—and arguably most important—piece of the workflow, which translated the change detection outputs into a useful product. Since AMS imagery is not high enough resolution for the use cases described in Section 4, we demonstrated possible usefulness by identifying fire houses in areas where change occurred, a proxy for possible damage. The following steps were followed in ArcGIS Pro.

1. Geoprocessing Tool: Raster to Polygon – "Input Raster" is the RIR-MAD output; "Value" is the field indicating detected change

2. Definition Query: filter polygons to those with change detected (gridcode = 1)

3. Select by Location: Load fire station data and select points within 20 m of change

Figure 51. Images of analysis process for Las Vegas demonstration.

We found that 20 fire stations were in POST grids, 1 fire station was in the change area, and no fire stations were in both. For this example, since the data were fabricated, we did not expect a high correlation between detected change, POST, and the locations of features of interest. However, we did use these data to generate example datasets that demonstrate what a final product might look like.

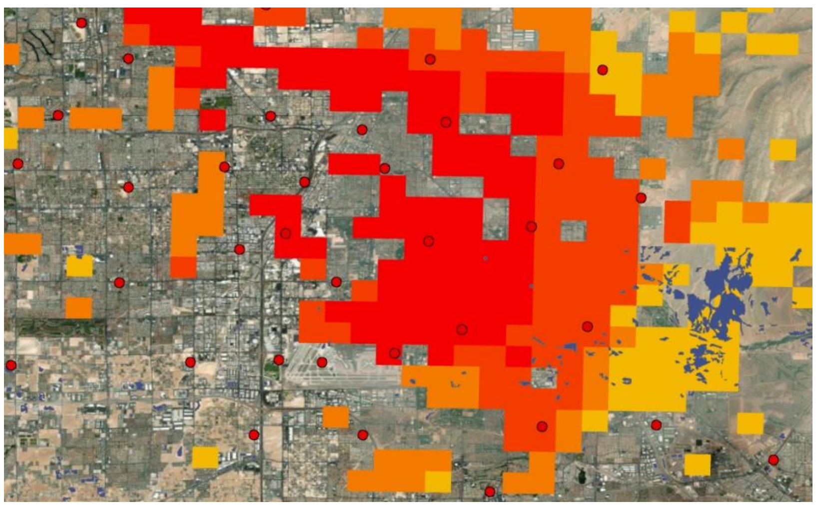


Figure 52. Change detection polygons, POST raster, and point data indicating the locations of fire houses.

In conjunction, we developed an automated model for this analysis to deliver useful products in the future. The model ingests the RIRMAD change detection raster, an index listing lifeline datasets (data of interest), shapefiles with the lifeline datasets of interest and other foundational data, and POST polygons. We developed the concept for a damage inference exploitation model that would ingest these data and deliver geographic datasets indicating facilities of interest and other lifeline-related data in the area of change. Figure 53 depicts the data model and this process.

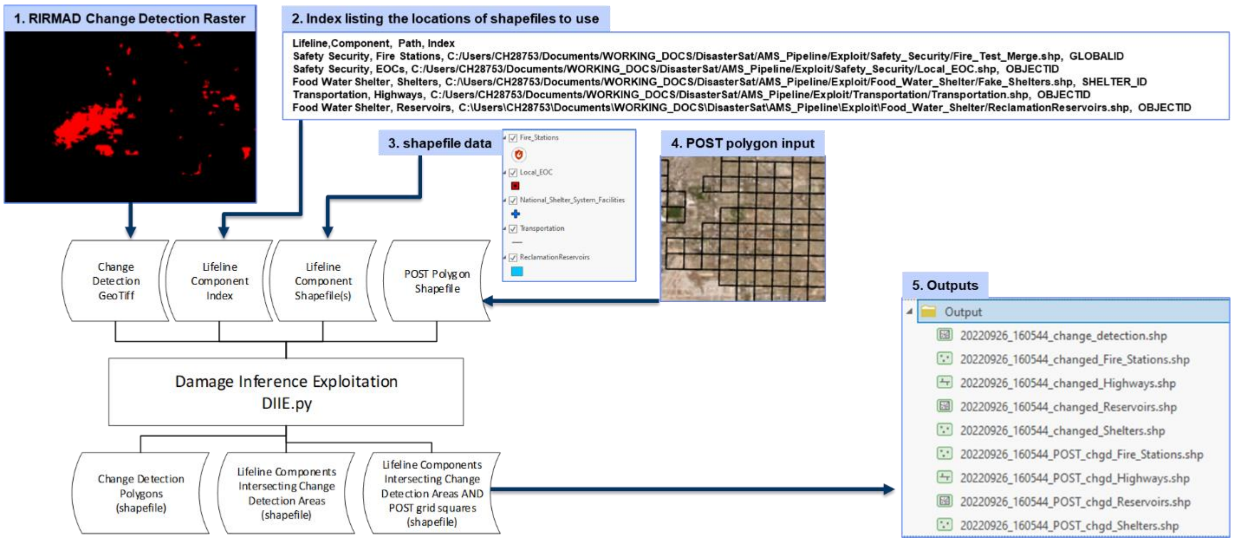


Figure 53. Data model for damage inference estimation using RIRMAD, POST, and foundational data.

We tested the damage inference model on demo data from the Las Vegas collection. The damage inference exploitation model performed as expected, identifying a firehouse that had been added for the model to find. Figure 54 shows the model inputs and outputs.

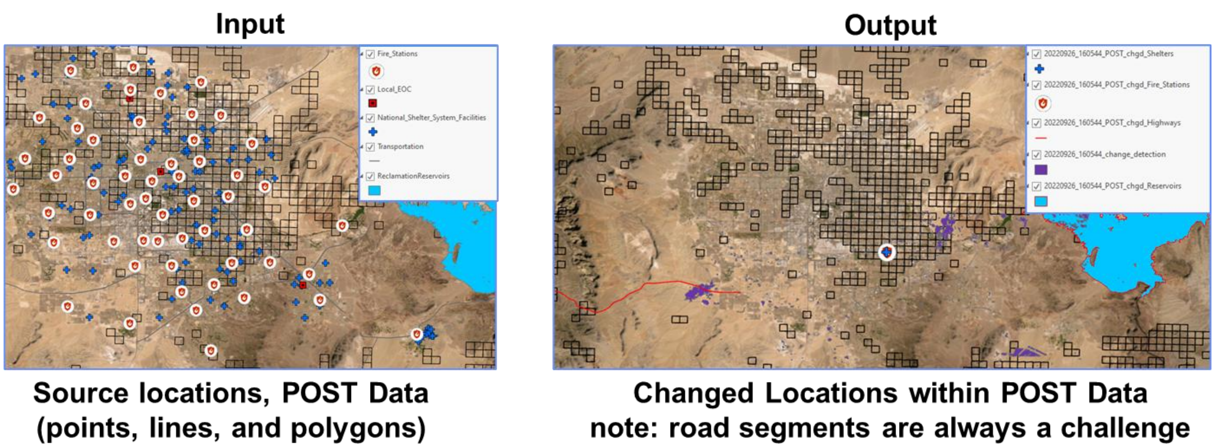


Figure 54. Damage inference model inputs and outputs.

As a final step, products were loaded into ArcGIS Online and served publicly in a web application (Figure 55). Each image was uploaded as a raster layer, and the damage outlines were uploaded as polygon data. The swipe tool was included for easy comparison of pre- and post-imagery.

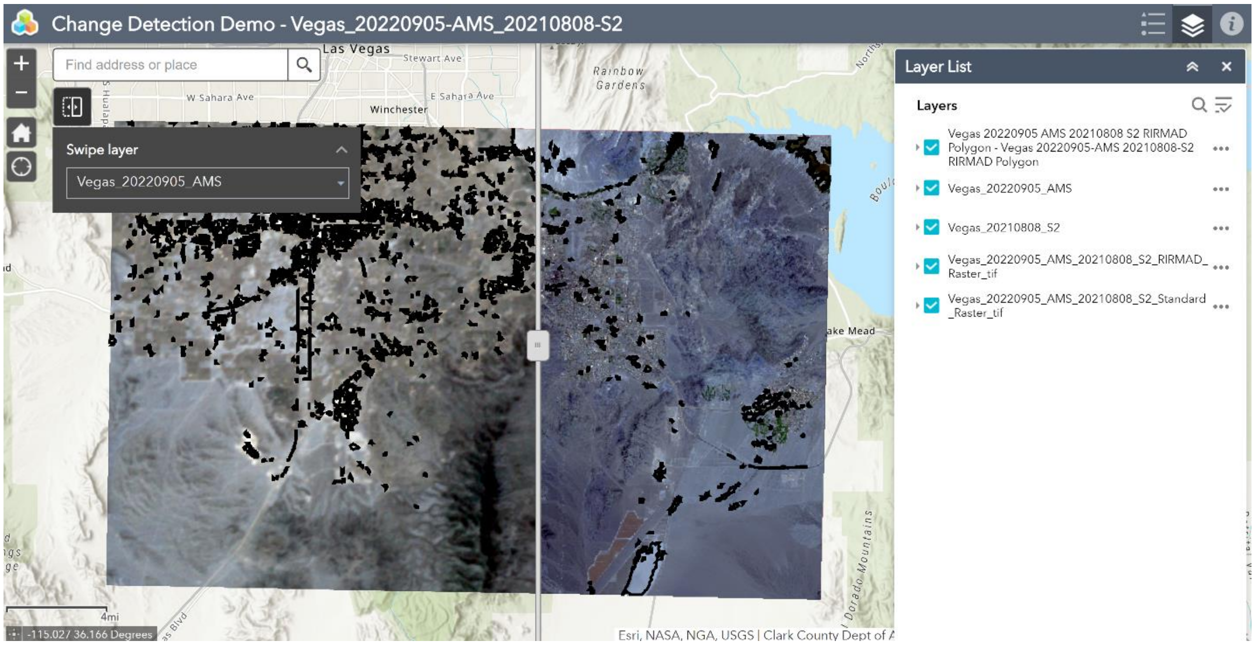


Figure 55. Screenshot of the ArcGIS Online web application with hosted data layers.

6.6.5 Hurricane Fiona

The first "gray sky" demo was conducted during Hurricane Fiona, which made landfall in Puerto Rico on 18 September 2022, only a week after the blue-sky test was completed. We received a POST dataset from FEMA the day prior to landfall (17 September). Tasking, collection, and processing were completed by 21 September, around the same time imagery from aerial assets became available. The images were quite cloudy, so no subsequent analysis was performed.

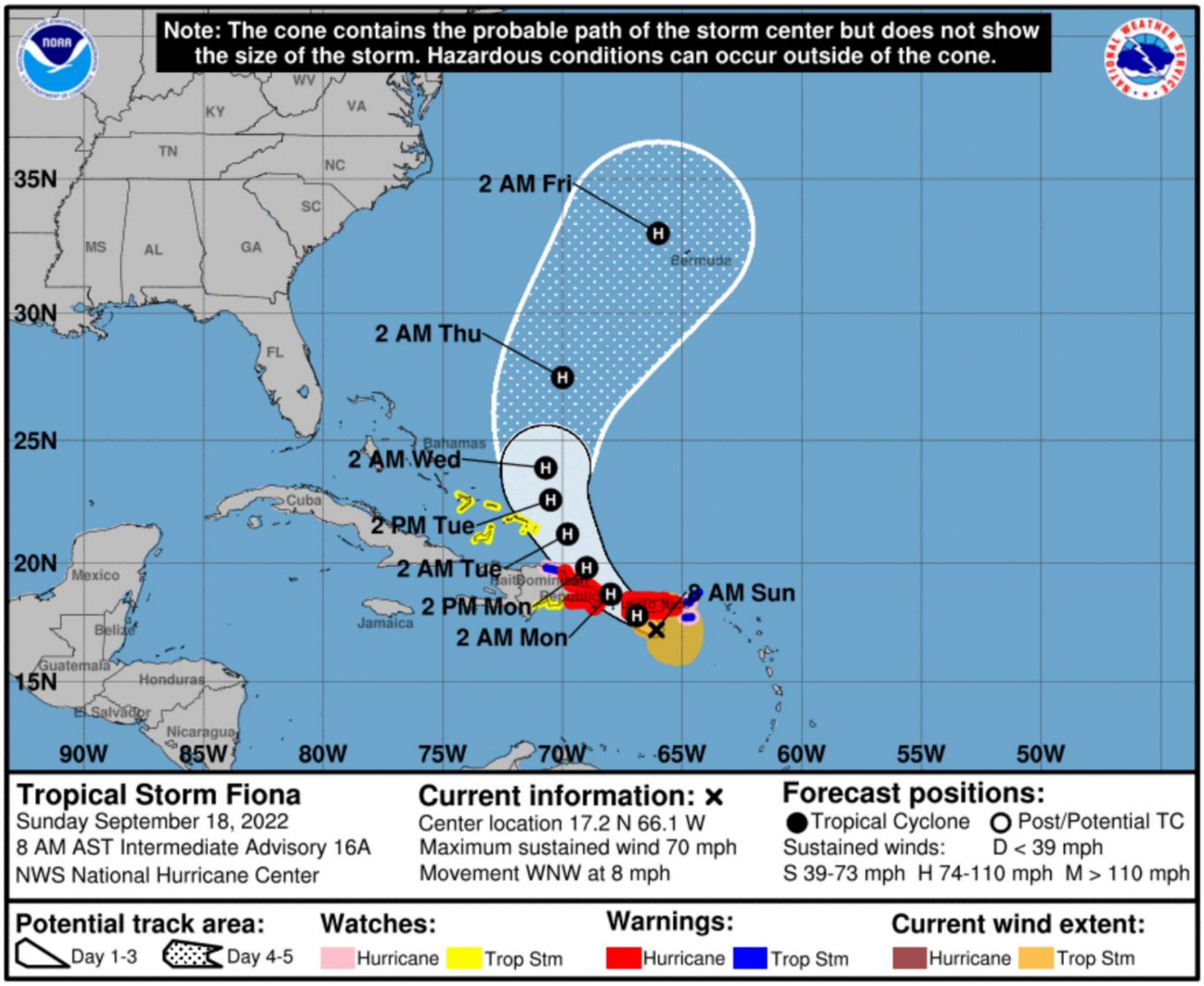


Figure 56. Forecast track of Hurricane Fiona on the day of landfall from the National Hurricane Center [78].

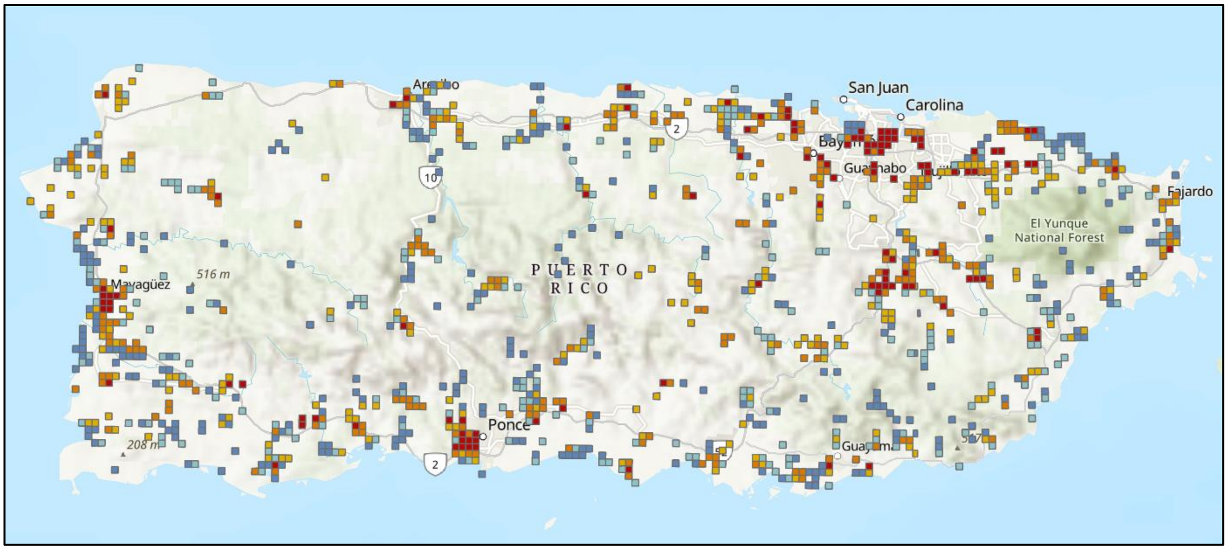


Figure 57. Screenshot of POST data used to prioritize AMS collections with the disaster tasking model for Hurricane Fiona.

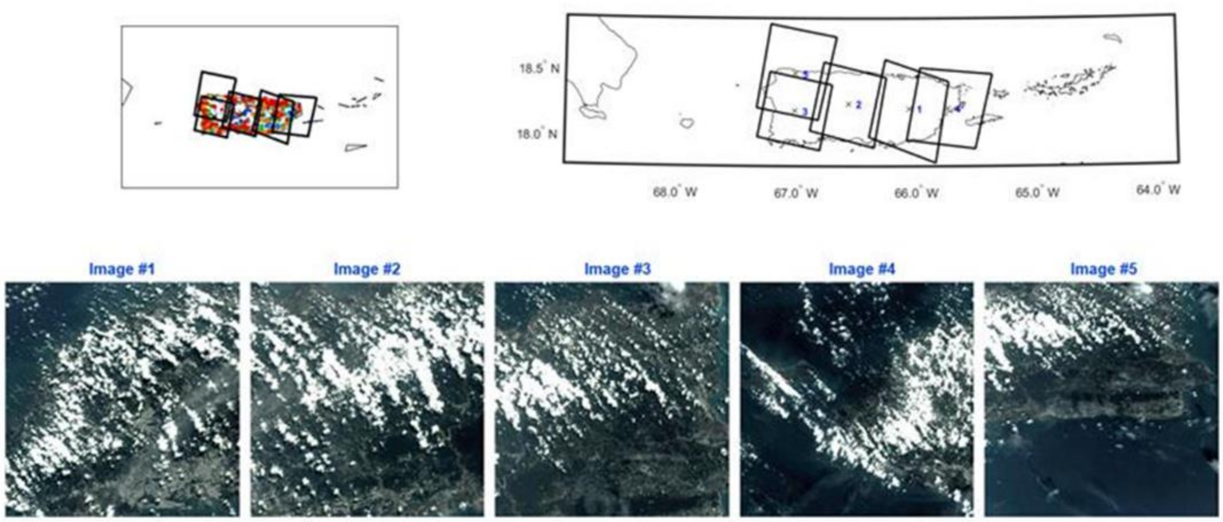


Figure 58. Image footprints and previews of images collected after Hurricane Fiona.

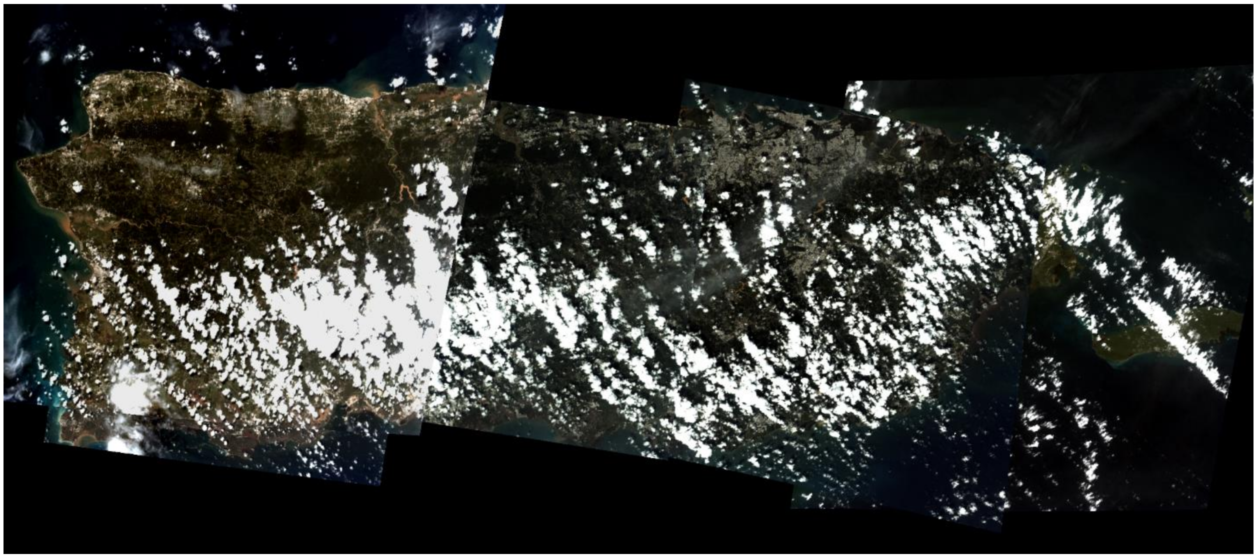


Figure 59. AMS images of Puerto Rico after Hurricane Fiona stitched together.

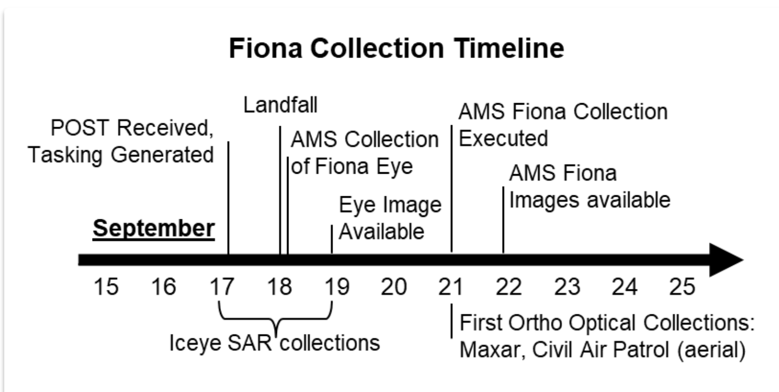


Figure 60. Timeline of events for collections after Hurricane Fiona.

6.6.6 Hurricane Ian

Another gray sky demonstration was attempted during Hurricane Ian, which made landfall near Fort Myers, FL, on 30 September 2022. With high uncertainty in the data, POST outputs were not available in advance of the incident. Instead, we used data from the GISCorps Photomappers[14] project to prioritize tasking. When activated, Photomappers is a crowdsourcing project where volunteers create a publicly

[14] In full disclosure, Katie Picchione helps run the PhotoMappers project in a volunteer capacity.

available map of photos posted to social media and other internet sources in the immediate aftermath of disasters. Typically, volunteers find and map photos in the first 24–48 hours after an incident, before other imagery is available and prior to clouds clearing. Though these data do not indicate different priority levels, the set of point targets was used to concentrate collections over areas with known impacts.

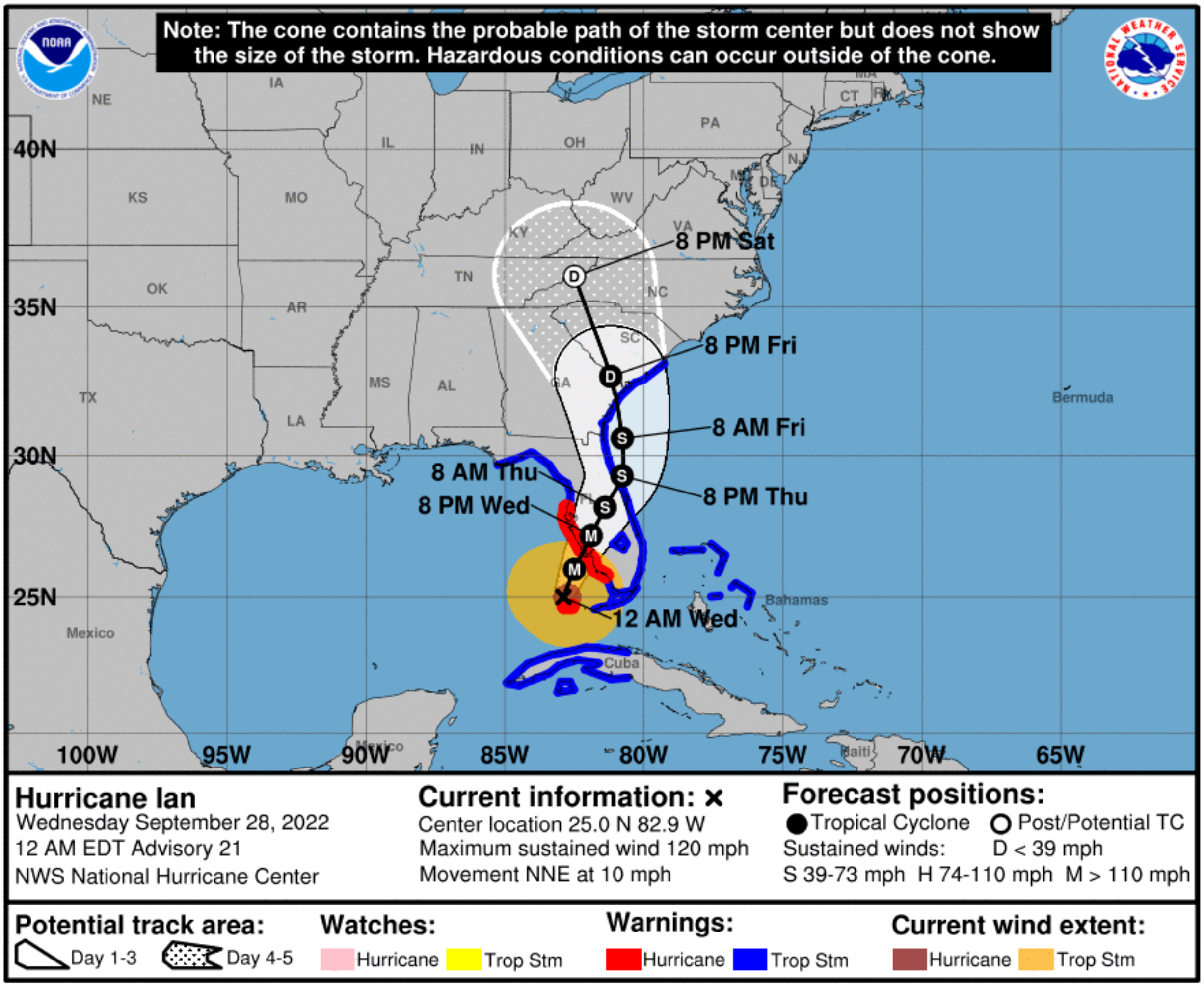
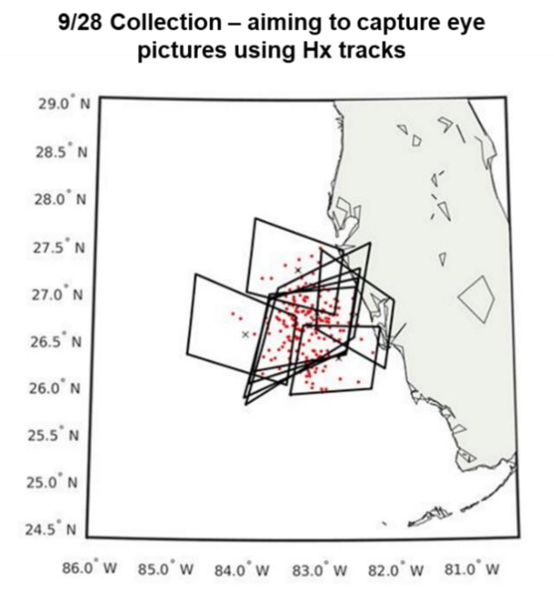
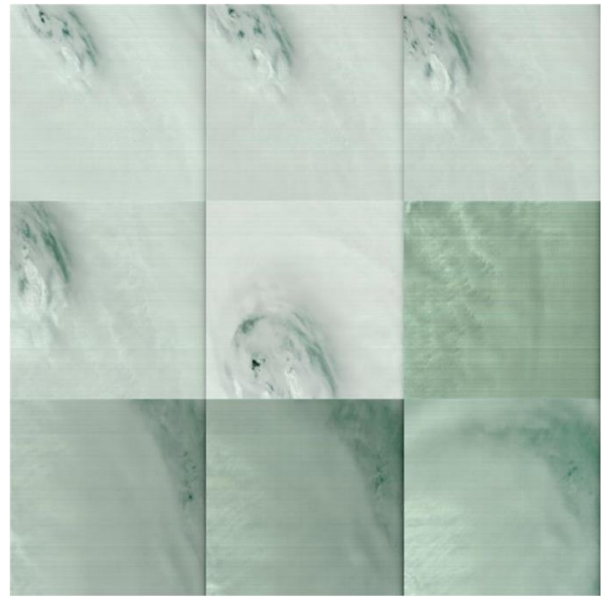


Figure 61. National Hurricane Center advisory for Hurricane Ian on the day of landfall [79].

Prior to landfall, we used AMS to collect images of the hurricane itself on 28 September. Hurricane Ian made landfall during the day on 30 September, and AMS images were collected the following day on 1 October. Like Fiona, this timeline was commensurate with the timeline of other optical imagery providers.





e

Figure 62. Images tasked and collected of the eye of Hurricane Ian.

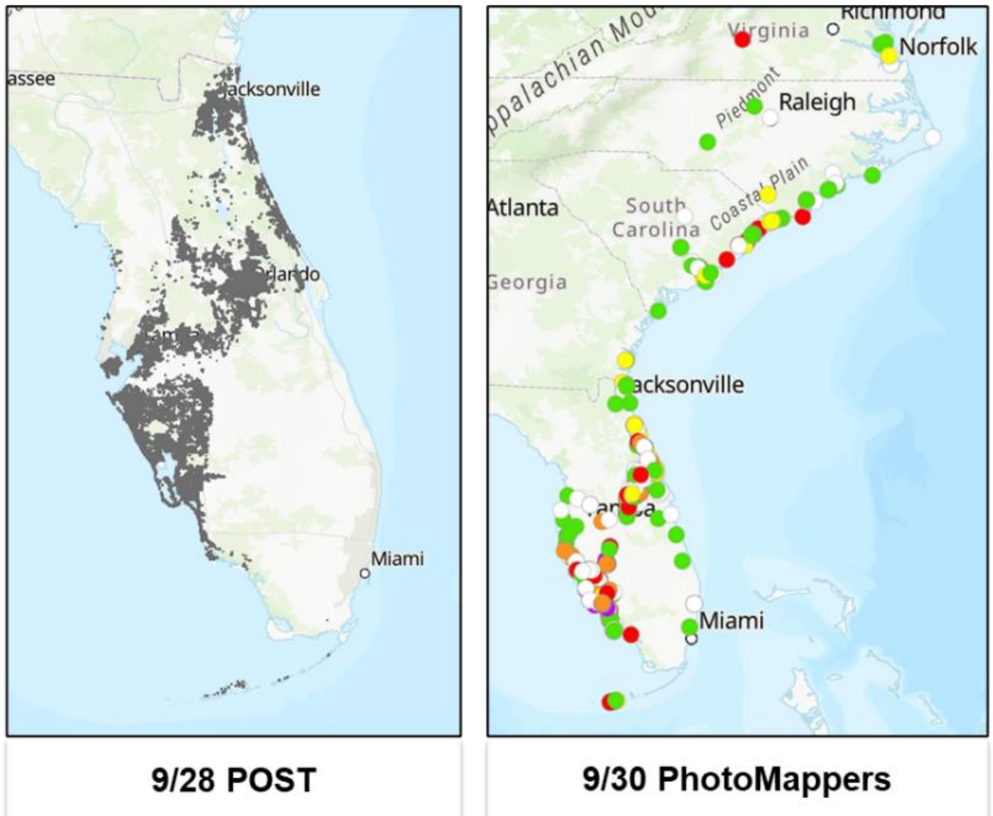


Figure 63. Screenshots of data used to task AMS collections after Hurricane Ian.

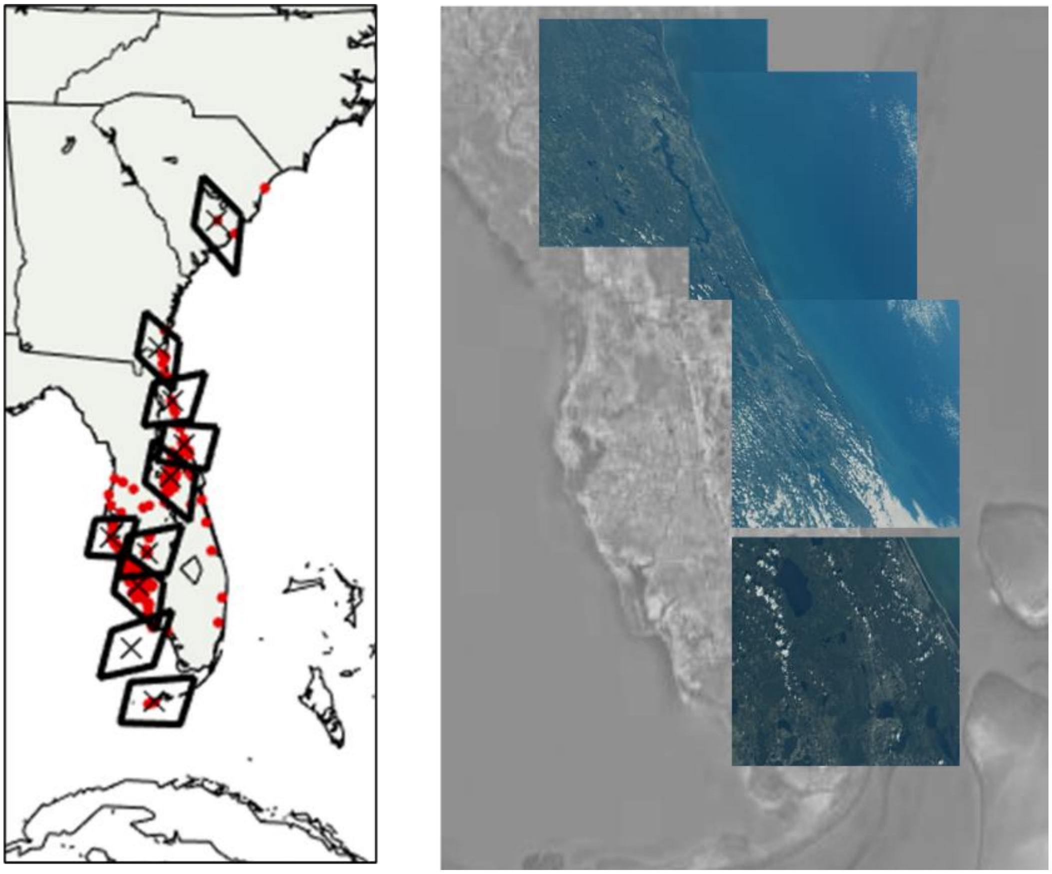


Figure 64. Tasked images and images actually collected. Additional images were collected, but were obscured by clouds.

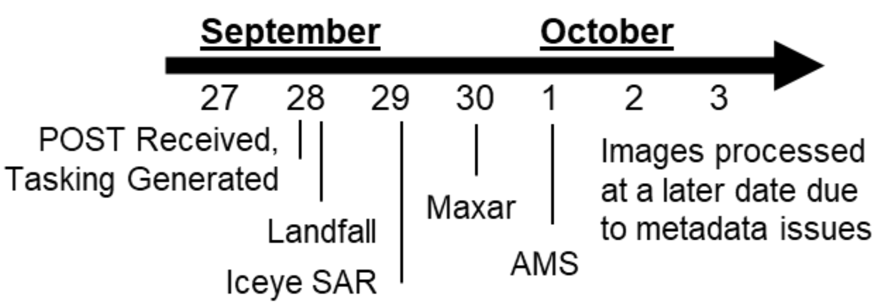


Figure 65. Hurricane Ian timeline of main events.

6.6.7 Outcomes and Lessons Learned

Several lessons learned were recorded from the AMS demonstration of the concept of operations and architecture for satellite remote sensing in disasters.

1. We developed a novel satellite tasking optimization tool that leverages real datasets to maximize limited satellite sensing capacity. A tool like this can be used to optimize collections for larger constellations and across constellations as well.

2. We developed a novel change detection tool that uses algebraic transforms to minimize variance across images collected at different times, under different conditions, by sensors of varied bands and resolutions. The RIRMAD tool is also extensible to SAR and other data types.

3. A complete pipeline begins with tasking and ends with dissemination. During domestic disaster response, these responsibilities are currently spread over a large number of stakeholders who do not all have a shared vision. We hope that this demonstration illustrates an end-to-end solution that delivers truly impactful data products.

4. Satellite imagery can be collected, processed, analyzed, and disseminated with a fairly small team, tight budget, and short timeline. AMS was an experimental cubesat with a low-resolution camera. The tasking model, change detection workflow, analysis, and dissemination were all done with in-house resources by a small team working part time on this project. If we can do it, so can industry. Coordination failures continue to limit the use of satellite remote sensing for a wider variety of disasters, particularly for Type 3 incidents.

5. Clouds are a persistent problem in the first days after hurricanes. This comes as no surprise, but was reinforced by the poor-quality images collected after incidents.

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7. TOWARD SYSTEMATIC USE OF SATELLITE REMOTE SENSING IN DISASTERS

In this report, we have documented the need for satellite remote sensing in disaster response, articulated use cases for satellite data, analyzed requirements for an end-to-end tasking to decision support system, proposed an architecture and concept of operations, and demonstrated a prototype of the mission concept.

We arrive at a critical question: how do we, the emergency management community and partners, realize this vision? Several critical gaps have not yet been discussed, including both technological and social barriers. In this chapter we explore pathways to creating a sustainable “DisasterSat” system and technical considerations for the operation and design of assets. We hope these ideas speak to government, private sector, and academic partners who are already working diligently to advance the use of satellite remote sensing in disasters.

A number of barriers exist to using satellite remote sensing consistently during disasters.

- Information asymmetries: Not the right word, but we need to comment on the fact that we don’t know where a disaster will take place before it happens, even with sophisticated predictions. Bayesian?
- Coordination failures and centralization: Priorities coming from multiple independent actors, different stakeholders are responsible for completing each part of the process. No single entity has taken responsibility for executing the required steps for every incident.
- Capability gap: Most state and local agencies do not have the manpower or skills on staff to request or work with imagery data.
- Processing steps: Although the industry standard for tasking turnaround times is less than 24 hours, this is for a single product, typically of a point target. An example at the other extreme, it takes Google several months, up to a year, to update the Google Earth base maps. [80]
- Data size: Capturing 5 m GSD imagery over the whole world requires trillions of pixels.
- Authorizing users, data access: Federated accounts enable data sharing, but managing accounts across organizations and platforms continues to be a challenge that limits access.

The commercialization of key critical technologies makes satellite remote sensing in disasters not only possible, but also feasible. With rapid growth in the space sector, computing technologies, and sensor design, current systems might be improved and connected. TABLE 31 briefly notes key enabling technologies and challenges that remain.

TABLE 31

Enabling Technologies

Enabling Technology/Concept	Benefit	Challenges
Edge Computing	Completing initial image processing and analysis onboard the spacecraft enables more rapid data transfer and dissemination	Changing use cases, non-standard products, chip design
Cloud Services and Webhosting (e.g., Amazon Web Services, Esri ArcGIS Online)	Hosting and disseminating data from cloud storage enables broad access and use; cloud-based tools also enable decentralized analysis	Optimizing cloud usage, cost, user authentication across organizations, security concerns
Machine Learning and GeoAI Models (e.g., damage detection and classification models)	Automate image analysis and spatial analysis to expedite disaster decision making	Data size, data fusion
Launch Services	Widely available and economical for launching small satellites	Environmental impact of launch and use of space
Commercial Small Satellite Capabilities	Small satellites can now be manufactured at low cost using COTS components	Space is crowded, possible duplication of effort
Space-to-Earth Communication Systems (e.g., inter-satellite link relays, laser communications)	Reduce the time to transmit data enabling near rea-time satellite remote sensing from low-Earth orbit for the first time	Increasingly complex communications systems and frequency spectrum use

7.1 FEDERAL

One pathway to establishing sustainable satellite remote sensing in disaster operations is for the U.S. federal government to fund and procure the means. There are two ways this could happen, one where the government creates a DisasterSat program to run in-house, and one based on contracts with private sector partners.

The first scenario follows the precedent of Landsat, GOES, JPSS, and other Earth-observing satellite programs run by NASA, NOAA, and USGS. Establishing a new "DisasterSat" program following this model requires authorization for a new satellite program, funding, and execution. It could unfold like this.

1. Congress introduces and passes a bill to authorize a DisasterSat program, following any of the usual processes (agendas developed by representatives and senators according at the request of constituents, lobbying, priorities passed from federal agencies, reports and hearings from

academicians and non-profits, etc.) and designates a federal agency to lead the execution of the program.

2. Congress appropriates funds for a DisasterSat program.

3. The lead federal agency issues solicitations, and ultimately contracts, to design the mission, design and build assets, and launch.

4. The lead federal agency establishes mission control, assumes operation of the spacecraft, and builds or leverages existing systems for data processing, analysis, and dissemination infrastructure.

5. The lead federal agency adapts the DisasterSat concept of operations, builds relationships with stakeholders, and responds to incidents.

In the spirit of other Earth-observing system programs, a DisasterSat program would likely be a partnership across multiple U.S. agencies and/or a collaboration with foreign governments. NASA, NOAA, and USGS are the agencies best poised to operate a civil DisasterSat mission.

The NASA disasters program already leverages existing NASA assets and satellite data to create information products during and after disasters. These products are disseminated through the NASA Disasters Mapping Portal and are widely available to the public. NASA maintains partnerships with imagery providers through the Commercial Smallsat Data Acquisition (CSDA) Program. With a long history of designing and launching satellites for civil and scientific applications and making data widely available through the Earth-Observation System Data and Information System (EOSDIS), NASA would be a logical home for a federal DisasterSat mission.

NOAA also operates several Earth-observing satellites, including the Geostationary Operational Environmental Satellites (GOES) and the Joint Polar Satellite System (JPSS), which is co-led by NASA. NOAA uses satellite data to produce frequent information weather forecast products, which are already used to inform operational decisions in emergency management. NOAA also conducts post-incident damage assessments after tornadoes and severe storms. The National Geodetic Survey has a well-established disaster remote-sensing mission under which it maintains aircraft for high-resolution imagery collections of coastal areas after severe disasters. A DisasterSat program led by NOAA, possibly through the National Environmental Satellite, Data, and Information Service (NESDIS) would complement the agency's existing resources for weather monitoring.

The USGS Hazards Data Distribution System (HDDS) is the U.S. government's official repository of disaster imagery. Many imagery datasets collected during incidents are copied into HDDS. However, HDDS lacks a user-friendly interactive interface for non-technical users and requires imagery data to be downloaded as tiles. USGS is a partner in Landsat and hosts Earth-observation data in the Earth Explorer system. Although USGS does not operate satellites, they do disseminate numerous products related to disasters, in particular for geologic and seismic incidents, and would likely make a good partner in executing a DisasterSat program.

As a result of the Fourth Amendment of the U.S. Constitution, Title 10 limitations on the use of military resources for domestic surveillance, the Privacy Act, the Patriot Act, and other domestic privacy and surveillance legislation, the DOD and the intelligence community have limited authorities for collecting aerial and satellite imagery over the United States. A full policy analysis is outside the scope of this study. In practice, DOD partners do not collect, store, or analyze domestic overhead imagery for disaster response activities unless directed by FEMA. A DisasterSat program housed in the DOD or intelligence community would likely raise objections about the inappropriate use of military powers and domestic surveillance.

FEMA is not well-positioned to run a DisasterSat program. The agency does not own and operate aerial assets, but rather tasks federal partners and issues contracts for the use of aircraft and collection of imagery. Although FEMA would be a primary user, likely issuing tasking requests frequently and helping disseminate data products, they would not be developing or operating spacecraft.

In the second scenario, the federal government could issue a set of contracts to procure and disseminate commercial satellite data and derived products. Indefinite delivery vehicles or similar would allow satellite imagery to be tasked ad hoc as disasters occur. Previously, DHS issued an indefinite delivery indefinite quantity (IDIQ) contract with several aerial imagery providers for the purpose of collecting imagery during disasters for both federal and state emergency managers (https://www.dhs.gov/sites/default/files/publications/Overhead%20Imagery-508_0.pdf). Though seldom used at the time, the use of overhead imagery in disaster management has expanded in recent years, and a similar model would suit commercial satellite imagery.

7.2 PRIVATE SECTOR

The most likely near-term way to enable sustainable use of satellite remote sensing in disaster response is through the private sector. Although the existing International Charter for Satellites in Disasters enables private sector partners to provide imagery when requested, the charter is infrequently activated in response to domestic incidents in the U.S. Private sector partners have an opportunity to individually or collectively fill a much-needed gap proactively. We have several recommendations for private sector partners to consider.

1. **Prioritize disasters and task proactively.** Establish thresholds for tasking the collection of disaster imagery and collect proactively, even if an explicit request has not been made. This can reduce lead time and increase the utility of collected data. Establishing disaster response as a primary mission, rather than an ad hoc one, ensures that data will be available to emergency managers when they need it, not only when they request it.

2. **Deliver imagery products and data products through web services.** Imagery on its own can be analyzed by a customer, but analytic products on their own cannot be validated. The value of finished products is increased when delivered with a view of the underlying imagery data. Although SAR imagery is difficult to interpret without training, allowing users to view the source data is important for building trust and understanding. Many companies now routinely deliver imagery through both API REST services and through user-friendly interfaces. Products

delivered as PDF documents are less useful for many users. Many use cases can be satisfied by viewing an RBG image without access to the L1 or L2 products.

3. **Offer liberal end-user license agreements.** Emergency management requires collaboration among a large number of independent actors. Imagery can empower disaster survivors and impacted communities driving recovery. Liberal end-user license agreements are essential for maximizing the value of imagery in disasters. The data must be available to all partners involved in response and recovery.

4. **Develop mission-oriented business models.** Don't make emergency managers pay for the same data over and over. Sell the data to commercial customers, such as transportation companies, consumer goods stores, utilities, and, most importantly, insurance companies. Insurers already purchase overhead imagery data and have similar use cases to federal response partners. Then, data may be provided to emergency management agencies, volunteer partners, and local communities pro-bono. These activities could be part of a corporate social responsibility plan or as a public benefit corporation.

The private sector has ample—and increasing—capability in space. However, to fulfill mission requirements, these assets would need to be operated specifically for disaster response and product delivery would need to be tailored to a large number of changing users. Companies are already making significant contributions in this space and have an opportunity to expand their impact to a larger number of users in a larger number of incidents.

7.3 NONPROFIT/PHILANTHROPY

An alternative operational model would be for a nonprofit or a philanthropic arm of an existing organization to launch and operate a DisasterSat constellation for the sole purpose of providing disaster analytics. As a nonprofit, the organization would avoid the perverse incentives of maximizing profit while providing a public service. The main challenge with this model is that a large amount of capital is needed to launch and maintain a space system. However, the rapid increase in space system technology lowers upfront and launch costs and has greatly increased access to space.

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8. CONCLUSION

As persistent assets, satellites have three value propositions for remote sensing in disasters: 1) they can provide information during catastrophic and non-permissive incidents where field crews lack access, 2) repeat passes can show worsening conditions or track recovery, and 3) they enable the use of remote sensing for low-impact, widespread, and slow-moving disasters, such as rural floods, where aerial and UAV assets are seldom deployed. However, they are currently underutilized. Satellites can currently provide information within 48 or 72 hours, a timeline commensurate with aircraft. With a dedicated constellation of space-based assets and a pre-established tasking, processing, analysis, and dissemination pipeline, this timeline could be significantly reduced to provide information that is operationally relevant during the response phase of many more disasters than are currently served.

This study makes three several major contributions as documentation and exhortation on satellite remote sensing in disaster response. Section 4 documents stakeholder-specific use cases for satellite imagery and derived products, following a detailed discussion on use cases for remote sensing in disaster management in Section 2.4. Section 5 evaluates key requirements and recommends specifications to fulfill mission needs. Section 6 presents a concept of operations and high-level architecture to enable consistent use of satellite remote sensing in disasters. We then demonstrated this concept with a prototype workflow designed for use with the Agile MicroSat and responded to several incidents in 2022.

Future work follows several threads. First, we are working to use the tasking model to explore further questions about optimal constellation design for disaster response. Second, ongoing satellite design projects are exploring concepts for small satellite designs tailored to disaster response applications. Third, an extension of the system analysis presented here ought to consider how satellites, aircraft, UAVs, and other platforms could best come together to enable a multi-modal remote sensing architecture to meet emergency managers' needs.

In summary, satellite remote sensing continues to hold great promise for applications in emergency management. We have been discussing this for the better part of 40 years. Today we have unprecedented access to space that makes satellite remote sensing in disasters feasible. A dedicate, built-for-purpose constellation could be manufactured and launched for less than $100M. We hope this report elucidates what it would take to have satellite imagery and derived information for every disaster, big or small, and provides a vision that motivates discussion of how to bring this system into existence.

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APPENDIX A. ANNOTATED BIBLIOGRAPHY ON USE CASES FOR REMOTE SENSING IN DISASTER RESPONSE

Numerous reports in the latter half of the 20th century pointed toward optimistic future applications of satellite remote sensing in disasters. Excerpts from several reports focusing on satellite imagery are highlighted here.

- *Current Status of NASA's National Resource Program,* NASA (1966). "An important advantage of satellite photography is the aspect of real-time data acquisition. With these characteristic remote areas of special significance could be canvassed on short notice, thus providing information on impending disasters such as tsunamis, and forest fires, and studying disaster areas which result from storms, Earthquakes, etc. Many of these problems such as Earthquakes, volcanoes, air-sea interactions, fish migrations, crop growth, and disease, etc., are global in nature and are consequently best studied by globe encircling data gathering systems." [51]

- *Public Health Implications of Remote Sensing*, (1971). This report suggests several ways remote sensing could shed light on disaster conditions in the context of sensing for public health, including, "location of water and sewerage line breaks, human and animal bodies, damaged life-support shelters, energy and power loss, debris and rodent harborages, food, water, and emergency health requirements, and impending epidemic danger. [24]

- *Planning for a Civil Operational Land Remote Sensing Satellite System: A Discussion of Issues and Options*, Joint Satellite Taskforce (1980). "Information from [Landsat] has proven of value to a variety of public and private sector users in the United States and abroad for helping to make decisions related to such areas as agricultural crop forecasting, rangeland and forest management, mineral and petroleum exploration, mapping, urban and regional land use planning, water quality assessment and disaster assessment." [52]

- *The Future of Remote Sensing from Space: Civilian Satellite Systems and Applications*, U.S. Congress Office of Technology Assessment (1993). "Satellite images can be used whenever a major natural or technological disaster strikes and massive breakdowns of communication, transportation, public safety, and health facilities prevent the use of normal means of inventory and assessment… properly interpreted data used with models can be used to predict the onset of natural and technological disasters." [27]

- *Remotely Sensed Data Technology, Markets, and Management*, U.S. Congress Office of Technology Assessment (September 1994). "As the recent experiences of Hurricane Andrew, with the Midwest floods, and the Los Angeles Earthquake have demonstrated, remotely sensed data can be extremely useful for assessing the damage after a natural disaster. Of more Importance, such data can also be used to prepare for natural disasters by analyzing areas most at risk, identifying escape routes, and making specialized maps to guide assistance efforts. The broad availability of digital data and geographic Information systems for analysis makes these complicated tasks much easier than ever before. Thorough citizen preparation in land and coastal regions at risk could save millions of dollars in state and federal disaster relief and possibly save lives as well. However, such preparation will require a coordinated effort by local, state, and federal agencies." [26] This source also identifies insurance companies as a potential consumer of historic climate data to settle weather-related disaster claims.

- *Civilian Satellite Remote Sensing: A Strategic Approach*, U.S. Congress Office of Technology Assessment (1994). "GIS technologies have proved especially useful in creating geographic overlays that show the extent of damage, the locations of potential emergency centers, and the best routes for moving people and emergency supplies through affected areas. State and local governments feed into the development of the GIS by supplying data about the locations of state and local facilities. 12 For example, the Army Corps of Engineers, FEMA, and state agencies collaborated on assessing damage from the 1992 floods along the Missouri and Mississippi Rivers. Such assessments helped in determining which areas were most severely affected and how to allocate disaster relief funding." [53]

In 1973, a severe tornado occurred in Pierre, South Dakota. The University of South Dakota Remote Sensing Institute collected aerial photographs on film the following day [14]. In their report to NASA documenting the incident, authors Rusche and Myers identify 11 actions that can be informed by aerial imagery.

1. Restoration of lines of communication such as roads, streets, telephone lines and airport facilities
2. Elimination of health hazards such as ponded water, exposed breaks in sewer and water lines, broken electrical lines, damaged sewage treatment areas, etc.
3. Assessment of property damage for mortgage and insurance purposes
4. Establishment of overall damage cost to support emergency funding requests
5. Determination of temporary housing needs
6. Location of central points for disaster aid stations
7. Observation of vegetation destruction to determine reseeding and replanting requirements
8. Recommendations for rezoning to avoid similar damage in case of future flooding
9. Assessment and impact of crop damage
10. Determination of crop spraying or reseeding requirements
11. Determination for the requirement for alert messages to surrounding areas in the case of crop disease or insect infestation

They note the importance of capturing imagery as soon as possible after a disaster to inform post-disaster cleanup and recovery operations. This paper was written six years before FEMA was established and primarily reflects state and local use cases.

In a 1976 NASA-funded study, *Potential Role of Remote Sensing in Disaster Management,* researchers at the University of Texas Health Science Center highlight the importance of early information during disasters and call out several areas where early information shared widely can avoid duplication and enable more effective decisions [13]. Notable decisions they discuss are summarized in TABLE 5.

TABLE 32

Decisions Supported by Imagery, Summarized from [13]

Information Derived from Imagery	Decisions Enabled
Number of persons dead, persons with injury or illness, persons hospitalized	Scale and locations to provide medical services
Degree of damage to residential structures and businesses	Number of shelters and amount of food required
Damage assessments	Recommend a federal disaster declaration.
Damage to transportation infrastructure	Determine routes for bringing in supplies and personnel
Information on recovery of water and sewage infrastructure and damage to transportation systems	More efficient resource allocation and prioritization
Population and area size affected	
Identify standing water	Vector control
[Pre-disaster] Identification of vulnerable facilities	Mitigation and preparedness activities

The authors identify several advantages to using remote sensing, specifically aerial imagery, in disasters.

- Remote sensing may be the only form of information if field operations are not possible, such as in fire, high floods, or radiation environments
- Pre- and post-disaster images can be used together for future incident planning
- Photographs provide a permanent record of damage
- Show spatial extent of the disaster and geographic distribution of impacts

They suggest that imagery can be used to reduce the time and manpower required to collect this information, given the right conditions. As an example of the potential benefits, the authors state that it would take 1000 volunteers 2–3 weeks to survey damage in a city the size of Houston after a disaster, and that 3–5 Red Cross nurses would need 3–4 days to estimate the number of ill and injured patients. Although this information could presumably be provided more quickly with less effort through imagery, baseline data, pre-incident imagery, a reliable communication network, and mechanisms for rapid collections must exist, and the collection planes, crews, equipment, and laboratories must be available.

This report is the earliest analysis we found that specifies which *essential elements of information* for disaster response could be obtained with remote sensing, reproduced in the box below.

Identifiable Items on Aerial Photographs [13]

1. Structural Damage

Community facilities

- Hospitals and medical
- Schools
- Churches
- Fire stations
- Police stations

Developed recreational areas

- Civic buildings
- Buildings designated as shelters

Residential

- Single family
- Mobile homes (Trailers)
- Multi-family 1-3 story
- Multi-family - over 3 story

Commercial

- Office
  - Highrise
  - other
- Retail outlets
- Motels and hotels

Industrial

- Large manufacturing
- Light industrial
- Wholesale and warehouse
- Storage tanks

Agriculture

- Farming
- Forage

2. Damage to Transportation Routes

Streets

- Obstructed trees/poles
- Structural debris
- Road washout
- Disrupted road surface

Collapsed bridges

Collapsed elevated roadways and subways

Disrupted railroad lines

Airports

- Structural damage
- Damage to runways

Harbors

Ports

3. Damage to Utilities

Broken water mains

Contaminated reservoirs or wells*

Damage to pumping stations

Broken sewer lines

Damaged pumps

Damage to treatment plant

Power plant damage (atomic, regular)

Transformer stations

Downed power/phone lines

4. Areas of Inundation
5. Occurrence of ponded water areas (a potential health hazard)
6. Accumulated rubble and brush
7. Fire damage
8. Safe or shelter areas

This study also specifies information needs related to decision making around infrastructure [13].

- Info needed about water: (1) Is the pumping and distribution system undamaged and operating? (2) Is power available to operate the pumps? (3) Is potable water available? (4) Is the water contaminated? (5) Are supplementary water supplies needed?

- Sewer system questions: (1) Is the sewer system (collection system and treatment plants) working? (2) Is there a need for supplementary facilities?(3) Are these facilities available locally? Sewer systems are underground and cannot be seen with aerial imagery.

- For assessing the number, location, and capacity of shelters needed, the following information: (1) an assessment of the degree of damage to residential areas, (2) an estimate of the population evacuating who suffered major damage to residences, (3) an assessment of the degree of damage to shelters, and (4) information about whether transportation routes to shelters are open. Aerial imagery can show the number of homes damaged (and therefore an estimate of displaced population) and may be used to select sites for temporary housing.

- Food: (1) Is the food supply contaminated? (2) Is the local food supply sufficient? (Figure 5) The information needed to answer these questions includes: (1) an estimate of the number of people who need to be fed and the duration of this need; and (2) an estimate of the quality and quantity of food locally available for use. Imagery may be used for identifying food distribution points and routes to shelters, hospitals, and populated areas.

- Transportation: Condition of major transit routes and whether they are open; prioritize route clearance and repair; designate alternate routes; blockages and damage to roads; condition of bridges, railroads, terminals, runways, overpasses, and tunnels.

In 1979, the National Research Council examined the extent to which remote sensing at the time could be used to aid in international disaster response [25]. Acknowledging that remote sensing provides great utility for weather sensing, hazard prediction, and land use planning, the authors describe the promise and limitations of remote sensing. “Theoretically, remote sensing also offers the possibility of acquiring data over regions made inaccessible by disruption of normal transportation and communications systems in such areas, information may be needed about debris or sediment deposits and similar problems that threaten health and life. In practice, however, remote sensing data may not be obtained soon enough after a disaster to be used for this purpose.”

They identify several problems with the proposal to use early Landsat data in disaster response: low resolution (80 m), long revisit times (18 days), the need to handle huge amounts of data, optical sensors inhibited by clouds, expertise needed to interpret imagery, and the cost of acquiring data. Limitations with aircraft include large area coverage is costly and time consuming, and limited number of highly capable aircraft.

ESA Satellite Remote Sensing in Hazard Monitoring and Disaster Evaluation [44]

- Observing rain clouds and flooded areas

- Tracking hurricane path, windspeed, rainfall
- Monsoon monitoring
- Focused on natural hazard monitoring, for which remote sensing has become commonly used over the last 50 years

In the late 1990s, discussions around the use of remote sensing in disaster response became more common. The response to the September 11th terrorist attacks on the World Trade Center was one of the first catastrophic incidents where overhead imagery was used to provide operational information, specifically for… [10]. In a contemporaneous conference, emergency management professionals discussed that having technical experts advise a centralized remote sensing coordination unit enables more effective remote sensing tasking and dissemination [11].

Hurricanes Charley and Ivan in 2004 are considered the first major hurricanes in the U.S. for which high-resolution satellite imagery was available [12].

In 2007, the National Research Council published another report, *Successful Response Starts with a Map* [28], that documents the importance of—and challenges with—imagery and other geospatial technologies in disaster response.

A 2008 article proposed a spatial data infrastructure (SDI) for utilizing remotely sensed data and GIS to assist the Government of India's emergency response operations [43]. They note that the goal of decisions is to reduce vulnerability to hazards, diminish the impact of disasters, and to prepare for, respond to, and recover from those that occur. Geospatial tools provide the following information: the extent of the area affected, location specific details, population affected, evacuation routes, and rapid damage assessments. Data can be used for early warning, risk prediction, situational analysis, damage assessment, and thematic hazard maps

The authors provide an example of how specific data can be used to select shelter locations. They list four site selection criteria and describe the required analysis steps.

Shelter Site Selection Criteria

- The location should be accessible through road with in 2 km
- It should be located in a village/settlement
- The area should not be affected by an historic flood incident
- It should be on a relatively high ground.

Analysis Approach

1. Using the road network, create a 2 km buffer zone around roads

2. Extract villages/settlements within the buffer zone
3. Using historic flood inundation data, delineate areas inundated and not-inundated in the last 10 years
4. Extract selected villages / settlements that were not inundated during last 10 years
5. Using the elevation data, assign the elevation to each of the settlements

For the system described in this study, users would be able to access the results of this automated analysis through a web browser and download the recommended shelter location sites.

Utilizing New Technologies in Managing Hazards and Disasters [19]

The University of South Carolina has produced several notable studies on the utility of overhead imagery in disaster response. [33, 31, 41, 32]. In 2005 and 2011, with support from the Department of Homeland Security Science and Technology Directorate, Michael Hodgson's research group conducted two surveys—as far as we know, the only such ones—on how State and Local emergency managers use geographic data and imagery. In the 2005 survey, they found that emergency managers perceive imagery to be quite useful across disaster types, but barriers to adoption include cost, collection time, processing time, staff technical skill, and accuracy [33].

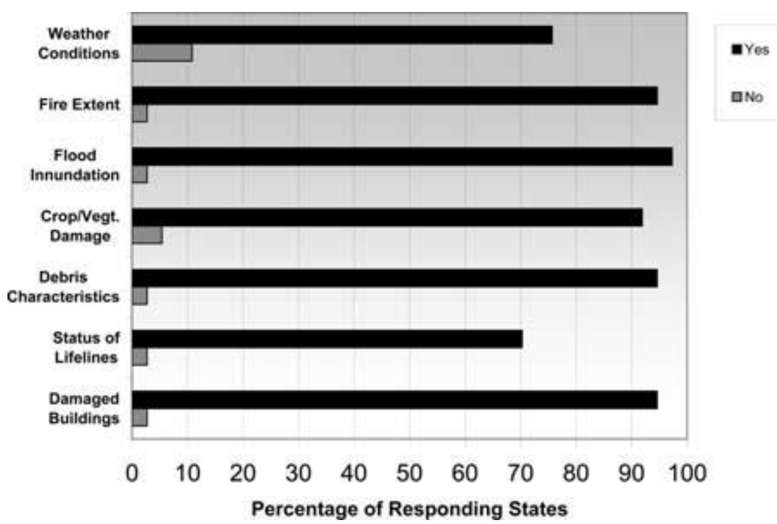

Figure 66. Perceived utility of remote sensing for different phenomena, post-disaster, if resources were available for collecting imagery, reproduced from [33].

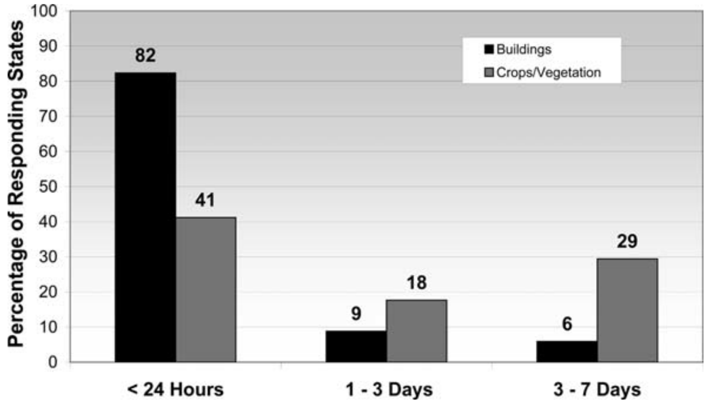

Figure 67. Information regarding damage to buildings or crops/vegetation needed within a specified time period after a disaster incident, reproduced from [33].

In the 2011 study, Hodgson's team found that aerial imagery was the second most important baseline GIS data layer among respondents and that understanding the extent of the disaster and damage to transportation systems is crucial. While some sources report that imagery is most useful for response decision making within the first 100 hours after an incident [5], Hodgson’s team also found and that imagery-derived information on building damage, critical infrastructure damage, and transportation damage is most useful within 24 hours of an incident and becomes only moderately useful after 72 hours [32]. Many state emergency managers indicated an expectation that the federal government would collect and pay for imagery.

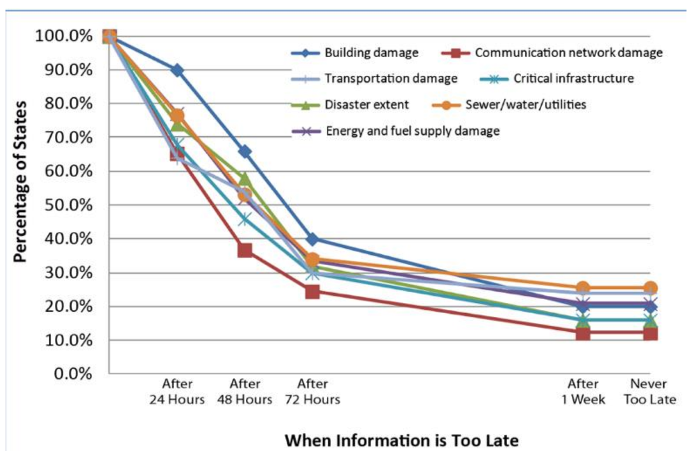

Figure 68. Empirical curve derived from state responses for when post-disaster imagery information is too late for the emergency response phase, reproduced from [41].

In 2012, Hodgson's team conducted a cognitive study on the image resolution required to determine building damage severity [31]. They found that, for panchromatic imagery, resolutions finer than 1 m GSD did not improve interpretability in a statistically significant way, and that 1.5 m GSD was the threshold for acceptable resolution.

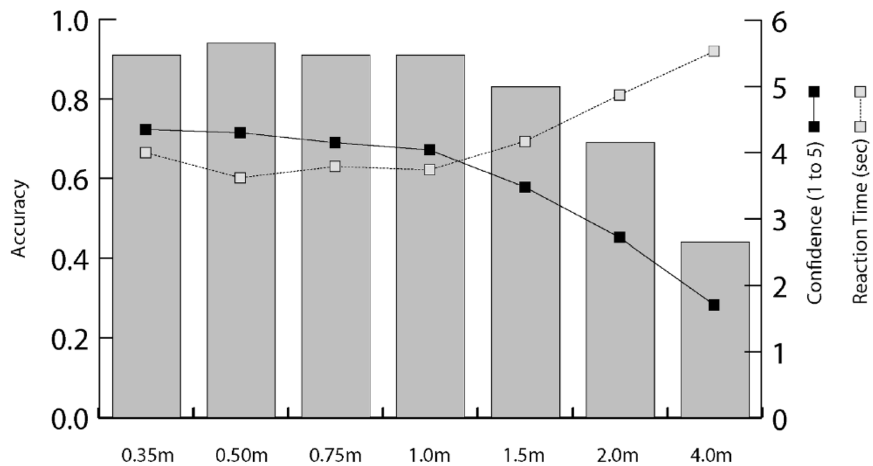

Figure 69. Relationship between image resolution and accuracy, reaction time, and confidence aggregated across experience levels, from [31].

A 2011 report commissioned by FEMA explored uses of remotely sensed data to conduct damage assessments after tornadoes in Joplin, MO; Tuscaloosa, AL; and Birmingham, AL [30]. They describe three levels of damage assessment: determining the geographic extent of visible damage, profiling the severity of damage by square kilometer, and conducting structure-level damage assessments. For the latter, they found that 25 cm aerial imagery was ideal for determining the level of damage to buildings. In these two cases, imagery was available one to two days after collections, took three days to analyze, and took two days to validate. NOAA aerial imagery was used because available satellite images from Geoeye-1, Ikonos, Spot, Landsat 5 and 7, and ASTER had limited coverage or resolution was too low. The team developed the damage assessment scale reproduced in TABLE 4 to describe features of buildings that have sustained different levels of damage.

TABLE 33

ImageCat Damage Protocol Remote-Sensing Damage Classification Scale Utilized in Tuscaloosa/Birmingham/Joplin Tornado Damage Assessments [30]

FEMA DAMAGE CLASSIFICATION			REMOTE SENSING BASED CLASSIFICATION			
DAMAGE LEVEL		OBSERVED DAMAGE	Roof Covering	Roof Diaphragm	Collapsed Walls	Other Considerations
LD	Limited Damage	Generally superficial damage to solid structures (loss of tiles or roof shingles); some mobile homes and light structures damaged or displaced.	Up to 20%	None	None	Gutters and/or awning; loss of vinyl or metal siding
MD	Moderate Damage	Solid structures sustain exterior damage (e.g., missing roofs or roof segments); some mobile homes and light structures are destroyed, many are damaged or displaced.	>20%	Up to 20%	None	Collapse of chimney; garage doors collapse inward; failure of porch or carport Mobile homes could be partially off foundation
ED	Extensive Damage	Some solid structures are destroyed; most sustain exterior and interior damage (roofs missing, interior walls exposed); most mobile homes and light structures are destroyed.	-	>20%	Some exterior walls are collapsed.	Mobile home could be completely off foundation – if appears to be repairable.
CD	Catastrophic Damage	Most solid and all light or mobile home structures destroyed.	-	-	Majority of the exterior walls are collapsed.	-

A subsequent 2013 report captured case studies on Hurricane Katrina in 2005, the 2011 tornado in Joplin, Missouri, the 2011 Souris River flood in Minot, North Dakota, and the 2010 Haiti Earthquake [16]. The authors state, "Remote sensing technologies are currently the most advanced technology readily available hat is able to communicate rapidly the magnitude and spatial extent of damage and to provide actionable information." As a benefit, remote sensing can enable better, faster damage assessments, diminish the number of disaster-related causalities, and reduce hazards for disaster personnel and survivors.

The following data products were developed from remotely sensed data.

- Nadir orthographic optical (RGB) images
- Nighttime lights data
- Power outage maps

- Video feeds from the field
- Inundation boundaries and estimated depths

Across these cases, imagery was used to provide the following information.

- Extent of impact
- Areas of most severe impact
- Situational awareness
- Hazard locations (e.g., which areas are flooded)
- Logistical concerns to transportation
- Impact to at-risk communities
- Potential risks of cascading impacts
- Condition of lifeline infrastructure
- Building-by-building damage assessments

Imagery was also used to inform the following decisions and actions.

- Streamlining disaster declarations
- Navigating in the field
- Search and rescue prioritization and operations
- Relief distribution
- Declarations (via preliminary damage assessments)
- Monitoring recovery progress

They describe several modes through which imagery is utilized for these purposes.

- Loaded into mobile devices
- Loaded onto laptops
- Served into GIS and web-mapping applications

"Responders distrust products, such as interpreted damage, that is delivered when either the source data or the processing steps are not transparent."

They note that satellite imagery, specifically, provides insight on the regional extent of damage, severity of damage, and environmental constraints that affect response.

"Deploying remote sensing data with field tools allows for the validation of preliminary damage estimates, situational awareness, and widespread dissemination of a common operating picture."

TABLE 34

Remote Sensing Damage Assessment from the Case Studies and Recent Incidents [16]

Type of Incident	Hazard Extent	Building Damage	Infrastructure
Flood	• Inundation area • Duration of flooding • Flood surface depth	• Presence of flooding • Depth of flooding above first floor elevation	• Blocked roads • Submerged bridges • Bridge washout/collapse • Overtopped dams and levees • Inundated power plants, factories
Surge and Tsunami	• Presence of debris • Surge extent (wrack line)	• Complete and extensive building damage • Indications of non-catastrophic inundation	• Damage to roads • Blocked roads • Bridge damage • Bridge washout • Displaced oil rigs • Port and marina damage • Nuclear reactor status
Earthquake	• Fault rupture and displacement • Liquefaction • Inundation from subsidence • Landslides	• Complete and extensive building damage • Number and square footage of damaged buildings (leading to estimated loss) • Building debris	• Blocked roads • Bridge damage • Damage to wharfs, ports, and piers
Wind (hurricane and tornado)	• Wind speed estimation • Debris estimation (urban and forestry)	• Complete and extreme damage, some moderate	• Levee failure • Damage to wharfs, ports, piers • Power outage • Offshore oil rig damage/extent

RS in Haiti EQ building damage assessments [29]

U.S. government reports are a primary source of information on uses for remotely sensed data in domestic disaster operations [34, 35, 36, 37, 38, 39, 40].

- FEMA Remote Sensing in Federal Disaster Operations Standard Operating Procedure – the first known doctrine produced by FEMA on the use of remote sensing [34]
- FEMA Geospatial Framework – describes which geospatial data products might be created as a disaster unfolds [35]
- Satellite Data for Preparedness and Response [36]
- Emergency Response Remote Sensing Products [37]
- FEMA Geospatial Guide to Disaster Operations, also called the GeoGuide – offers guidance to federal, state, and local emergency managers on using geospatial technologies in disasters [38]
- DHS GeoConops – originally launched in 2010, this online resource lists existent geographic datasets and provides guidance to emergency management practitioners on how to use available tools [39]
- IS-922.a Applications of GIS for Emergency Management – FEMA's Emergency Management Institute offers an online course that includes use cases for imagery in emergency management [40]

Report from the Workshop of Field-Based Decision Makers Information Needs [81]

[5]

Role of Geospatial Technologies in the Continuum of Natural Disasters [75]

OGC Development of Disaster Spatial Data Infrastructures for Disaster Resilience, 2018 – shows how imagery fits into a larger geographic data schema for disasters. [82]

Standardizing Remote Sensing Data Collection at FEMA, Ran 2019 https://www.gim-international.com/content/article/standardizing-remote-sensing-data-collection-at-fema

GIS in Humanitarian Assistance a Meta-Analysis [83]

In 2021, the FEMA Response Geospatial Office conducted a study, led by one of the authors in a previous position, to identify use cases and requirements for an imagery management system [42]. The study proposes a generalized framework of abstract use cases, visualized below, focused on the administrative functions achieved by using information from imagery. These four categories are useful for thinking about motivation and end goal at a highly abstracted level.

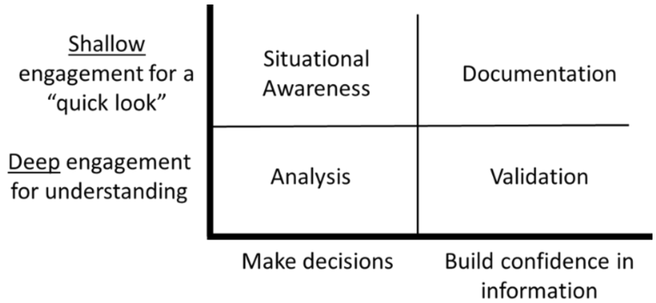

Figure 70. Abstract uses for remotely sensed data in emergency management.

Situational awareness, also described as “sense-making”, is to gain a broad, unstructured understanding or picture of what is happening on the ground during response operations or program delivery. Quantitative or qualitative analysis may be used to derive new data or new information from imagery. Imagery is regularly used as evidence of disaster damage and to document disaster impacts. Finally, imagery is used to validate, or gain confidence, in third-party reports.

The study also explored how users want to interact with imagery and identified four types of end-users.

- Viewers: use imagery to quickly learn about conditions on the ground during or after a disaster (situational awareness) and to document incident conditions or damage.
- Visual Analysts: visually interpret imagery to derive new information or validate third-party information.
- Computational Analysts: use algorithms and local or cloud processing to derive new information from imagery.
- Subsequent Data Managers: add data to their applications for their users.

This study identified 14 "user needs," or, actions users wish to perform with imagery data, and 8 corresponding requirements for imagery data management systems. Tables summarizing findings have been reproduced in Appendix B for reference.

APPENDIX B. USER NEEDS AND IMAGERY DATA REQUIREMENTS

Reproduced from [42]

User Needs

	Users Need to… [Needs]	**Main Users**	**Description**
1	Know Where Imagery Will Be Collected	Data Managers, End Users, Imagery Collection Managers	Need to know what imagery will be collected, what area will be covered, and when it will be available. Visibility into tasking and delivery timelines helps users plan operations and identify additional collection requirements.
2	Ingest Data Automatically	Data Managers	Data managers can set up automated pipelines to ingest, process, index, and publish new imagery from known suppliers as soon as it is available.
3	Acquire, Process, Host Versatile Data Types in a Single Location	Imagery Collection Managers, Data Managers	Data managers need to be able to ingest, index, process, and host various types of data in multiple formats in one system. See Appendix F for a complete list.
4	Comply with Privacy Office Requirements	End Users, Data Managers	RGO staff must review certain datasets to identify and remove incidental PII using manual or automated processes.
5	Add Data to Web Applications	Data Managers, Subsequent Data Managers	Data managers and subsequent data managers frequently make imagery available to other end users by adding imagery layers to custom web applications and mobile apps.
6	Manage Access	Data Managers	Data managers ensure users have access to the imagery they need through federated accounts, that public imagery remains public, and that imagery data with restricted use requirements remains protected.
L	Find Available Imagery for a location	All End Users	Users need to be able to indicate a point or area of interest and receive a list of imagery layers available for that location. Ideally, this list would also provide some information on the quality of the imagery (e.g.,

			resolution, time of collection, whether it contains clouds, completeness of metadata) or include thumbnail excerpts. Users then need to be able to select desired imagery sets and view the indicated location directly in the browser.
8	View Image Footprints	End Users	Users need to know what imagery was collected and what area is covered by a given dataset or point photo.
9	View Pre- and Post-Incident Imagery	Viewers, Visual Analysts	Many users expressed the desire to compare pre- and post- incident imagery, viewing it side by side or in a format that allows a user to easily toggle back and forth.
10	Download or Capture Images	Viewers, Visual Analysts	Users must be able to either indicate an area to download or to take a screenshot of imagery.
11	Use Imagery in Models in Conjunction with Other Types of Data	Computational Analysts, Data Managers	Users need to be able to integrate imagery pixels, points, and derived products into models.
12	Visually Analyze Imagery	Visual Analysts	Users visually analyze imagery to assess and validate damage to structures, identify and type debris piles, determine viable locations for temporary housing, and derive or validate other information about an incident.
13	Edit Symbology (Pixel Values)	Visual Analysts	Viewers and visual analysts may wish to edit pixel symbology, such as contrast, band balance, saturation, or exposure, to better see what is depicted in an image.
14	Computationally Analyze Imagery	Computational Analysts	Through automated imagery exploitation, users can rapidly extract information about disaster damage, priority areas, or other impacts from imagery. Algorithms require a large amount of scalable processing power.

Requirements

	Requirement	Related Needs	Description
1	Upload Images	1, 3	System must allow users to upload all types of imagery.
2	Index Images	1-3, 7-9, 11, 12	System must automatically index new imagery by spatial and temporal attributes and other metadata.
3	Host Imagery with REST Endpoints	3, 5, 7, 9-13	System must host all imagery with OGC-compliant REST services.
4	Support Cloud-Based Geoprocessing Services	2-4, 8, 11, 14	System must allow users to automate imagery ingestion, process, exploit imagery, and complete other computational processes in the cloud.
5	Send Notifications	1, 2, 4 ,7	System must have the capability to alert users on the status of designated processes (e.g., uploading images, processing imagery).
6	Control Access	2-6, 8, 14	System must allow Data Managers to set user permissions and designate access levels for datasets and other capabilities.
7	Scalable Storage, Processing, and Bandwidth Capability	2, 3, 5, 7, 9, 14	System must be able to adapt to uncertain and extreme changes in the number of users, processing power, and storage required, especially during response incidents when usage is likely to surge.
8	Feed Specific Applications	1, 5, 7-10, 12-14	System must provide specified applications for users to interact with imagery and allow imagery to be useful when served into external apps.

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APPENDIX C. FIELD DEFINITIONS OF THE OPERATIONAL SPACEBORNE IMAGING SATELLITE SURVEY

Appendix primary author: Sean Anklam

SATELLITES SURVEYED

Owner/Operator	Nationality	Owner/Operator Type	Platform Name	Sensor Name
MAXAR Technologies	USA	Commercial	WorldView-3	WorldView-3 MSI
MAXAR Technologies	USA	Commercial	WorldView-3	WorldView-3 Pan
MAXAR Technologies	USA	Commercial	WorldView-3	WorldView-3 SWIR
MAXAR Technologies	USA	Commercial	WorldView-3	WorldView-3 CAVIS
MAXAR Technologies	USA	Commercial	WorldView-2	WorldView-2 Pan
MAXAR Technologies	USA	Commercial	WorldView-2	WorldView-2 MSI
MAXAR Technologies	USA	Commercial	WorldView-1	WorldView-1 Pan
NASA/USGS	USA	Civil	Landsat-8	OLI
NASA/USGS	USA	Civil	Landsat-8	TIRS
NASA/JPL/METI	USA, JP	Civil	Terra	ASTER
ESA/Copernicus	EU	Civil	Sentinel-2a/b	Sentinel-2a/b
ESA/Copernicus	EU	Civil	Sentinel-1a/b	Sentinel-1a/b
Airbus Defence & Space/CNES	FR	Joint	Pleiades-a/b	Pleiades-a/b
Airbus Defence & Space	FR	Commercial	SSTL-S1	Vision-1
Airbus Defence & Space	FR	Commercial	SPOT 6/7	SPOT 6/7
Airbus Defence & Space/DLR	FR, GER	Joint	TerraSAR-X	TerraSAR-X
Airbus Defence & Space/DLR	FR, GER	Joint	Tandem-X	Tandem-X
Airbus Defence & Space	FR, ES	Commercial	PAZ	PAZ
Airbus Defence & Space	FR, UK	Commercial	NOVA SAR	NOVA SAR
Airbus Defence & Space	FR	Commercial	Pleiades-Neo 1-4	Neo 1-4
SI Imaging Services	SK	Commercial	KOMPSAT-2	KOMPSAT-2

SI Imaging Services	SK	Joint	KOMPSAT-3A	KOMPSAT-3A
SI Imaging Services	SK	Joint	KOMPSAT-3	KOMPSAT-3
SI Imaging Services	SK	Joint	KOMPSAT-5	KOMPSAT-5
Planet Labs (formerly Sky Box)	USA	Commercial	SkySat-C 2 - 21	SkySat-C MSI 2 - 21
Planet Labs (formerly Sky Box)	USA	Commercial	SkySat-C 2 - 21	SkySat-C FMV 2 - 21
Planet Labs (formerly Black Bridge)	USA	Commercial	RapidEye 1 - 5	RapidEye 1-5
Planet Labs	USA	Commercial	Dove 1 - 180	PlanetScope-1 - 180
ICEYE	FIN	Commercial	ICEYE-X 1-10	ICEYE-X 1-10
Capella Space	USA	Commercial	Denali	Denali-1 - 6
CSA/MDA	CAN	Joint	RADARSAT-2	RADARSAT-2
JAXA	JP	Civil	ALOS-2	PALSAR-2
JAXA	JP	Civil	ALOS-2	PRISM
Maxar Technologies	USA	Commercial	GeoEye-1	GeoEye-1
Satellogic	AR	Commercial	NuSat	Aleph 1 - 17
Satellogic	AR	Commercial	NuSat	Aleph 1 - 17
Satellogic	AR	Commercial	NuSat	Aleph 1 - 17
GeoSat	ES	Commercial	GeoSat-1	GeoSat-1
GeoSat	ES	Commercial	GeoSat-2	HiRAIS/EOS-D
Spire Global	UK/LU	Commercial	Lemur	Lemur 1 - 143
BNISR/CCRSDA	BR/CN	Government	CBERS-4	MUXCAM
Space Will	CN	Commercial	SuperView-1 - 5	SuperView
ImageSat International	IL	Commercial	EROS-B	PIC-2
Chang Guang Satellite Technology	CN	Commercial	Jilin-1-O	Optical
Chang Guang Satellite Technology	CN	Commercial	Jilin-1-H	Hyperspectral
Chang Guang Satellite Technology	CN	Commercial	Jilin-1-SV	Smart-Video

BlackSky	USA	Commercial	Global 1 - 12	SpaceView-24
Orbita Aerospace	CN	Commercial	Zhuhai 1	OVS-1A/1B
ST Electronics	SG	Commercial	Teleos-1	Teleos-1
KNSA	KZ	Government	KazEOSat-1	KazEOSat-1
NSPO	TWN	Government	FORMOSAT-5	FORMOSAT-5
CNS	CN	Government	GAOFEN-5	AHSI
GHG Sat Inc.	CA	Commercial	GHG-SAT	GHG-SAT-D
Geo Optics	USA	Commercial	CICERO	CICERO-6
Orbital Micro Systems	USA	Commercial	GEMS	GEMS 1-50

SURVEY FIELD DESCRIPTIONS

1. **ID:** 3 number ID for Owner, 4 letter/number Acronym for Sensor/Platform. Example, NASA Landsat-8 OLI = 001LS8O or Maxar WorldView-3 Panchromatic = 002WV3P

2. **Owner/Operator**: Name of corporate or government entity that owns and operates the satellite. Sometimes the owner is different from the satellite operator

3. **Nationality**: Country of origin of the satellite owner; expressed as a 2–3-digit country code

4. **Owner/Operator Type**: Commercial (private), Civil (government), or Joint (both)

5. **Manufacturer**: Name of the entity that created the satellite which is often different than the Owner/Operator

6. **Platform Name**: Name of the satellite bus that houses the sensor(s). Some satellite platforms contain multiple sensors performing vastly different functions

7. **Platform Type**: Standard form factor options include

   - Large Sat
     i. Dimensions: L is >2.5 m, D is >2 m, W>3 m
     ii. Weight: >1,000 kg
     iii. Reference: generally ranges in size from a large van to a full-sized school bus

   - Small Sat
     i. Dimensions: L is <3 m & >1 m, D is <2 m & >75 cm, W is <2.5 m & >75 cm
     ii. Weight: <1,000 kg & >100 kg
     iii. Reference: generally ranges in size from a full-sized refrigerator to a mini fridge

   - Micro Sat

    i. Dimensions: L is <75 cm & >25 cm, D is <75 cm & >20 cm, W is <30 cm
    ii. Weight: <100 kg & >10 kg
    iii. Reference: generally ranges in size from a desktop computer tower to a shoe box

- Nano Sat
    i. Dimensions: L is <25 cm, D is <20 cm, W is <20 cm
    ii. Weight: <10 kg
    iii. Reference: generally smaller than a shoe box and can be as small as a rubix cube

Note: Satellite size and weight definitions are fuzzy and some satellites, for example, can be extremely large in one set of dimensions and disproportionally small in others. Generally, the largest dimension on both large sats and small sats will be their fully deployed solar array width, which can be as large as 7–10 m across. Conversely, the array width is typically the smallest dimension on a micro-sat and nano-sat as they don't have deployable solar arrays and instead use small solar cells fixed to the body of the cube-sat form factor typical of satellites in these two classes. Weight can also fluctuate quite dramatically for large sats. Large sats in the 1,000 kg–2,000 kg range typically have a single sensor payload, whereas large sats with multi-sensor payloads can weigh as much as 3,000 kg–7,000 kg. Large satellites deliberately designed for very long-term life cycles will have a great deal of extra weight dedicated to redundant sub-systems, multiple forms of propulsion for orbital maintenance, multiple large and heavy batteries, enormous solar arrays, and heavy fuel payloads for the propulsion systems. For example, the Terra satellite which carries a six-sensor payload and was designed for a 20-year life cycle weighed 5,190 kg at the time of launch, is 6.8 m long, 3.5 m in diameter, and has a nearly 8 m wide solar array.

9. **Sensor Name**: Full name of each sensor on the platform. Each sensor on a platform should have its own entry in the database

10. **Constellation Size**: Number of satellites in the constellation

11. **Imaging Modality**: Primary domain of energy capture; options include
    - Optical: Solar
    - Optical: Thermal
    - Optical
    - Microwave
    - Radio
    - Non-Imaging

12. **Imaging Modality Subtype**: Options include
    - Panchromatic
    - Multispectral
    - Multispectral/panchromatic (some sensors are able to co-collect both modalities)
    - Hyperspectral
    - Polarimetric

- Laser altimeter
- Laser interferometer
- Radiometer
- Radar
- Radar altimeter
- Synthetic aperture radar
- Scatterometer
- Reflectometer
- Ultra-low-light
- Sounder
- Spectrometer (line-of-sight)
- Full motion video
- Occultation

13. **Energy Type**: Does the sensor create its own energy or passively rely on energy from an external source? Options are Active or Passive

14. **Launch Date**: Month, Day, Year of launch to orbit. For constellations with multiple launches, the earliest launch date of the <u>oldest currently active</u> satellite in the constellation will be used

15. **Launch Vehicle**: Describe the vehicle used to launch the rocket into space or "unknown"

16. **Launch Vehicle Manufacturer**: Name of the entity that built the launch vehicle or "unknown"

17. **Launch Location**: Name of the space port used to launch the satellite or "unknown"

18. **Multi Launch**: Were multiple satellites in the constellations launched at different times? Yes or No

19. **Sensor/Platform Cost**: Combined cost of the platform and sensor. For multi-sat constellations, 1 individual satellite in the constellation

20. **Operations Date**: Date data became available from the satellite (typically the first collection in the archive)

21. **Life Cycle**: Estimated in years; many satellites often vastly exceed their projected lifespan

22. **Orbit Altitude**: Orbital altitude classification of the satellite; options include
    - LEO (low-Earth orbit)
    - MEO (mid-Earth orbit)
    - GSO (geo-stationary orbit)
    - GEO (geo-synchronous orbit)
    - HEO (high-Earth orbit)

23. **Orbit Inclination**: Orbital inclination classification of the satellite; options include
    - Polar
    - Ecliptic
    - Equatorial
    - Near-equatorial
    - Non-polar inclined

24. **Orbit Direction**: Directional classification of the satellite; options include
    - Prograde
    - Retrograde

25. **Orbit Eccentricity**: Eccentricity classification of the satellite; options include
    - Circular
    - Elliptic
    - Parabolic
    - Hyperbolic
    - Radial

26. **Orbital Synchronicity**: Synchronicity classification of the satellite; options include
    - Sun synchronous
    - Dawn/dusk synchronous
    - Geo synchronous
    - Stationary (Lagrange)
    - ISS
    - Transfer
    - None

27. **Orbital Period**: Time in minutes to complete one complete orbital revolution around the Earth

28. **Apogee Height**: Exact distance of the satellite from Earth's surface expressed in km

29. **Inclination**: Orbital inclination of the satellite expressed in degrees

30. **Power Source**: Primary source of energy for the satellite or "unknown"; some satellites have more than one power source, so all will be listed here

31. **Propulsion Type**: Describe the propulsion system on the satellite or N\A or "unknown"; not all satellites have propulsion systems and other satellites might have more than one propulsion system, all of which will be denoted here

32. **Downlink**: Describe the method by which the satellite transmits data to Earth

33. **RF Communication**: RF band of data downlink with data transmission rate in megabytes per second (MBps)

34. **Onboard Data Storage**: Hard drive capacity and type for local data storage on the satellite or “unknown”

35. **Spatial Resolution**: Expressed in meters squared at Nadir or as close to Nadir as the satellite is capable of achieving. For example, most optical satellites begin at Nadir, but most SAR satellites are not capable of collecting data at Nadir. Nadir looking always results in highest resolution

36. **Spatial Resolution Category**: Options include
    - Very-high spatial resolution: <1 m GSD
    - High spatial resolution: 1 m–5 m GSD
    - Moderate spatial resolution: 5 m–30 m GSD
    - Low spatial resolution: 30 m–100 m GSD
    - Very-low spatial resolution: 100 m–1 km GSD

37. **Look Angle**: Maximum look angle of the satellite when collecting data starting from Nadir looking or as close to Nadir looking as the satellite is capable of achieving. For example, most optical satellites begin at Nadir, but most SAR satellites are not capable of collecting data at Nadir. Expressed in degrees

38. **Swath Width**: Dimensions of imaging footprint x-axis of the sensor expressed in km

39. **Absolute Geolocation Accuracy**: Based on CLEO90 and expressed in m

40. **Spectral Region Designation**: Describes sub-regions of the electromagnetic spectrum the sensor’s bands fall within; options include
    - UV
    - VIS
    - NIR
    - VNIR
    - SWIR
    - MWIR
    - LWIR
    - X-band
    - C-band
    - S-band
    - L-band
    - P-band
    - UHF
    - EHF

    or some combination of two or more of these options

41. **Spectral Wavelength Range**: Maximum spectral window collected by the sensor, expressed in nm, um, mm, cm, m, and km

42. **# Of Spectral Channels**: Total number of spectral bands for each sensor

43. **Spectral Channel Bandwidth**: The full-width half-maximum of the narrowest and widest spectral band of each sensor, expressed in nm, um, mm, cm, m, and km

44. **Spectral Channel Classification**: Broadband (>10 nm) or narrowband (<10 nm)

45. **Spectral Channel Configuration**: Discrete (gaps between channels) or continuous (no gaps between channels)

46. **Spectral Resolution Category**: Options include
    - Very-high spectral resolution: Hyperspectral, continuous, more than 150 bands, less than 10 nm FWHM
    - High spectral resolution: Hyperspectral, continuous, 50–150 bands, narrow bands between 10 nm–20 nm FWHM
    - Moderate spectral resolution: Multispectral, discrete, 8–49 bands, broad bands (>20 nm FWHM)
    - Low spectral resolution: Color/multispectral, discrete, 3–7 bands, broad bands (>20 nm FWHM)
    - Very-low spectral resolution: Panchromatic, discrete, 1 band, broad bands (>20 nm FWHM)

47. **Radiometric Resolution**: The ability of the sensor to distinguish varying illumination levels. Expressed in bits (e.g., 8 bit = $2^{8 \text{ or}}$ 256)

48. **Dynamic Range**: Min and Max digital number per pixel per sensor (e.g., for 8 bit expressed as 0-255)

49. **Radiometric Resolution Category**: Options include
    - Very-high radiometric resolution: 16 bit
    - High radiometric resolution: 12–14 bit
    - Moderate radiometric resolution: 10–11 bit
    - Low radiometric resolution: 8 bit
    - Very-low radiometric resolution: <8 bit

50. **Data Format**: Which raster data format is primarily used when images are delivered to customers? Options include
    - GeoTIFF (most common generic raster format)
    - JP2 (JPEG2000 second most common generic raster format)
    - HDF4/5 (very common for NASA/NOAA/ESA/JAXA scientific instruments)
    - NetCDF3/4 (less common for NASA/NOAA/ESA/JAXA scientific instruments)
    - BEAM-DIMAP (common synthetic aperture radar raster format)
    - DAT (common hyperspectral image format ".dat" otherwise known as a data cube)
    - FAST format (common USGS image format)

- DEM (common USGS digital elevation model format ".dem")
- ECW (common European/South American image compression format ".ecw")
- IMG (common North American & Asian image compression format ".img")
- CADRG (common DoD raster format)
- NITF (common DoD/IC raster compression format)
- TFRD (less common DoD/IC raster compression format)
- CIB (native format for controlled image base ".cib")
- ECRG (less common DoD raster format)
- GRID (common ESRI binary raster format)
- SID (less common proprietary image compression format ".sid")
- MP4 (used with full-motion-video datasets)
- Unknown

51. **Polarization Mode**: Is the sensor polarized? Options include
    - N\A
    - Single
    - Dual
    - Quad

    and polarization channels used. Polarization channel options include
    - hh
    - vv
    - hv
    - vh
    - circular
    - linear
    - elliptical
    - selectable (if noted, it means the polarization modes can be swapped which is not uncommon dual single and dual polarization systems)

52. **Interferometric Collection**: Does the sensor collect phase data? Yes or No

53. **Stereo Collection**: Can the sensor collect optical stereo pairs? Yes or No

54. **Daylight Dependency**: Is the sensor dependent on sunlight for energy? Yes or No

55. **Weather Dependency**: Is the sensor disrupted by cloud cover? Yes or No

56. **Data Processing Levels**: Will use L0, L1, L2, L3, L4 system. See the end of this document for more details.

57. **Local Time at the Equator**: The time the satellite passes over the equator while in descent each day expressed as local military time

58. **Passive Global Revisit**: How long does it take for a given satellite or constellation to revisit the same place of interest passively. Expressed as days, months, or annually

59. **Tasked Global Revisit**: What's the maximum revisit capacity of a satellite or constellation if tasked. N\A or expressed in days or hours

60. **Temporal Resolution Category**: Options include
    - Very-high temporal resolution: Revisits 3 or more times per day
    - High temporal resolution: Revisits 1–2 times per day
    - Moderate temporal resolution: Revisits every 2–4 days
    - Low temporal resolution: Revisits weekly
    - Very-low temporal resolution: Revisits monthly

61. **Daily Data Capacity**: How much data the sensor collects in a given day; expressed in km^2

62. **Data Freely Available**: Freely available means no charge for the data; Yes or No

63. **Data Publicly Available**: Publicly available means does the data require special access granted from government organizations? Yes or No

64. **Archive Waiting Period**: Some commercial vendors place mandatory waiting periods on newly collected satellite imagery before its allowed to be sold at cheaper archival prices; options are N\A or expressed in number of days

65. **Minimum Archive Order Area**: Many commercial vendors set a minimum purchase area for archival data acquisition; options are N\A or expressed in km^2

66. **Minimum Archive Area Price**: The total price of the minimum archive order area; options are N\A or expressed in USD

67. **Minimum Tasked Order Area**: Many commercial vendors set a minimum purchase area for tasked data acquisitions; options are N\A or expressed in km^2

68. **Minimum Tasked Area Price**: Many commercial vendors place sliding pricing premiums on tasked data acquisition. The price can vary dramatically depending on the speed in which the collection takes place. Options are N\A or a minimum vs maximum price expressed in USD

69. **Emergency Tasking Available** (sub 48 hours): Many commercial vendors offer "emergency tasking" which is usually defined as a tasked satellite data acquisition taking place within 48 hours of making the request. Options are Yes or No

70. **ITARS Restrictions**: Is the sensor's data subject to U.S. DoC/DoS ITARS restrictions against foreign export and sale? ITARS restrictions can be placed on any USA-based satellite imagery company. Options are Yes or No. For "Yes", additional details about the specific restrictions should be added to "ITARS Notes"

71. **NGA/NRO/DoD Emergency Tasking ROFR**: Does the NGA, the NRO, and/or the DoD have contractual right of first refusal for sub-48-hour emergency tasking on the particular asset? Options are Yes or No. Note: NGA/NRO/DoD not only negotiate ROFR with American companies, but have been known to do so with foreign satellite imagery companies as well

72. **International Charter Access**: Is the specific satellite sensor made available to the International Charter Space and Major Disasters? Yes or No. If yes, see the "Charter Notes" field for more information. Note that organization membership does not imply access to a specific sensor. For example, MAXAR will make WV-2 and WV-1 data available, but not WV-3

73. **Sensor Tasking Access**: URL to the asset's tasking interface

74. **Data Archive Access**: URL to primary data archive for the asset

75. **Products Available**: Coded list of products on offer from data provider where applicable

76. **Additional Notes**: Misc. noteworthy discussion points for each sensor

77. **ITARS Notes**: Describes the precise terms of ITARS restrictions where applicable; exact terms of ITARS restrictions are frequently revised due to pressure from industry and the terms described here should be revisited annually

78. **International Charter Notes**: Describe the terms of the membership and which assets are on offer

DATA PROCESSING LEVELS DISCUSSION (FIELD 53)

Since each satellite sensor gets an independent entry in the database, data processing levels should be tailored to the imaging modality and sub modality. For example, "L1" will mean something completely different for SAR data than it will mean for multispectral data. Partial definitions include the following.

Passive/Solar Modalities: UV, VIS, NIR, SWIR in panchromatic, multispectral, and hyperspectral configurations

L0 = Uncorrected lamp data (raw sensor response)

L1a = Calibrated to spectral radiance (might include dark noise, wavelength calibration, and bad pixel mapping and compensation)

L1b = Calibrated to top-of-the-atmosphere (ToA) reflectance (typically satellite only)

L1c = Orthorectified spectral radiance or ToA reflectance

L2a = Calibrated to at-surface or bottom-of-the-atmosphere (BotA) reflectance (solar/atmospheric/adjacency corrections)

L2b = (SWIR only) calibrated to brightness temperature

L2c = Orthorectified BoA reflectance or brightness temperature

L3 = Spectroradiometric indices

L4 = Analysis Product

Passive/Thermal Modalities: MWIR and LWIR in panchromatic, multispectral, hyperspectral configurations

L0 = Uncorrected lamp data (raw sensor response)
L1a = Calibrated to spectral radiance
L1b = Calibrated to ToA brightness temperature
L2a = Calibrated to at surface brightness temperature
L2b = Calibrated to at-surface spectral emissivity
L2c = Orthorectified reflectance, temperature or emissivity
L3 = Spectral, thermometric and emissivity indices
L4 = Analysis product

Active Optical: Green and near-infrared in laser ranging/altimetry, laser interferometry configurations

L0 = Raw waveforms
L1 = Structured point cloud with ground elevation, canopy top height, relative height metrics
L2 = Geolocated point cloud with metrics
L3 = Rasterized surface models
L4 = Analysis products

Active Microwave: X, C, S, L, P band SAP in single, dual, and quad polarization configurations

L0 = Uncompressed backscatter
L1 = Range and azimuth compressed single-look complex backscatter, phase, and polarization data
L2a = Interferogram
L2b = Polarimetric decomposition
L2c = Ground range detected data
L3 = Radiometrically calibrated and flattened range-terrain-Doppler corrected data
L4 = Analysis product

APPENDIX D. ANALYSIS OF CLOUD COVER LIMITATIONS FOR OPTICAL SENSING

Section primary author: Chad Council

A key consideration for a space-based constellation of multispectral sensor is the prevalence of cloud cover preventing a clear image of the area of interest. The DisasterSat goal is to deliver post-disaster imagery within 72 hours or less of a disaster, which means that in order for a space-based multispectral sensor to be a viable solution, the satellite orbit time to get on station during daylight hours, for a cloudless day over the area of interest, must also be less than 72 hours. Assuming the constellation design supports daily revisits, the area of interest cannot have 72 hours (3 days) of continuous cloud cover.

In this section, we use historic cloud cover data to look at the probability that areas in the U.S. that are most likely to experience a disaster that would benefit from timely satellite imagery would experience cloud cover for three continuous days. We sought to understand and characterize which areas in the U.S. are most susceptible to disaster and will have three days of continuous cloud cover, preventing the timely collection of multispectral imagery from a space-based platform.

APPROACH

A similar analysis was done to explore the global risk of cloud cover in the context of countries at risk for severe Earthquake damage [84].

To answer this question, three pieces of information are required: (1) What geographic areas in the United States are most susceptible to disaster impacts? (2) What geographic areas in the United States are susceptible to three days of continuous cloud cover? And lastly, (3) What are the characteristics of the geographic areas where 1 and 2 overlap?

Two datasets were used to support this analysis.

1. The National Risk Index (NRI): A Census Tract based geospatial product released by FEMA. The NRI provides both quantitative and qualitative assessments of risks for individual disaster types, community resiliency to disasters, the vulnerability of the population. Overall risk for a census tract is summarized into five categories: Very Low, Relatively Low, Relatively Moderate, Relatively High, and Very High. For the purposes of this analysis, the focus was placed on Census Tracts that were ranked with an overall risk of Relatively High or Very High.

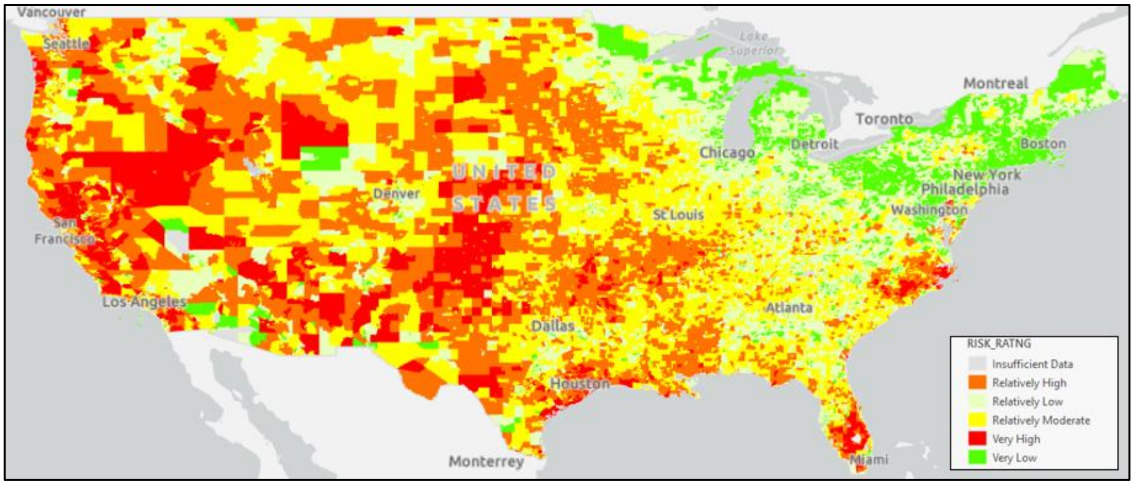

Figure 71. Map of the continental U.S. showing the overall risk rating for census tracts as determined by the National Risk Index.

2. MODIS Cloud History Data: A global compilation of 15 years of cloud cover data presented at 1-km resolution. The MODIS Cloud History dataset provides a geospatial raster for each month of the year. Each 1km cell for this raster represents the percentage of days in that month that were cloudy over the 15-year time period.

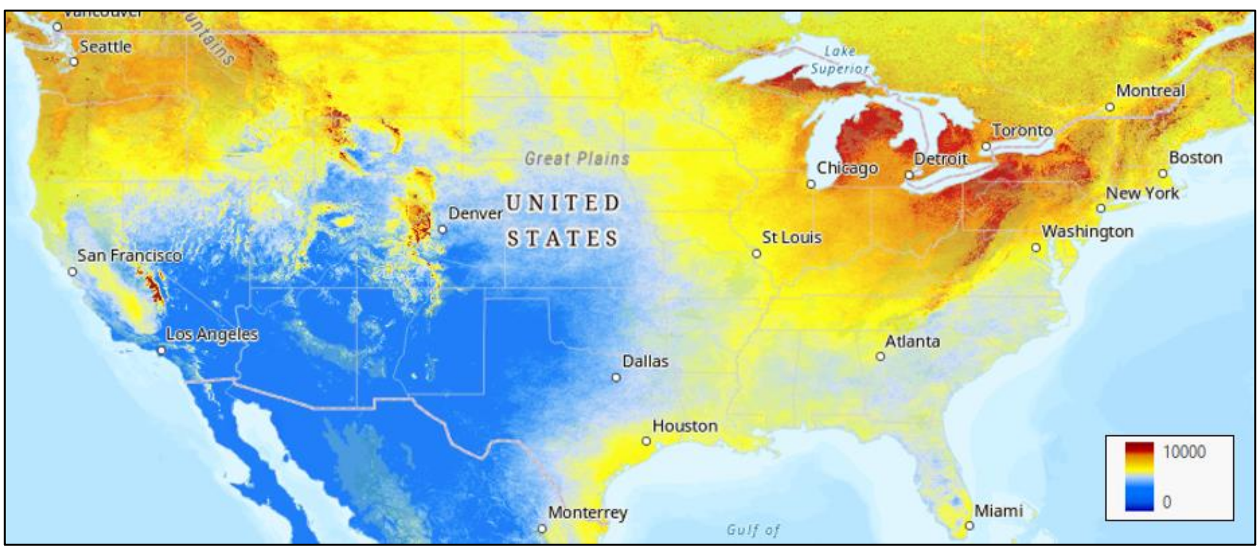

Figure 72. Map of the continental U.S. showing the percentage of days in January that experienced cloud cover over 15-year period.

DATASETS

The final analysis required to answer the question about populations at risk for both disasters and three days of cloud cover requires a number of intermediate analyses. Each of these intermediate products are described below.

1. **High Risk of Three Days of Clouds**: For each of the 12 months, the MODIS dataset provides a global 1 km raster representing the percentage of days of cloud cover for that month. The goal of this analysis step is to produce a new raster for each month where the grid cells contain the probability of cloud cover for three consecutive days. All of the raster operations were done manually using ArcGIS Pro Raster Calculator.

    a. The dataset values represented probability on a 0–10,000 scale (vs. 0–100), with values over 10,000 being outliers. Cleaning the outliers was done with the raster calculation.

    ```
    Con("input_raster.tif" > 10000, 0, "input_raster.tif")
    ```

    b. Each cell contains the number of days out of the month that are likely to be cloudy, represented as a percentage. This is seen as the probability of cloud cover for any given day during that month.

        i. Assumption: cloud cover on any given day is an independent event

        ii. The probability P of independent events X occurring N times in a row is $P(X)^N$

        iii. Accounting for the 0–10,000 and the three-day time span, we multiply the grid cell by 0.0001 and raise it to the third power in a raster calculation: Power(("input_raster"*0.0001) ,3)

    c. Because we are looking for areas where the cloud cover is more likely to persist for three days, we then create a raster mask where cells with a three-day cloud probability less than or equal 50% are set to 0 and cells with a three-day cloud probability greater than 50% are set to 1. The raster calculation for this is Con("input_raster " > 0.50,1,0).

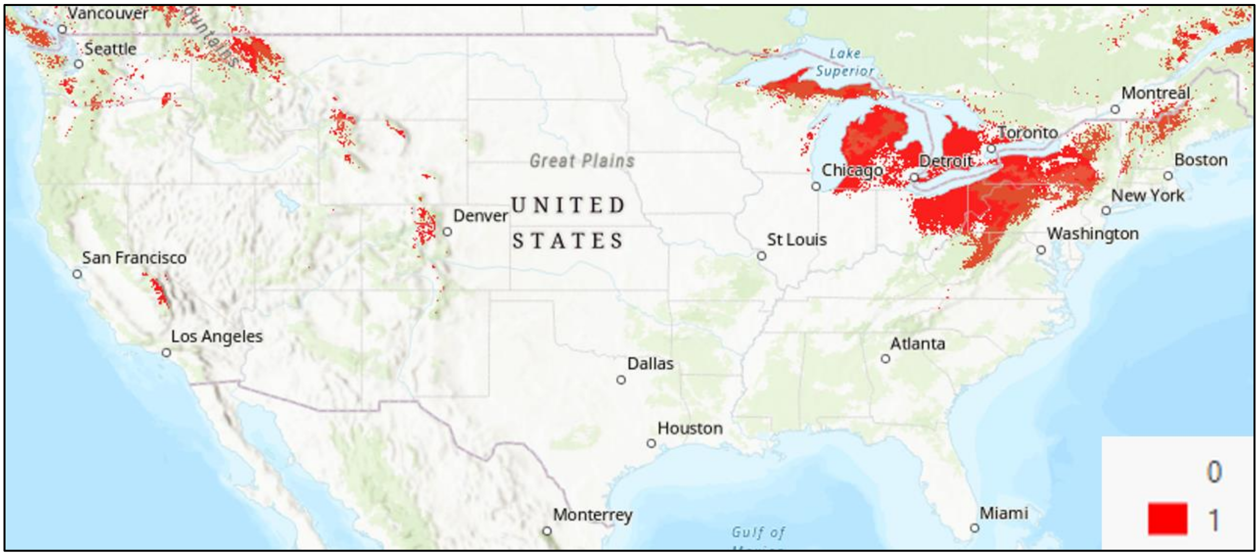

Figure 73. Sample raster mask for areas with >50% chance of three days of cloud cover for January.

This method was performed for each of the 12 months, resulting in 12 raster masks.

2. **Increased Disaster Risk Areas**: The National Risk Index was filtered to census tracts where the overall risk of disaster impacts (stored in the RISK_RATING attribute) was higher than others. As stated earlier, the risk rating is broken into five categories. Isolating the census tracts that are at more risk for disaster impacts, and therefore more likely to benefit from space-based multispectral imagery, the filter was set where RISK_RATING='Relatively High' or 'Very High'.

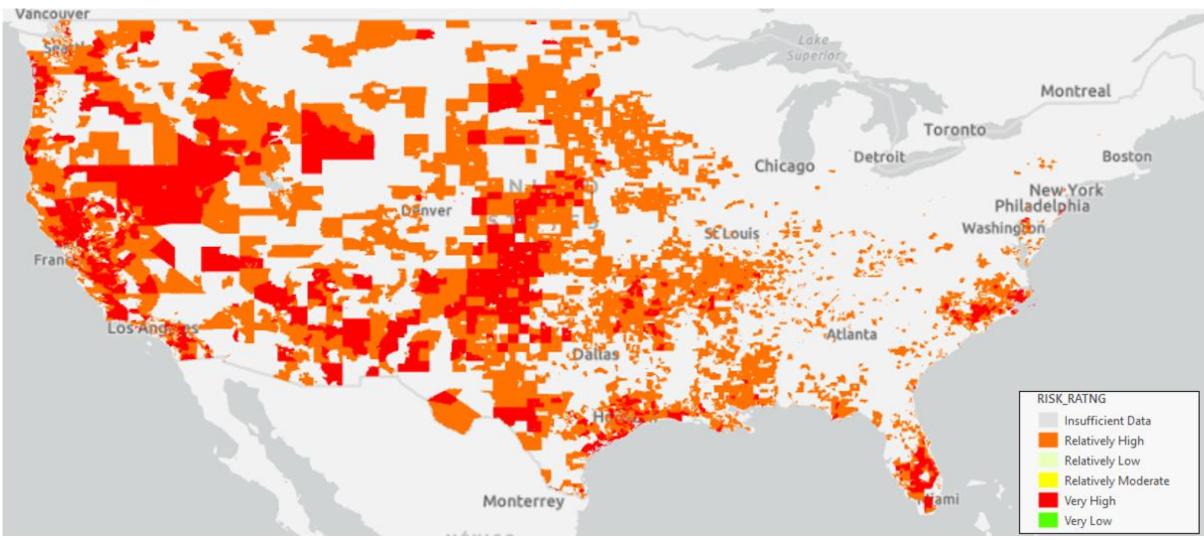

Figure 74. National Risk Index filtered to Relatively High and Very High.

3. **NRI Cloud Risk**: The National Risk Index dataset was enriched with 13 additional columns. For each of the 12 months, a spatial intersection was performed to determine if that census tract had a greater than 50% chance of three days of cloud cover for that month. If so, the attribute was set to 1, otherwise was set to 0. The 13th additional column is the total number of months for that census tract where the risk of three days of cloud cover exceeded 50%. This attribute was populated using a simple field calculation that summed the values of the 12 monthly risk attributes. A sample of a spatial intersection is illustrated in Figure 75 and a snapshot of the final dataset is shown in Figure 76.

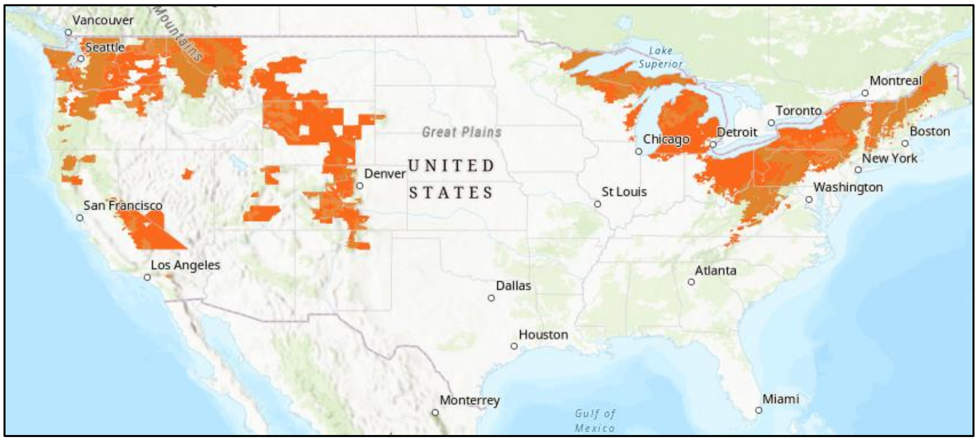

Figure 75. National Risk Index census tracts that intersect the three-day cloud risk for January.

COUNTY	TRACT	JanCloud	FebCloud	MarCloud	AprCloud	MayCloud	JunCloud	JulCloud	AugCloud	SepCloud	OctCloud	NovCloud	DecCloud	MonthsClou
Fremont	000300	1	1	1	1	1	1	0	0	0	1	1	1	9
Josephine	360300	1	0	0	0	0	0	0	0	0	0	0	1	2
Bonner	950700	1	0	1	1	0	0	0	0	0	0	1	1	5
Kootenai	000100	1	0	1	1	0	0	0	0	0	0	1	1	5
Flathead	000201	1	1	1	1	1	0	0	0	0	0	1	1	7
Flathead	000202	1	1	1	0	0	0	0	0	0	0	1	1	5
Cowlitz	001800	1	0	1	1	1	0	0	0	0	0	1	1	6
Cowlitz	002001	1	0	1	1	0	0	0	0	0	0	1	1	5
Cowlitz	002002	1	0	1	0	0	0	0	0	0	0	1	1	4
Skamania	950400	1	1	1	1	0	0	0	0	0	0	1	1	6
Lincoln	000300	1	1	1	1	1	0	0	0	0	0	1	1	7

Figure 76. Data snapshot showing the months per census tract that had high risk of three days of clouds.

The NRI Cloud Risk dataset represents, at a Census Tract level, the year-round risk of disaster combined with the chance of experiencing three continuous days of clouds for any given month in the year.

The additional data provided with the NRI such as population and building values can help characterize the overall exposure to risk for a community, and how likely or unlikely it is that satellite imagery could be collected over that community in a timely manner.

INITIAL RESULTS

Visualizing the NRI Census tracts that are at higher risk for disaster impacts, with an indication of how many months per year they are likely to have 3 days of cloud cover provides a clear indication that the three-day cloud cover risk is of some concern, but not as significant a concern as first assumed. In Figure 77, the vast majority of census tracts appear yellow, or have 0 months of the year with a greater than 50% chance of three days of cloud cover.

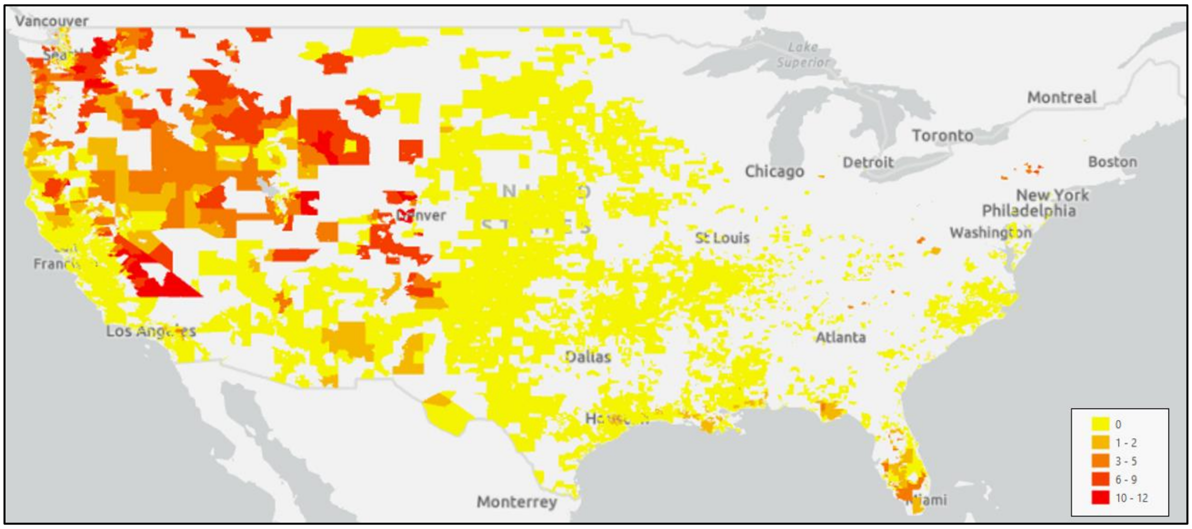

Figure 77. NRI Census tracts, color coded by number of months with three-day cloud risk.

Visualizing a histogram of the NRI Census Tracts as a function of the number of months with higher three-day cloud risk shows that 8,124 out of the 9,486 tracts (85%) have 0 months with that risk. Inspecting the histogram, it is apparent that the distribution of census tracts with higher three-day cloud risk drops off very quickly, indicating that the year-round risk of three-day cloud coverage is quite low.

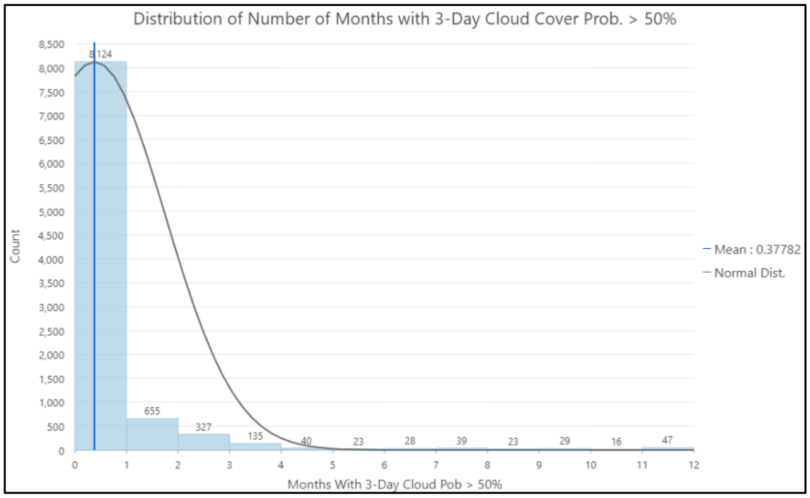

Figure 78. NRI Census tract distribution of months with three-day cloud cover risk.

For the purposes of the rest of this study, the focus will be on the NRI census tracts that have 6 or more months of a greater than 50% chance of three-day cloud coverage. Geographically, these highest risk census tracts are primarily in the mountain's regions of the western United States, Alaska, and Hawaii.

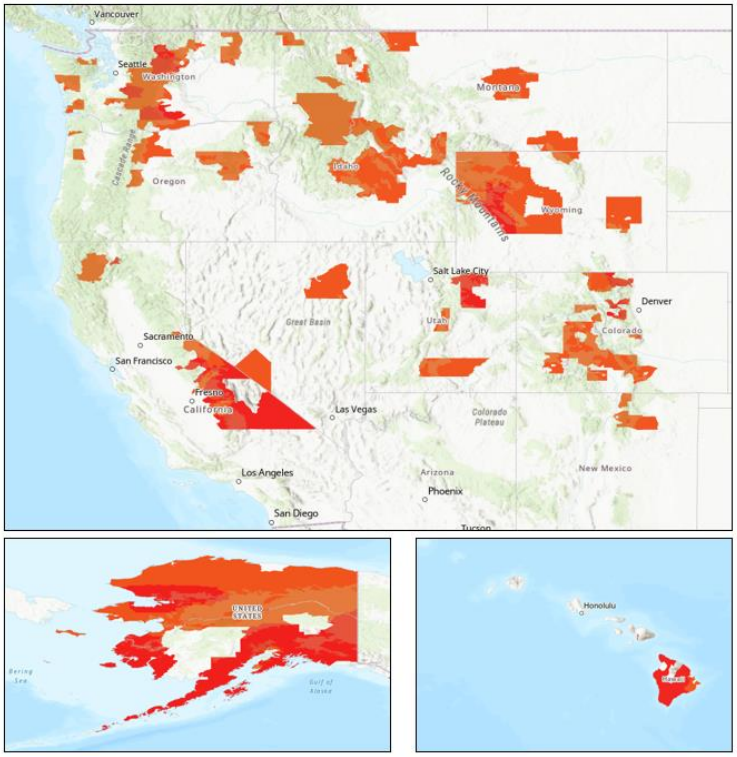

Figure 79. NRI Census tracts with higher risk of disaster impacts and have 6 or more months of higher risk of three-day cloud coverage.

POPULATION ANALYSIS

Exploring the population and building value of these Census tracts offers a way to characterize the relative risk of these communities to experience a disaster and have cloud cover prevent the timely delivery of satellite-based imagery.

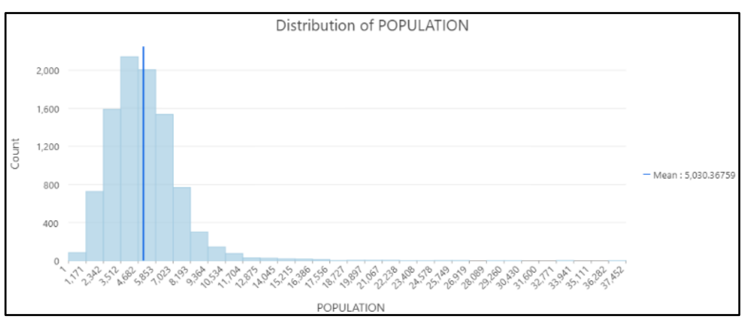

Figure 80. Distribution of population amongst NRI Census tracts at higher risk of disaster.

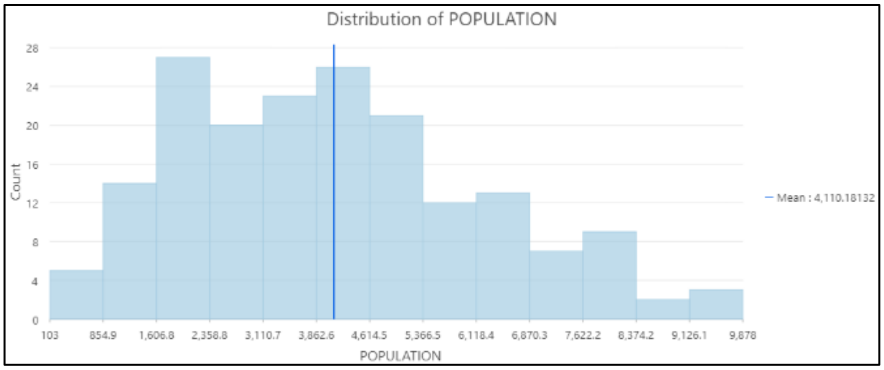

Figure 81. Distribution of population amongst NRI Census tracts at higher risk of disaster and six or more months of three-day cloud cover risk.

Of the 72,739 Census tracts in the U.S., there are 9,486 tracts ranked with a "Relatively High" or "Very High" disaster risk rating. For these tracts, the total population represented is 47,718,067, with a mean population of 5,000.

By comparison, the NRI Census tracts that are ranked with a "Relatively High" or "Very High" disaster risk rating, and also have 6 or more months with a greater than 50% chance of having three consecutive days of cloud cover, constitute only 182 Census tracts. The population of these tracts is 748,053, with a mean of 4,000.

In summary, the population that is at elevated risk of disaster and also at greatest risk of cloud cover preventing satellite imagery being collected in three days is quite small. The nationwide Census population for the NRI is 308,745,538, placing this highest at-risk population to around 0.2% of the total population and 1.59% of the population that is at elevated risk of disasters.

BUILDING VALUE ANALYSIS

A similar comparison can be made using the building value within Census tracts, yielding similar results and conclusions.

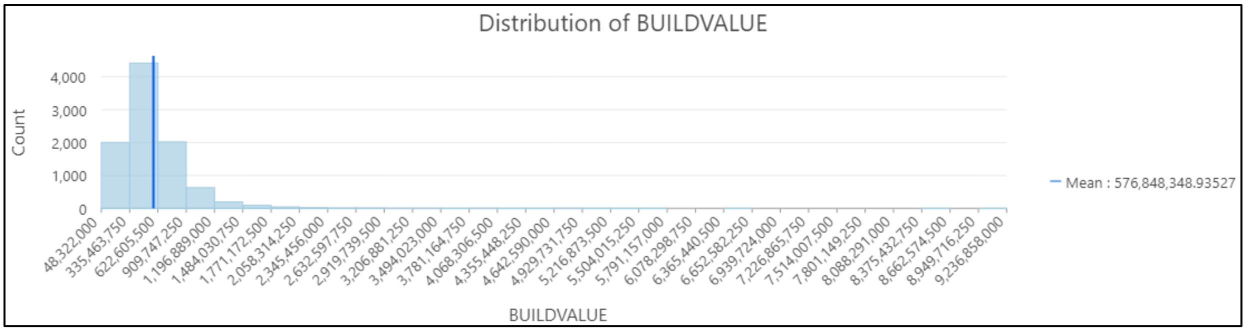

Figure 82. Distribution of building value amongst NRI Census tracts at higher risk of disaster.

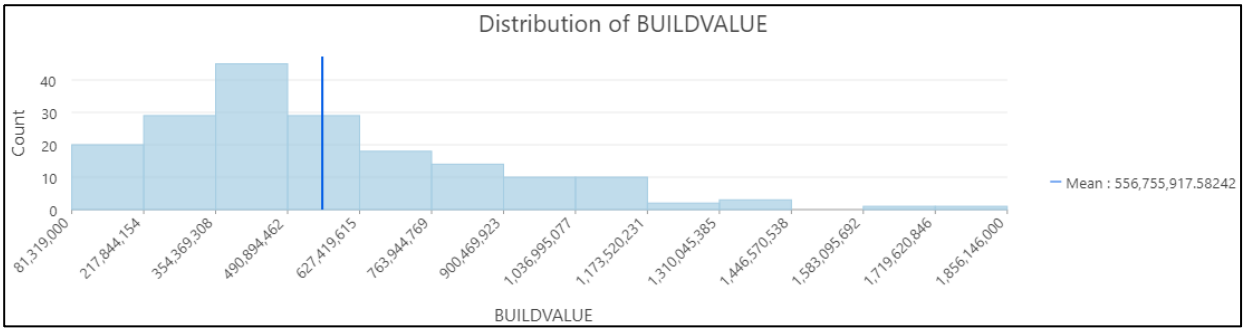

Figure 83. Distribution of building value amongst NRI Census tracts at higher risk of disaster and six or more months of three-day cloud cover risk.

Of the 9,486 tracts ranked with a "Relatively High" or "Very High" disaster risk rating, the total building value is $5.4 Trillion, with a mean building value of $575 Million.

By comparison, for the 182 NRI Census tracts that are ranked with a "Relatively High" or "Very High" disaster risk rating, and also have 6 or more months with a greater than 50% chance of having three consecutive days of cloud cover, the building value of these tracts is $101 Billion, with a mean of $557 Million.

In summary, the build value that is at elevated risk of disaster and also at greatest risk of cloud cover preventing satellite imagery being collected in three days is quite small. The nationwide Census building value for the NRI is $35.4 Trillion, placing this highest at-risk population to around 0.28% of the total building value in the U.S. and 1.87% of the building value that is at elevated risk of disasters.

SEASONAL DISASTERS AND RISK

The preceding analysis looked at overall disaster risk throughout the year, regardless of season. There are, however, specific disasters that have both seasonality and geographic constraints. A sample analysis was conducted to explore the population and building value risk for Census tracts exposed to elevated risk of hurricanes and the likelihood of three days of cloud cover in the month of September.

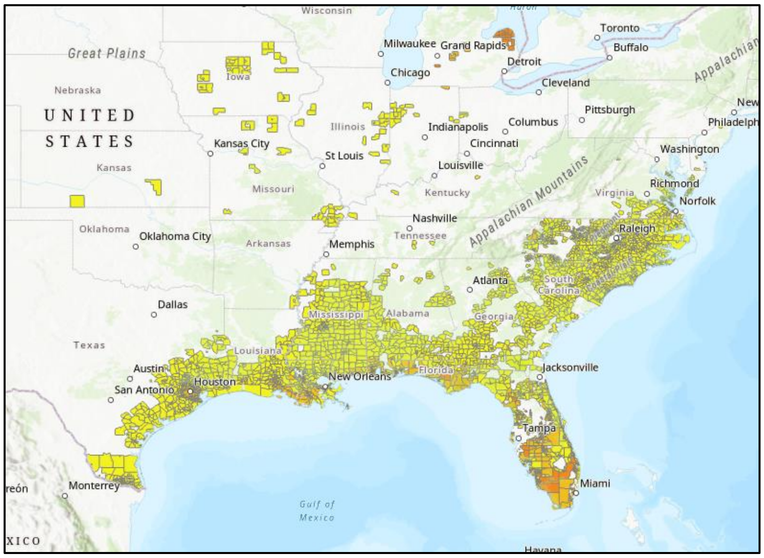

Figure 84. NRI Census tracts with elevated risk for hurricane impacts.

The NRI census tracts that intersect the High Risk of clouds for three days for the month of September is limited to just a very small number in southern Florida. The total population of these high-risk tracts is 1.09 million people and the building value is $124 Billion. Very similar to the nation-wide, year-round risk, this accounts for about 2% of the total population and building value exposed to the elevated hurricane risk.

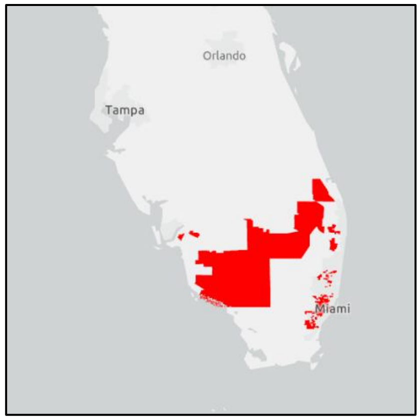

Figure 85. NRI Census tracts with elevated hurricane risk and high chance of three-day cloud cover in September.

CLOUD COVER ANALYSIS SUMMARY

The intent of this analysis was to determine if it was likely that a space-based network of multispectral sensors would be able to capture a cloud free image within 72 hours of an incident. Based on the analysis conducted, the following statements can be made.

- It is likely that satellite imagery could be captured within three days of an incident, for most months of the year, for 98% of the population and total building value in Census tracts that have a "relatively high" or "very high" risk rating in the NRI.
- It is less likely that satellite imagery could be captured within three days of an event, for most months of the year, for 2% of the population and total building value in census tracts that have a "relatively high" or "very high" risk rating in the NRI.

The areas at elevated risk that are likely to have three-day cloud cover for six or more months of the year account for 0.2% of the total U.S. population and 0.28% of the total U.S. building value.

APPENDIX E. SCRIPT FOR PDA TIME ANALYSIS IN R STUDIO

```
library(tidyverse)
library(httr)
library(jsonlite)
library(ggthemes)

#PDA Data: This data includes IA and PA indicators
res <-
GET("https://www.fema.gov/api/open/v2/DisasterDeclarationsSummaries.json")
#rawToChar(res$content)
data <- fromJSON(rawToChar(res$content))
decs <- data$DisasterDeclarationsSummaries

#---Format Dates and Calculate no. of days from incident to dec.---------------
decs$incidentBeginDate <- as.Date(decs$incidentBeginDate)
decs$incidentEndDate <- as.Date(decs$incidentEndDate)
decs$declarationDate <- as.Date(decs$declarationDate)
decs$pdaTime <- decs$declarationDate - decs$incidentBeginDate
decs$pdaTime <- as.numeric(decs$pdaTime)

# Select Major Disaster Declarations only
DR <- decs[decs$declarationType == "DR", ]

# Filter for recent incidents
#And finally, from the beginning of the 2017 hurricane season to the beginning of
the 2023 hurricane season
DR_2017 <- DR[DR$incidentBeginDate > "2017-06-01" & DR$incidentType !=
"Biological" & DR$incidentBeginDate < "2023-06-01", ]
summary(DR_2017)

ggplot(DR_2017, aes(x=incidentType)) +
  geom_bar() +
  coord_flip() +
  ggtitle("Disaster count by incident type, June 1, 2017 - June 1, 2023")


#---Now filter by IA/IHP-----------
```

```
DR_2017_IHP <- DR_2017[DR_2017$ihProgramDeclared == TRUE,] # & DR_2017$incidentType != "Volcanic Eruption" & DR_2017$incidentType != "Snowstorm" & DR_2017$incidentType != "Winter Storm", ]
summary(DR_2017_IHP)

## Histogram of number of counties declared for each incident type
ggplot(DR_2017_IHP, aes(x=incidentType)) +
  geom_bar() +
  coord_flip() +
  ggtitle("Disaster count by incident type | June 1, 2017 - June 1, 2023 [IHP Dec]")

## set plotting theme
theme_set(theme_few())

## Create Violin plot of time to IA PDAs by county
ggplot(DR_2017_IHP, aes(y=pdaTime, x = incidentType, fill = incidentType)) +
  #geom_boxplot()+
  geom_violin(aes(color = incidentType, fill=NULL), ) +
  geom_hline(yintercept=8, linetype = "dashed", color = "black")+
  geom_hline(yintercept=19.8, linetype = "dashed", color = "red")+
  geom_dotplot(aes(color = incidentType), binaxis = "y",
               dotsize = 1,
               stackdir = "center",
               binwidth = 0.01,
               #method = "histodot",
               position = "jitter") +
  #position = position_nudge(-0.025)) +
  ylab("Time from incident start to declaration (days)") +
  xlab("Incident Type") +
  coord_flip() +
  ggtitle("Time to conduct PDAs that resulted in IA declarations for natural hazards | June 1, 2017 - June 1, 2023")+
  annotate( "text", label = c("Median [8]","Mean [19.8]"),
            x = c(0.5,0.5), y = c(8, 19.8), hjust = c(-0.1,-0.1),
            size = 3, colour = c("black", "red"))


##--------Aggregate by DR number -------------
DR_numbers <- unique(DR_2017_IHP$disasterNumber)

decCount<- c()
```

```
maxPdaTime <- c()
minPdaTime <- c()
incidentStartDateVar <- c()
incidentTypeVar <- c()

for (i in 1:DR_numbers){
  #find all columns for a given DR #
  #return the total number of counties
  len_var <- nrow(DR_2017_IHP[DR_2017_IHP$disasterNumber==DR_numbers[[i]],])
  #return the longest pdaTime
  max_var                                                                    <-
max(DR_2017_IHP[DR_2017_IHP$disasterNumber==DR_numbers[[i]],]$pdaTime)
  min_var                                                                    <-
min(DR_2017_IHP[DR_2017_IHP$disasterNumber==DR_numbers[[i]],]$pdaTime)
  startdatevar                                                               <-
min(DR_2017_IHP[DR_2017_IHP$disasterNumber==DR_numbers[[i]],]$incidentBeginDate)
  type                                                                       <-
min(DR_2017_IHP[DR_2017_IHP$disasterNumber==DR_numbers[[i]],]$incidentType)
  #print(len_var)
  #print(max_var)
  decCount <- append(decCount, len_var)
  maxPdaTime <- append(maxPdaTime, max_var)
  minPdaTime <- append(minPdaTime, min_var)
  incidentStartDateVar <- append(incidentStartDateVar, startdatevar)
  incidentTypeVar <- append(incidentTypeVar, type)
}

DR_2017_summary <- data.frame(DR_numbers, incidentStartDateVar, incidentTypeVar,
decCount, maxPdaTime, minPdaTime)

disasterTypes <- unique(DR_2017_IHP$incidentType)
disatertypecount <- c()
maxpdatimecount <- c()

for (i in disasterTypes) {
  dtypes <- nrow(DR_2017_summary[DR_2017_summary$incidentTypeVar == i,])
  maxpdatimevar                                                              <-
max(DR_2017_summary[DR_2017_summary$incidentTypeVar==i,]$maxPdaTime)
  disatertypecount <- c(disatertypecount, dtypes)
  maxpdatimecount <- c(maxpdatimecount, maxpdatimevar)
}
```

```
disasterTypeCounts <- data.frame(disasterTypes, disatertypecount, maxpdatimecount)

summary(DR_2017_summary)

ggplot(DR_2017_summary, aes(y=maxPdaTime, x = incidentTypeVar, fill = incidentTypeVar)) +
  #geom_boxplot()+
  geom_violin(aes(color = incidentTypeVar, fill=NULL), scale="width", kernel = "gaussian") +
  geom_hline(yintercept=17, linetype = "dashed", color = "black")+
  geom_hline(yintercept=27, linetype = "dashed", color = "red")+
  geom_dotplot(aes(color = incidentTypeVar), binaxis = "y",
               dotsize = 0.9,
               stackdir = "center",
               binwidth = 1,
               method = "histodot",
               #position = "jitter") +
               position = position_nudge(-0.025)) +
  geom_text(data=disasterTypeCounts,
            aes(x=disasterTypes, y=maxpdatimecount,
                label = disatertypecount,
                fill=disasterTypes, hjust = -1))+
  ylab("Time from incident start to declaration (days)") +
  xlab("Incidents (by Declaration Number)") +
  coord_flip() +
  ggtitle("Time to conduct PDAs that resulted in IA declarations for natural hazards | June 1, 2017 - June 1, 2023")+
  annotate( "text", label = c("Median [17]","Mean [27]"),
            x = c(0.75,0.75), y = c(17, 27), hjust = c(1.1,-0.2),
            size = 3, colour = c("black", "red"))


##________Now PA Only______
DR_2017_PA <- DR_2017[DR_2017$paProgramDeclared == TRUE,]
summary(DR_2017_PA)

DR_numbers <- unique(DR_2017_PA$disasterNumber)

decCount<- c()
minPdaTime <- c()
incidentStartDateVar <- c()
```

```
incidentTypeVar <- c()

for (i in 1:DR_numbers){
  #find all columns for a given DR #
  #return the total number of counties
  len_var <- nrow(DR_2017_PA[DR_2017_PA$disasterNumber==DR_numbers[[i]],])
  #return the shortest pdaTime for PA since some PDAs do not appear to be complete
  min_var                                                                    <-
min(DR_2017_PA[DR_2017_PA$disasterNumber==DR_numbers[[i]],]$pdaTime)
  startdatevar                                                               <-
min(DR_2017_PA[DR_2017_PA$disasterNumber==DR_numbers[[i]],]$incidentBeginDate)
  type                                                                       <-
min(DR_2017_PA[DR_2017_PA$disasterNumber==DR_numbers[[i]],]$incidentType)
  #print(len_var)
  #print(max_var)
  decCount <- append(decCount, len_var)
  maxPdaTime <- append(maxPdaTime, max_var)
  minPdaTime <- append(minPdaTime, min_var)
  incidentStartDateVar <- append(incidentStartDateVar, startdatevar)
  incidentTypeVar <- append(incidentTypeVar, type)
}

DR_2017_summary <- data.frame(DR_numbers, incidentStartDateVar, incidentTypeVar,
decCount, minPdaTime)

disasterTypes <- unique(DR_2017_PA$incidentType)
disatertypecount <- c()
minpdatimecount <- c()

for (i in disasterTypes) {
  dtypes <- nrow(DR_2017_summary[DR_2017_summary$incidentTypeVar == i,])
  minpdatimevar                                                              <-
max(DR_2017_summary[DR_2017_summary$incidentTypeVar==i,]$minPdaTime)
  disatertypecount <- c(disatertypecount, dtypes)
  minpdatimecount <- c(minpdatimecount, minpdatimevar)
}

disasterTypeCounts      <-      data.frame(disasterTypes,      disatertypecount,
minpdatimecount)

summary(DR_2017_summary)
```

```
ggplot(DR_2017_summary, aes(y=minPdaTime, x = incidentTypeVar, fill = incidentTypeVar)) +
       #geom_boxplot()+
       geom_violin(aes(color = incidentTypeVar, fill=NULL), scale="width", adjust = 0.5) +
       geom_hline(yintercept=60, linetype = "dashed", color = "black")+
       geom_hline(yintercept=62, linetype = "dashed", color = "red")+
       geom_dotplot(aes(color = incidentTypeVar), binaxis = "y",
                    dotsize = 1,
                    stackdir = "center",
                    binwidth = 1,
                    method = "histodot",
                    #position = "jitter") +
                    position = position_nudge(-0.025)) +
       geom_text(data=disasterTypeCounts,
                 aes(x=disasterTypes, y=minpdatimecount,
                     label = disatertypecount,
                     fill=disasterTypes, hjust = -1))+
       ylab("Time from incident start to first PA declaration (days)") +
       xlab("Incidents (by Declaration Number)") +
       coord_flip() +
       ggtitle("Minimum time to conduct PDAs that resulted in PA declarations for natural hazards | June 1, 2017 - June 1, 2023")+
       annotate( "text", label = c("Mean [60]","Median [62]"),
                 x = c(0.75,0.75), y = c(60, 62), hjust = c(1.1,-0.2),
                 size = 3, colour = c("black", "red"))
```

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13. SUPPLEMENTARY NOTES

13. ABSTRACT
Disasters annually cost the U.S. billions of dollars in direct costs and economic loss. In particular, the increasing frequency and intensity of natural hazard incidents, such as hurricanes, tornadoes, floods, and wildfires, strains the nation's emergency management enterprise. Knowing that the current approach to emergency management is unsustainable, practitioners and policy makers look to use new tools and technologies to mitigate, prepare for, respond to, and recover from disasters. One of those technologies is satellite remote sensing. As persistent assets with a wide area collection ability and a variety of viable sensing modalities, satellites seem positioned to shed light on the nature of disaster impacts and support decisions made in the first 24 hours after disasters happen. Satellites are particularly promising for providing information on incidents that occur slowly and in rural areas. However, satellite imagery supports early response decisions and operations for only the most severe incidents in the U.S. This report explores reasons satellite imagery is under-utilized in domestic disaster response and proposes ideas toward solutions. Through systems engineering, combined with quantitative modeling and prototyping, this report offers the following. 1. An analysis of stakeholder decisions and use cases for satellite remote sensing in disasters 2. An evaluation of requirements for imagery and derived data products to support decisions 3. A description and demonstration of a concept of operations and high-level system architecture

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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