Advanced International Journal of Multidisciplinary Research
E-ISSN: 2584-0487 editor@aijmr.com
Volume 3, Issue 5, September-October 2025
CrossRef DOI: 10.62127/aijmr.2025.v03i05.1139

Smart Outage Detection via Satellite Systems and SysML

Rian Sanju Alunkal[1], Ajay Palanisamy[2], Dheeikshith Jaiganesh[3], Nandita Arun[4], Arush Sadhukhan[5]

[1]St. Aloysius Gonzaga Secondary School, 2800 Erin Centre Blvd, Mississauga, ON L5M 5Z7, Canada
[2]Seven Lakes High School, South Fry Road Cinco Ranch Katy, United States
[3]Ardrey Kell High School, 10220 Ardrey Kell Road, Charlotte, NC 28277, United States
[4]Foothill High School, 4375 Foothill Rd, Pleasanton, CA, United States
[5]Eisenhower Middle-High School, 4333 S Sunnyslope Rd, New Berlin, WI 53151, United States

Abstract:
The contemporary world is challenged by sustaining the availability of electricity through a rising population, climatic unpredictability, and poor infrastructure, with risks of disruptions rising. The ground-based power outage detection methods are subject to limitations arising from difficulties such as partial coverage and loss of communications. In this research, we will illustrate that satellite-based systems can likely be a facilitator of real-time Outage monitoring and maintenance, and we exemplified that in modeling by employing SysML (Systems Modeling Language), defining a theoretical fault-tolerant satellite-based power system architecture powered by Space-Based Solar Power (SBSP) and supporting remote outage detection and providing resilience to our infrastructure. Satellite types are able to provide observation, utilization, reduced latency for detection, and the like. We looked at sensors from the VIIRS DNB, which identify outages by detecting reductions in light emissions during nighttime. Inmarsat provided us with limited communications capability where terrestrial communications were weak, and also the Denoising Autoencoder, WeCare, and the Remote Agent Experiment, which provided us with additional environmental and infrastructure information to utilize in developing and prioritizing our situational awareness. The overall findings of this study show that the use of satellite technology will increase control and security for our grids and enable complex models and reliable, sustainable grid systems throughout the globe.

Keywords: Disaster Recovery, Outage Detection, Satellite Technology, SysML.

1. INTRODUCTION

Humanity stands at an important juncture, marked by rapidly advancing technology, rapidly escalating energy demands, and the transition to sustainable power sources. By 2050, global energy consumption is expected to grow by 50%, further supporting the pressure on current infrastructures and resources [1]. Furthermore, we are dealing with a lack of access to energy supplies throughout the world due to a country's financial state or its geographic location.[2]. Over 660 million People across the world still lack access to basic electricity in their regions because of these problems. Fortunately, This can be fixed using smarter energy resources and power grids that help maximize sufficient and better energy to regions across the world [3].

In our day-to-day lives, we are dealing with electricity problems more frequently than ever before. People who live in areas with persistent disasters have zero to few accesses to electricity sufficient for their survival. Electricity is integrated so much into society that it would be hard for a person to live without sufficient electricity in situations of disaster. Disaster relief can be especially hard without the use of satellites, as they function coherently with no such disturbances at all compared to terrestrial networks and communication. With the ever-increasing world population, we are faced with increasing demands for power supply. Such supply could be considered taxing without the usage of satellites and satellite monitoring. While methods of satellite monitoring have been studied extensively, there have been very few findings on distribution and management of energy through satellite utility and its integration in real scenarios [4]. As science and technology advance, the use of satellites is crucial not only to our everyday lives but also to the progression of our civilizations and further expansion throughout space [5]. Our everyday lives rely on technologies that involve the use of satellites, electricity that surrounds us through power grids, and safety that can only be analysed through satellite imagery. The integration of satellite technologies with system modelling approaches such as SysML can increase the resiliency of power grids through better monitoring and quicker outage detection and management, which is important for disaster-prone areas and remote access. Although satellite technologies play an important role in disaster response, environmental monitoring and communications continuity support, their potential uses are usually discounted in plans that are based on broader energy infrastructure considerations. For example, the Canadian Space Agency emphasizes satellite systems' support for wildfire tracking, emergency mapping, and public safety coordination [6], and companies like Viasat provide satellite internet connectivity in circumstances where terrestrial networks have been compromised in disasters [7].

This leads us to the main premise of this research, as we delve deeper into these uses and explain how they impact us both in the present and the future. In this study, we will be discussing various satellite technologies, use cases, and tools to help structure the creation of these satellites. We will also discuss the future outlook of these satellites and how they will continue to contribute to our research, as well as their relation to the original purpose of our research. The ultimate goal here is in identifying the combined potential of satellite technologies and SysML for power grid resilience.

2. METHODOLOGY AND ANALYSIS

2.1 Satellites technologies used in power grids

This section evaluates how satellite technologies enhance modern power grid monitoring and outage detection, especially in disaster-prone and remote regions.

2.1.1 Power Grids

Power grids are vast networks of power lines that are responsible for transferring electrical energy from energy-producing power plants to consumers, including businesses, homeowners, cities, and factories. This energy transfer must be as efficient and timely as possible, as providing energy for a growing population that uses gadgets and tools that are more energy-intensive than ever becomes increasingly challenging. Unfortunately, most power grids are susceptible to common problems, including overloads, blackouts, and storm damage. Smart grids are required to ensure such problems do not prevent continuous electric flow from being disrupted for long. Satellites enhance smart grids by enabling remote monitoring, outage detection, and faster system response.

2.1.2 Process of Detecting a power outage

2.1.2.1 At Night and During Day

Outage detection at night is by far the easiest, especially when compared to outage detection in the day. Suomi-NPP and NOAA-20 VIIRS satellites are used for detecting night outages. Devices, like synchrophasors, often use measurements such as the on ground Phasor Measurement Units,closely coordinate and work with satellites to send reports to control systems about power grid status by tracking the ground continuously at the rate of 50 to 60 Hz [8]. When they detect an abrupt drop in light intensity for more than a few seconds, they immediately report an outage, which saves both time and money in repairs.

This was put to the test during Hurricane Sandy, where it found outages by processing the data at high granularity using a neural network. Similar results were obtained during Winter Storm Uri in Texas.[9] on the other hand The EMS (energy management system) usually has supervisory control and data acquisition (SCADA) every two to four seconds [10]. During the day, satellite-based outage detection relies on indirect indicators—such as thermal infrared imagery and reflectivity changes—since visible light is naturally present and tends to interfere with detection, as there is no change in visible light during a power outage in the day. Thermal bands on sensors like VIIRS (the Visible Infrared Imaging Radiometer Suite) can capture heat dissipation differences when power-dependent equipment (e.g., transformers or industrial machinery) goes offline, while Surface Reflectance (SR) data helps distinguish between typical infrared signatures and anomalies due to outages. Studies in Maharashtra, India, have found strong correlations ($R^2 \approx 0.85 - 0.88$) between daytime fee. Smart grids are required for on-line voltage data and nighttime radiance, validating daytime outage detection using long periodsetrics [11]. Additionally, machine learning classifiers, such as random forests, trained on VIIRS radiance combined with ground voltage data have shown promise in estimating daytime outage rates with reasonable accuracy.

2.1.3 Utility of Satellites in Disaster Recovery and Management

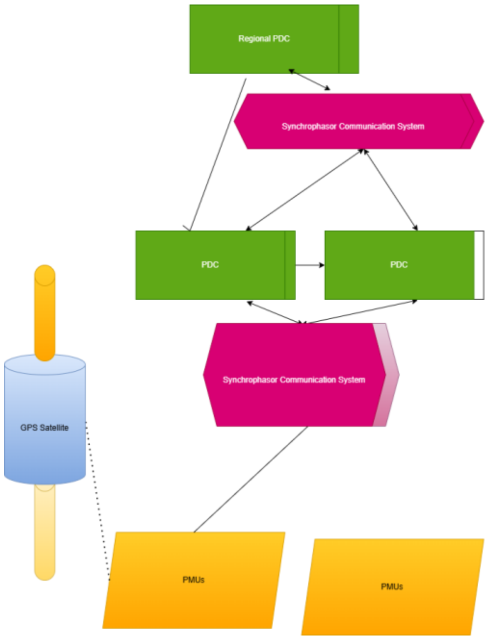
Satellites play a pivotal role in disaster management and recovery since they provide essential unaffected communication to central command centers when terrestrial communication infrastructures cannot. Satellites can establish communication links to regions where terrestrial networks are impacted, enabling quick and rapid restoration of electrical grids with ease. For instance, most smart grids in Japan utilize satellites to relay management and grid performance due to their frequent natural disasters in the country. Such rapid data transfers from satellites can enable quicker decision-making to restore power grids and load balancing. Satellites became an essential element for Japan’s disaster recovery strategy with zero to no power disruption during emergencies. The Table below can be used to see other significances of satellites during other events or disasters around the world.

Table 1:Summarizes case studies of grid managements and disaster recoveries around the world [4]

Case Studies	Utilization of Satellites	Outcome of The Recovery
Rural Electrification in Africa	Satellite Communication to Smart-Grids that are enabled in rural parts of Africa	This helped ensure faster maintenance and improved reliability of power supply. As a result, it helped improve economic growth and living conditions in the area
Grid Management in Japan	By utilizing satellites, data from smart meters and substations in affected areas was quickly relayed to control centers allowing quick decision-making for power restoration and load balancing.	Satellite communication provided a robust and reliable energy grid ensuring minimal disruption during disasters after the 2011 tsunami.

Remote Australia	Satellites are used to monitor, manage, and support power delivery. They provide real-time data on grid performance, enable remote fault detection, and assist in coordinating renewable energy sources across vast, hard-to-reach areas.	Strong connections to remote substations and power lines. This allowed the power grids to be managed with real-time data collection and analysis to further predict maintenance of electricity within power grids.

Figure 1: The figure above displays the various elements that are used for the Synchrophasor Communication Systems used for monitoring power grids from satellites. Synchrophasor measurements called PMUs can measure samples of power grids from 50 to 60 samples per second. These PMUs communicate with their PDCs, which transfer data to satellites with ease and efficiency. This allows satellites to monitor power grids in areas where there is little to no terrestrial communication surrounding the area and in situations where terrestrial communication is limited in the area.



2.2 Utility of SysML in Space Missions

This section covers how and why SysML is used in various space missions. SysML can provide organization between systems, aid in the interactions of each system, assign essential information, and make the structure of each system easier to understand with visual modeling. SysML is actively used in many missions and experiments involving its use in tandem with other tools.

A crucial part of the engineering design process involves analyzing and meeting the requirements as the mission or project progresses. SysML plays a significant role in tracking and linking requirements to each design element. This is essential because it allows for easy access to knowledge, whether or not a requirement is properly met [12]. Other than tracking requirements, it can also track important parametric data for quantitative experimentation. This is useful as it shows how SysML is used in a research setting, as the data can be properly analyzed with other software [13]. SysML is also used in defining various systems and how they interact. SysML uses visual modeling to represent how different design elements work together. Additionally, it shows how different systems progress as time moves on and how they ensure seamless integration while ensuring compatibility [14].

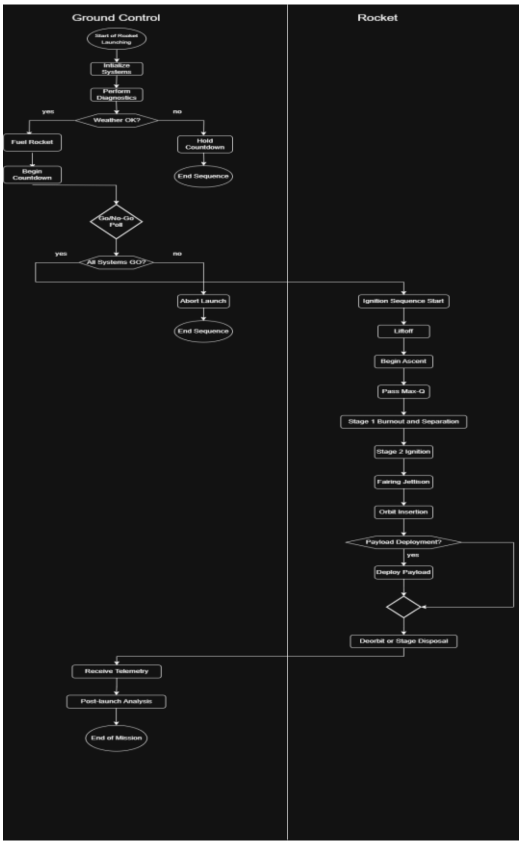
Model-Based Systems Engineering (MBSE) is essentially used when using SysML. MBSE is the methodology, while SysML is used to execute the methodology. MBSE is used to make formalized models, while SysML is used for the visualization and structuring of them. Using these ideas helps define, analyze, and organize many systems and results [15]. Hence, many different organizations use SysML and MBSE for their space missions. The following table can be used to see the practical applications of SysML.

Table 2:Summarizes SysML applications and outcomes used in various organizations [16][17][18][19]

Organization	**SysML Application**	**Outcome**
Nasa	Orion, Gateway, Artemis mission planning via SysML/MBSE	Unified system models with traceable requirements
ESA	SysML for satellite power subsystem design	Constraint modeling of battery cycles and efficiency
JAXA	MBSE for rover mobility and hazard detection	State machine and parametric models for terrain traversal
Northrop	Full spacecraft architecture modeling	Digital twin and simulation integration

Through the table, it can be seen how SysML is used by different organizations for different reasons. This can show the wide range of use cases of SysML besides space missions, as it can promote safer and more reliable systems while innovating more complex systems that can help create a sustainable and efficient engineering practice. Additionally, SysML is a tool of great importance that can be used to boost technological progress both on Earth and in space. However, SysML does come with some consequences, such as how it is expensive, time-consuming, and requiring other tools for it to work. Adding on the fact that it requires additional tools, it can be seen through experimentation with the RAX CubeSat that it needs outside tools, such as ModelCenter, a tool that wraps analysis models; MagicDraw's CST, the executor of the behavioral diagrams; and an MBSE Analyzer that enables the simulations [20]. This can add to the complexity of SysML, as it shows that in order for it to function accordingly, it depends on other software. But despite this complication, SysML is still helpful in engineering and various missions.

Figure 2: Simplified Rocket Mission Sequence. This flowchart is a simplified generalization of a rocket launch throughout its mission. It first begins with its launch and all its associated checks, then it progresses into the rocket launching into different stages while either flying or deploying a payload. Following this, further telemetry is gathered, and the mission is analyzed. This shows the basic layout of the mission, but further subsystems can be made with flowcharts, such as the initialization process, staging process, landing process, etc. All of which can be made with SysML to create a flowchart



2.3 Space-Based Solar Power and Energy Redistribution

This section discusses Space-Based Solar Power (SBSP) and its potential to revolutionize global energy distribution. SBSP systems capture sunlight in orbit and transmit the energy wirelessly to Earth, offering a continuous, clean energy source. Because they operate beyond Earth's atmosphere, these systems bypass terrestrial solar limitations such as cloud cover and night cycles, enabling uninterrupted energy flow.

Large solar power satellites convert sunlight into electricity, which is then beamed as microwaves or lasers to ground-based rectennas for integration into existing electrical grids [18]. A principal advantage of SBSP is its capacity for continuous energy delivery, which overcomes the irregularity of Earth-based solar systems. This constant power supply can stabilize electrical grids, complement intermittent renewable sources, and deliver energy to remote or disaster-affected regions [21].

Wireless energy transmission further enables flexible and targeted energy redistribution, optimizing power availability across geographic regions. However, integrating SBSP with terrestrial energy systems demands sophisticated engineering solutions.

Model-Based Systems Engineering (MBSE), using the Systems Modeling Language (SysML), plays a critical role in designing and simulating SBSP infrastructure. SysML parametric diagrams define mathematical constraints for energy conversion and transmission, improving precision and reducing costly redesigns prior to hardware deployment [13].

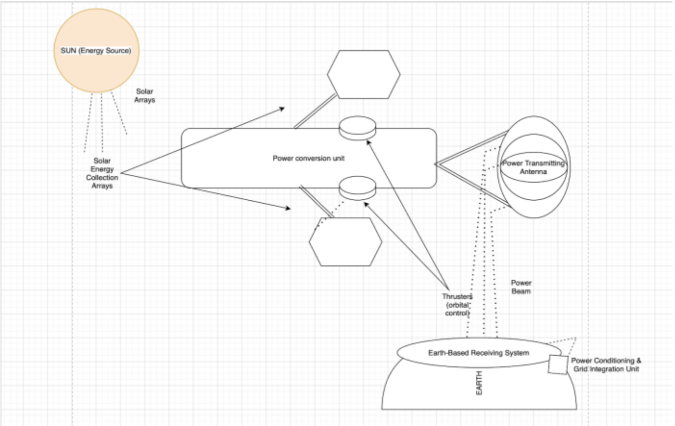
Organizations such as NASA have demonstrated the benefits of MBSE in complex aerospace projects, enhancing cross-disciplinary collaboration and enabling early detection of design issues—crucial for achieving reliability and safety standards [12]. Meanwhile, JAXA continues to advance space platform technologies that support foundational SBSP concepts [18].

Precision and synchronization technologies also play a key role in energy redistribution. Satellite time-synchronization systems enable real-time grid monitoring, providing accurate timing for demand response and dynamic stability control [22]. This synchronization is essential for incorporating energy from multiple space-based sources, thereby supporting smart grid resilience.

Table 3: Operational Characteristics of Precision Synchronization and Grid Monitoring

Characteristic	Value (approx.)	Unit	Source
PMU Sampling Rate	50-60	samples/s	Smart Energy, Wide Grid Monitoring, 2020
Typical Large Grid Components	Millions	Components	Smart Energy, Wide Grid Monitoring, 2020
Satellite Connectivity	Always on	N/A	Energy Digital, Role of Satellite in Smart Grid Development

Figure 3: This figure displays the complete architecture of a space based solar power system. Solar energy, captured in Earth's orbit by the Solar Energy Collection Array grids on the orbiting power satellite–to prevent terrestrial limitations such as weather or night cycles– is converted into electrical power and then transmitted to Earth through the power transmission. On Earth's grounds, a dedicated receiving station converts the beamed energy into usable electricity for terrestrial power grids, providing clean power.



Despite its promise, several challenges remain: high initial costs, the need for safe wireless power transmission, managing space debris, and navigating international regulatory frameworks [23]. However, recent advances in reusable launch vehicles, modular satellite architectures, and adaptive systems engineering are steadily reducing these barriers [24].

2.4 Potential Satellites for Power Grid Outage detection

This section evaluates different types of Earth-orbiting satellites to determine which satellite systems most effectively support real-time monitoring and rapid response in power grid outage scenarios, based on launch cost, latency, and coverage area. The most promising satellite types are those that are easy to launch, can cover large portions of the Earth's surface, and have a low latency. Satellites such as those equipped with the VIIRS DNB sensor detect outages by monitoring nighttime light patterns. A sudden drop in brightness in urban areas is interpreted as a power failure. These observations are relayed to ground stations and processed through decision-support systems to trigger alerts for grid operators. In addition they will be compared with ground satellites using code and real data to prove that they provide better coverage and protection.

This section evaluates different types of Earth-orbiting satellites to determine which satellite systems most effectively support real-time monitoring and rapid response in power grid outage scenarios, based on launch cost, latency, and coverage area. The most promising satellite types are those that are easy to launch, can cover large portions of the Earth's surface, and have a low latency. Satellites such as those equipped with the VIIRS DNB sensor detect outages by monitoring nighttime light patterns. A sudden drop in brightness in urban areas is interpreted as a power failure. These observations are relayed to ground stations and processed through decision-support systems to trigger alerts for grid operators. In addition, they will be compared with ground satellites using code and real data to prove that they provide better coverage and protection.

2.4.1 Criteria:

2.4.1.1 Cost of launch

The cost of launching satellites is one of the most critical aspects of evaluating whether a satellite should be used or ground sensors are preferable. As can be inferred, the higher the altitude of orbit, the costlier the price of the satellite, both due to increasing complexity of launch and the increased price due to greater fuel requirements [25].

2.4.1.2 Latency

Latency is the delay between sending a message from the satellite and receiving the message at the ground station. It is important, as the delay slows down detection and, in some cases, causes outages to go unnoticed. The higher the altitude of the satellite, the greater the latency. Naturally the satellites with lower delay are favored for real-time monitoring [26].

2.4.1.3 Coverage area

The coverage area of the satellite is the area of the earth visible to the satellite at any given moment. The smaller the coverage area, the more satellites are required to cover the whole planet's surface. It is important to ensure that all parts of the planet or target area are being viewed by at least one satellite at all times to ensure continuous monitoring. A satellite located close to the earth has a smaller coverage as compared to one that is farther away. [27]

2.4.2 Types of satellites based on orbital altitude

There are four distinct types of satellites that could be used: Geosynchronous Earth Orbit (GEO), Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Highly Elliptical Orbit (HEO) satellites. In Fig 3 below, the satellites and their respective orbits have been color-coded to show the difference in altitude and orbital path. Also, their features have been compared to ensure easier selection. Examples of each type of satellite are also provided [28].
Geostationary Earth Orbit (GEO) satellites are some of the most capable satellites available for this purpose. Their utility here lies in the fact that their orbit is at a fixed position relative to the Earth's surface, enabling consistent power beaming and constant solar exposure, except during the short eclipse period [29][30].However, they face high take-off costs due to extremely high altitudes (around 42,000 km) and congestion in the orbital belt, which is prevalent due to their widespread use in GPS systems, among other

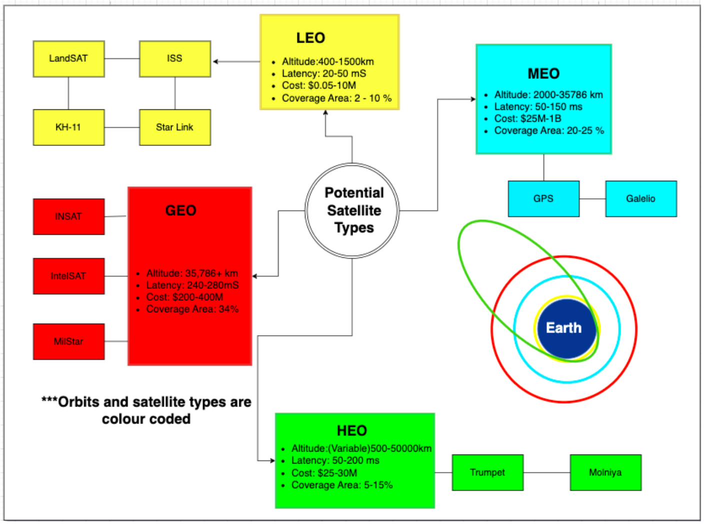
things.

Low Earth Orbit (LEO) satellites are significantly cheaper to deploy and benefit from the fact that lower-intensity signals are required for communication due to proximity to ground stations, which is a huge factor in increasing battery life. Their lower latency and proximity allow for faster outage detection. However, due to limited coverage, constellations of satellites are needed for continuous global monitoring. These satellites are often equipped with VIIRS DNB (Day/Night Band) sensors, which detect outages by observing sudden drops in nighttime brightness over urban and industrial areas. However, their fast orbits and smaller coverage areas necessitate constellations of satellites to ensure uninterrupted connections with all areas involved [27].

Medium Earth Orbit (MEO**)** satellites fly between LEO and GEO satellites (2,000 to 20,000 km) [31]. They possess the properties of both types of satellites, offering higher connectivity than GEO satellites (around 125 ms) and better coverage than LEO satellites (continents can be covered with each satellite). However, they face the same problems as LEO satellites: they require constellations of satellites, and, unlike LEO satellites, they are more expensive to launch and maintain [32].

Another interesting solution can be found in Highly Elliptical Orbits (HEO)—such as Molniya and Tundra—these allow for long periods of coverage over areas (8-12 hours) in higher latitudes. They can also ensure better connectivity by maintaining higher angles of elevation for a significant portion of their orbit. However, variable distances complicate beam targeting [33].

Figure 3: A simplified diagram of the different satellites, their features, and orbits



2.4.5 Proof of Concept

The first comparison involved satellites of varying altitudes and coverage areas, focusing on launch costs and the number of satellites required to achieve global coverage. Using averaged data from existing power grid satellites, a model was developed to compare satellite types while keeping most initial parameters constant. All satellites were assumed to be in the small satellite category (mass ≤ 500 kg, average = 350 kg). The base launch cost was adjusted based on altitude. The following Java methods implement the key calculations, from determining coverage angles and surface areas, to estimating constellation size, cost per unit, and overall deployment costs. This model enables a cost-effectiveness analysis that accounts for redundancy and technological scaling with altitude[34][35][36]. The base cost to launch was updated as the altitude increased. In the second program, in addition to conducting coverage and cost simulations, we assessed the effectiveness of satellites in detecting outages relative to ground sensors. To ensure accurate results, we simulated diverse terrestrial environments, each assigned distinct latency and detection levels to reflect real-world detection challenges. Terrains were allocated randomly. Each satellite was responsible for a specific region, with its coverage area varying according to time and orbital trajectory. The simulation incorporated both ground-based and orbital detection systems, quantifying accuracy and performance over multiple trials. [37][38][39][40][41][42]The results showed that LEO satellites (400–800 km) and MEO satellites (~2,000 km) performed best in terms of timeliness and reliability compared to both ground sensors and other satellites—and specifically, MEO (2,000–5,000 km) provided the optimal balance with cost. We also found that different terrains would be best suited by a different set up of satellites and ground sensors.

Table 4: Different locations that is suited by a different set up of satellites and ground sensors

Area/Circumstance	System	Reason
Urban Areas	Ground Sensors mainly with little satellite backup.	Presence of alot of infrasturceture and easy reportability of problems by civilians.
Rural Areas	Primary reliance on Satellite Detection.	Lack of Infrastructure and difficult terrain.
Critical Infrastruture	Multimodal Systems like (OmniSat)	Provides flexible, robust Earth observation across modalities when sensor availability is variable or new sensors are added.
Disaster-Prone Areas	Satellite Systems are required	For rapid Damage Assessment and quick repairs.

This aligns with real-world applications like the SPoRT team using Suomi-NPP/VIIRS DNB imagery during Hurricane Sandy to highlight regions lacking nighttime lights, aiding FEMA and response teams in identifying blackout zones [43][44][45].

To validate this further, we discuss two proof points:

- Scholarly evidence: Studies using VIIRS DNB imagery (e.g., datasets from Hurricane Sandy) have successfully detected outages and restored lighting patterns by comparing pre- and post-event nighttime brightness.
- **AI integration:** Neural-network-based approaches combining VIIRS radiance, population data, and utility networks achieved moderate predictive accuracy (Pearson r ≈ 0.5) [46]. Machine learning thus shows promise in enhancing detection from satellite imagery.

2.5 Outage Detection and Maintenance Enabled by Satellites

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

2.5.1 Roots of Outages

Outages can be described as a sudden stoppage of power, communication, or data as a result of an incident, a technical error, physical environmental events, or planning and coordination failures. Outages are disruptive and usually have varying effects throughout industries and residential households, often leading to disruptions or financial losses and safety risks. The increased utility of complex electrical and digital infrastructure has created a unique challenge for realizing and managing outages. Traditionally, the discovery of an outage relied on inspection of an event, follow-up reporting from users (delaying response), and often limited real-time reporting mechanisms. Major causes of outages include equipment failures, human error or planned work, cyberattacks or physical damage, natural events, overloading, etc. The frequency of each event is shown in Table 3.

Table 3: Occurrence of different events in percentage that caused power outages in the US in 2023 [47]

Causes	Percentage of Total (%)
Natural Events (Including Storms and Animal Interference)	61.1
Equipment Failures	20.3
Human Error/Planned Work	5.3
Unknown Causes	13.3

The following sections will explore some applications of advanced satellite technology that would help in preventing and extinguishing these issues.

2.5.2 Visible Infrared Imaging Radiometer Suite Day/Night Band

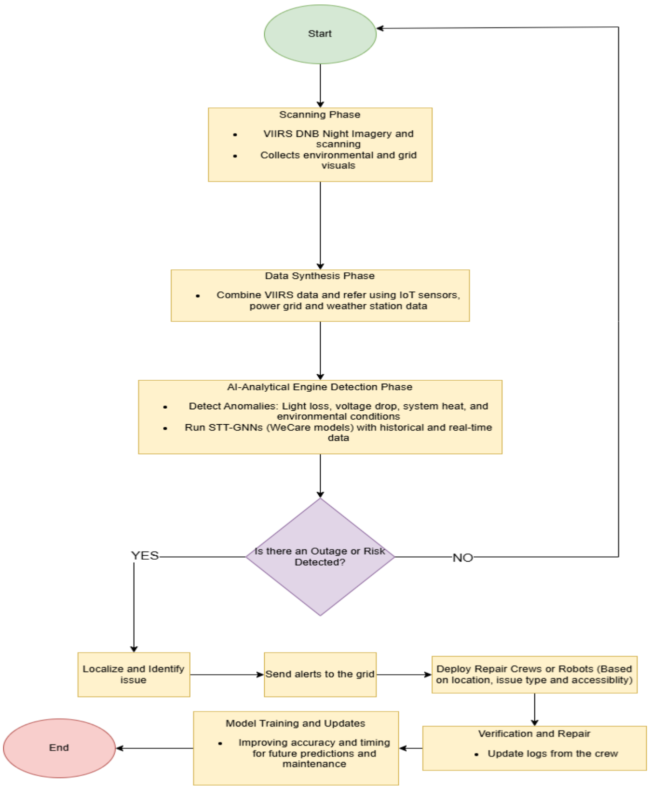
Satellites equipped with nighttime imaging capabilities, such as the Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB), play a crucial role in detecting power outages. By capturing nighttime light emissions, these satellites can identify areas experiencing outages by observing significant reductions in radiance. The power outage degree and spatial detection during a winter storm Uri, 13th February to the 17th, 2021, were done using a power outage detection model (PODM) and making a power outage spatial distribution map (POSDM). The steps involved in VIIRS DNB detections during storms include:

1. Image Selection & Filtering:Cloud-free VIIRS DNB images from S-NPP and NOAA-20 shall be selected in nadir and close-nadir view (<= 60 degrees). It collects data over a baseline period (e.g. 3 months pre-disaster) and then over a monitoring period (e.g. 15 days post-disaster).
2. Pre-processing: Quality Control, Lunar & Atmospheric Corrections: Low-quality images impacted by thick clouds or a high satellite zenith angle shall be filtered out. Measured radiance will need to be corrected for atmospheric effects (via MODTRAN using aerosol optical depth) and lunar illumination so that the baseline data are the same.
3. Outlier Detection & Removal: Outliers (defined as extremely high and low radiance) will be identified in each pixel's time series and iteratively removed until the standard deviation of the pixel series has been stabilized (i.e., a change of < 1 %) to minimize noise from transient events (e.g., wildfires, lightning).
4. Baseline Radiance Calculation: Once the baseline period images are cleaned, stack them together. The mean pre-disaster radiance will be determined for each pixel, now corrected for both lunar illumination and atmospheric effects.
5. Post-Disaster Observation: For each day of the monitoring period (e.g., the day following the storm), VIIRS will obtain the cleaned DNB image data, should there be an image, and make the same corrections.
6. Radiance Difference & Outage Detection (PODM): Compute the radiance difference for each pixel: $\Delta R=$

Rbaseline - Rpost-disaster. A significant drop (ΔR) indicates a likely power outage at that pixel
7. Quantifying Outages: Aggregate pixels where ΔR has exceeded some threshold in order to quantify the percentage of area with outages (PODM detected 28% outages compared to the 17% surveyed)
8. Spatial Mapping (POSDM): Map pixel-wise ΔR onto a spatial distribution map (POSDM) by mapping the geolocations of each pixel to geographic coordinates.This means extracting the geolocations of the pixels and then mapping them, with their ΔR values, to those geographic coordinates so we can see where (i.e., geographically) outages hit hardest.
9. Validation & Accuracy Assessment: Using the utility data we can compare percentages of detected outages with actual reported outages by performing bias calculations. In this case, we could report an 11% error, and conclude that PODM was reliable in areas affected. This shows that VIIRS DNB is a good prospect in smart outage detection [9].

An advanced technique for minimizing or avoiding outages is the WeCARE project, in which a spatiotemporal Graph Neural Network (ST-GNN) is used to help predict outages through understanding how disturbances propagate spatially and temporally. The power grid or communities can be modeled as a graph where the nodes (e.g. substations, census tracts) represent the reliable community or grid power sourcing locations, and edges represent the connecting infrastructures or are geographically linked. Each node can theoretically be populated with historic data – e.g. power outages, weather circumstances, radiance changes that have been derived satellite-based remote sensors etc; a ST-GNN will make an understanding of how going from a localized disturbed area impacts another local breached location to some graph or specific edge, but also over time. For example, graph convolutions (for determining spatial relationships) can be embedded into temporal models (such as Long Short-Term Memory (LSTMs)). In general, WeCARE will utilize ST-GNN to help predict which areas are at most risk during surprise events (hurricane, ice storm) in order to provide information to inform infrastructure planning and disaster response. ST-GNN models learn from historical satellite images and weather events like hurricanes or snowstorms to predict where outages historically occurred [48].

Figure 5: Simplified Integrated Outage Detection and Maintenance Workflow in a Satellite System Using VIIRS DNB and WeCare Framework. This flowchart highlights the major processes that make this system capable in detecting outages and undertaking predictive maintenance. There are 3 distinct processes that should exist and could be combined: Scanning Phase (SP), Data Synthesis Phase (DSP), and AI-Analytical Engine Detection Phase (AEDP). Firstly, SP is done by data collected by satellites using the DNB VIIRS and collecting terrestrial visuals using cameras. Then, it integrates the data from the ground stations to analyze in AEDP. Finally, AEDP detects if a risk of an outage is present and sends alerts, communicates and deploys crew members, and trains the model with the new verified data collected from the outage so that future risks are prevented.



2.5.3 Grid reliability with Inmarsat BGAN M2M and DAE

Ergon Energy in Australia leverages satellite communications (e.g., Inmarsat BGAN M2M) to connect reclosers and other grid devices. This approach enables real-time fault response in rural areas. Inmarsat's BGAN M2M (Machine-to-Machine) service, which offers a reliable, IP-based satellite communication network. This service enables real-time monitoring and control of reclosers—automated switches that isolate faults and restore power without human intervention. By integrating BGAN M2M, Ergon Energy can remotely manage these devices, reducing the need for on-field crews to travel to isolated locations, which in turn decreases response times and operational costs. One case study that exemplifies these points could be found in Ergon Energy - a utility that services a considerable electricity network spread across remote and rugged areas in Queensland, Australia. In order to monitor and control reclosers (automated electrical switches) in areas without cellular network coverage, Ergon installed hundreds of BGAN M2M satellite terminals in remote locations. The BGAN provided reliable and on-demand connectivity to allow continuous telemetry and remote switching, even in extreme weather conditions. The overall functionality of the system allowed Ergon to detect faults faster, automatically route power and improve the resiliency of the grid. In addition, BGAN M2M maintains a very low data usage profile, is easy to maintain and is cost-effective and scalable. Additionally, BGAN M2M provides a safe and orderly method to upgrade essential infrastructure in off-grid situations [49].

Another remarkable equipment is The Stage Training Denoising Autoencoder (ST-DAE), an advanced unsupervised deep learning model that screens for anomalies in satellite power subsystem telemetry. The model trains on progressively corrupted normal telemetry data and learns robust representations of reasonable system behavior. Using the model to detect errors in reconstruction allows for complete identification of sudden failures (e.g., battery failure) and subtle degradations (e.g., solar panel efficiency reduction). ST-DAE's unsupervised model detects power subsystem anomalies because labeled failure data is not easily accessible and notable detections are time sensitive, helping with proactive maintenance and improving overall satellite reliability [50].

2.5.4 Remote Agent Experiment

NASA's Remote Agent Experiment (RAE) on the Deep Space One mission (1999) was the first onboard autonomous control system, capable of fully controlling a spacecraft's operations without human intervention. The RAE system's architecture contained three tightly-coupled components: the Planner/Scheduler (PS) which used a heuristic chronological-backtracking search algorithm to generate temporally consistent plans so that mission goals were satisfied with the resource constraints, a Smart Executive (EXEC), a robust, multi-threaded, real-time executive to communicate, dispatch and monitor the concurrent execution of these plans, handling unexpected events through dynamic adjustments to real-time tasks, and a Mode Identification and Recovery (MIR) module that used model-based diagnostic reasoning to detect and isolate faults, mode changes, and would autonomous or self-heal from faults! The RAE's integrated architecture provided for autonomous operations, including real-time detection, diagnosis, and recovery from spacecraft hardware faults which can be substantial for long-duration, deep-space missions due to communication times from 15 minutes (Mars) to years (beyond Pluto). RAE was successful in cost-effectively demonstrating onboard AI-based spacecraft autonomy. It also provided the necessary groundwork for developing autonomy for the next generations of autonomous planetary rovers, satellites, and self-healing space systems[51].

2.6: Evaluation of Satellite-Enabled Power Grid Solutions

2.6.1 Benefits of Satellites in Grid management

The advent of the emerging satellite technology and equipment has ushered in the rise of smart infrastructure for power stations. These technologies put forward a multitude of benefits that have the potential to reduce costs and enhance reliability and extensive coverage. This section will look into some of the essential benefits of satellite technologies in managing power grids.

2.6.1.1 Cost Savings

- Reduced maintenance and labor costs: Satellite monitoring reduces the need for physical inspections, especially in remote or dangerous locations. This shift to satellite maintenance reduces fuel, vehicle use, and personnel hours, leading to substantial savings in operational budgets [52]. A good example is the RAE [51].
- Faster Response -Losses minimized: Real-time outage detection from smart satellite technologies minimizes downtime, helping industries and households resume and recover operations more quickly, leading to lesser losses caused by them [53].
- Predictive maintenance: AI-integrated satellites forecast failures before they happen, preventing expensive emergency repairs or equipment replacement [54]. One of the promising examples that uses this is the WeCare Project [48].
- Data efficiency: Smart algorithms by AI-integrated satellites optimize the use of bandwidth and processing resources, resulting in lower operational costs over time [55].

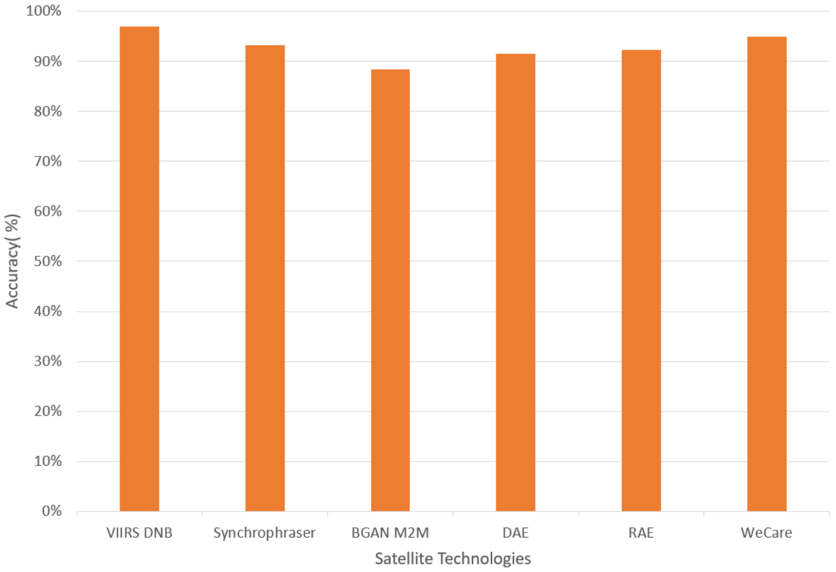
2.6.1.2 Enhancing Reliability

- Autonomous fault detection and response: AI-integrated satellite systems detect and resolve issues quickly and automatically, minimizing human error and effort. These satellite systems enhance grid reliability by identifying anomalies such as voltage drops, equipment overheating, or physical damage. These systems can trigger alerts, reroute power, or adjust load balance autonomously without human intervention, immensely reducing the time between fault detection and response. A great example is the RAE model [51].
- 24/7 real-time monitoring: Unlike ground-based monitoring systems, which may have blind spots or require manual oversight, smart satellites provide continuous, uninterrupted surveillance of the energy

grid. Satellites monitor grid health across entire continents, offering insights even in inaccessible zones [54].

- Available during disasters: In large-scale natural disasters, such as hurricanes, earthquakes, or wildfires, ground-based communication lines and control centers may be damaged or destroyed. In these desperate situations, satellites offer a reliable backup, maintaining connectivity between utility operators and field systems. This ensures uninterrupted grid control and monitoring even when terrestrial infrastructure is offline, which is critical for emergency responses [55].
- High Accuracy: The foundation of system reliability begins with accurate outage detection. Accurate and timely outage identification results in quicker response times and incident resolution. This reduces the duration and scope of outages, minimizes unnecessary interventions, and prevents cascading failures, ultimately maintaining a stable and continuous power supply. The bar graph below presents the accuracy percentages of the technologies we mentioned, which could be used in outage detection, illustrating their contribution to system reliability.

Figure 6: Comparative accuracy percentages of six outage detection technologies—VIIRS DNB, Synchrophasor, BGAN M2M, Denoising Autoencoder, WECARE, and RAE—measured to evaluate their effectiveness in identifying power outages. Higher accuracy directly supports improved reliability by enabling timely and precise detection, which is critical for minimizing downtime and maintaining stable power delivery.The accuracy values presented are based on experimental trials and published studies [56][50][57][58]which have validated the performance of these technologies under various conditions.



2.6.1.3 Extensive Coverage

- Connectivity in rural areas: One of the major challenges in grid maintenance is monitoring lines and stations in isolated or sparsely populated areas. Satellites, however, can provide seamless coverage, enabling even the most remote energy stations to be tracked in real-time without the need for additional infrastructure [53].
- Global Coverage: Satellites provide consistent and wide-area surveillance of energy infrastructure and surrounding environmental conditions across entire regions. Their high-altitude coverage allows utilities and grid operators to monitor transnational power networks and assess regional weather impacts across borders. This is especially valuable for supporting cross-border energy trade, managing interconnected grid systems, and enabling joint disaster preparedness across multiple jurisdictions [54].
- Scalability: Satellites with AI technology offer flexible scalability: A single network can be used to

monitor an entire nation-level grid or focus down to a city-level microgrid by adjusting the resolution and frequency of data collection. This adaptability enables smooth integration into both existing large-scale utility infrastructures and smaller, decentralized energy stations–without the need of costly infrastructure [55].

2.6.2 Challenges of Satellites in Grid Management

With the rise of global energy consumption and climate change, emerging technologies (particularly the integration of satellite communications and artificial intelligence (AI)) are transforming how energy systems are monitored, maintained, and protected from outages. With these new technologies come their challenges. The following section explores the challenges.

2.6.2.1 Technical Complexity

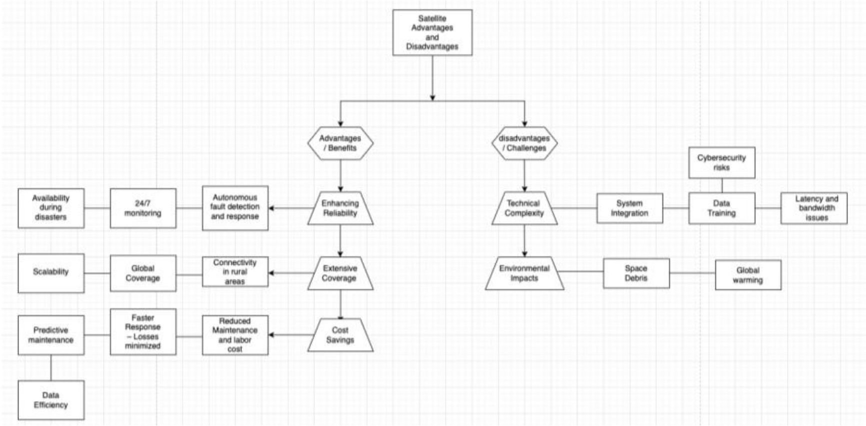
System Integration: Combining satellite communication systems, sensor networks, and advanced AI models into one cohesive infrastructure is technically demanding. Each component—ranging from ground sensors to low-orbit satellites—must collaborate seamlessly, often requiring custom interfaces and robust APIs [53].

- Data Training: Training effective AI models requires access to enormous and diverse datasets covering a range of weather events, failure scenarios, and grid behaviors. In many regions, such data is incomplete or unavailable [54].
- Latency and bandwidth issues: Satellite data may be delayed or limited. While low-Earth orbit (LEO) satellites can offer lower delays compared to geostationary systems, high-resolution images and telemetry require large data transfers, which can strain available bandwidth. In emergencies, any delay in transmitting or processing this data can prevent timely countermeasures. The need for high-performance edge computing solutions or ground relay networks means more technical demand [59].
- Cybersecurity risks: AI-based systems may be vulnerable to hacking. AI-driven grid management platforms are often cloud-based or remotely accessible, making them attractive targets for malicious thieves. Strong cybersecurity frameworks, including end-to-end encryption, AI-specific threat detection, and constant system auditing, are essential to mitigate these risks, therefore increasing tech-infrastructure [55].

2.6.2.2 Environmental Impacts

- Space Debris: The rapid growth of satellites raises significant concerns regarding the long-term sustainability of orbital space. Each new satellite adds to the crowding of low Earth orbit, increasing the risk of collisions and generating space debris. If satellites fail or are not properly removed at the end of their operational life, they can remain in orbit for a long time, posing a hazard to operational satellites [55].
- Global Warming: Rocket engines to send satellites release carbon dioxide, soot particles, and compounds like aluminum oxide into the upper atmosphere, where they can persist longer and cause disproportionate warming [54].

Figure 7: Advantages and Disadvantages of Satellite use in Power Grid management.This flowchart helps illustrate the advantages and disadvantages of using satellites for ensuring power grid efficiency and maintenance. The main advantages are: cost efficiency, Extensive coverage, Enhancing reliability. The disadvantages among others are : technical complexity, environmental impacts.



2.7: Modelling of Satellite-Enabled Outage Detection System Using SysML

In this section we outline the methodology we used to design and model AODS (Autonomous Outage Detection System) , a satellite system for power outage detection and response. The goal of our effort was to prove that we could incorporate Outage Detection technologies into one orbiting satellite constellation that would significantly reduce disruptions to power delivery. The AODS's system architecture is represented using SysML diagrams using Gaphor that we created to showcase major processes that are involved in AODS which proves that the further modelling of this prototype is possible using SysML and MBSE principles demonstrating not only the operational logic of the synchronized system but also the potential of SysML which could be further used to model and implement this system.

To formalize the concept, we used SysML to represent AODS from four perspectives:

1. Functional scope
2. Structural composition
3. Internal interactions
4. Operational sequence

2.7.1 Functional Scope

The functional scope of AODS is articulated through key use cases and interacting actors. The system's goal is to provide a rapid detection, independent assessment, and trustworthy communications of power outages. The functional scope of the synchronized satellite-based outage detection system is defined using a SysML use case model. In this context:

- System Components (Actors)
- Primary Use Cases

The key Actors that are present in AODS are:

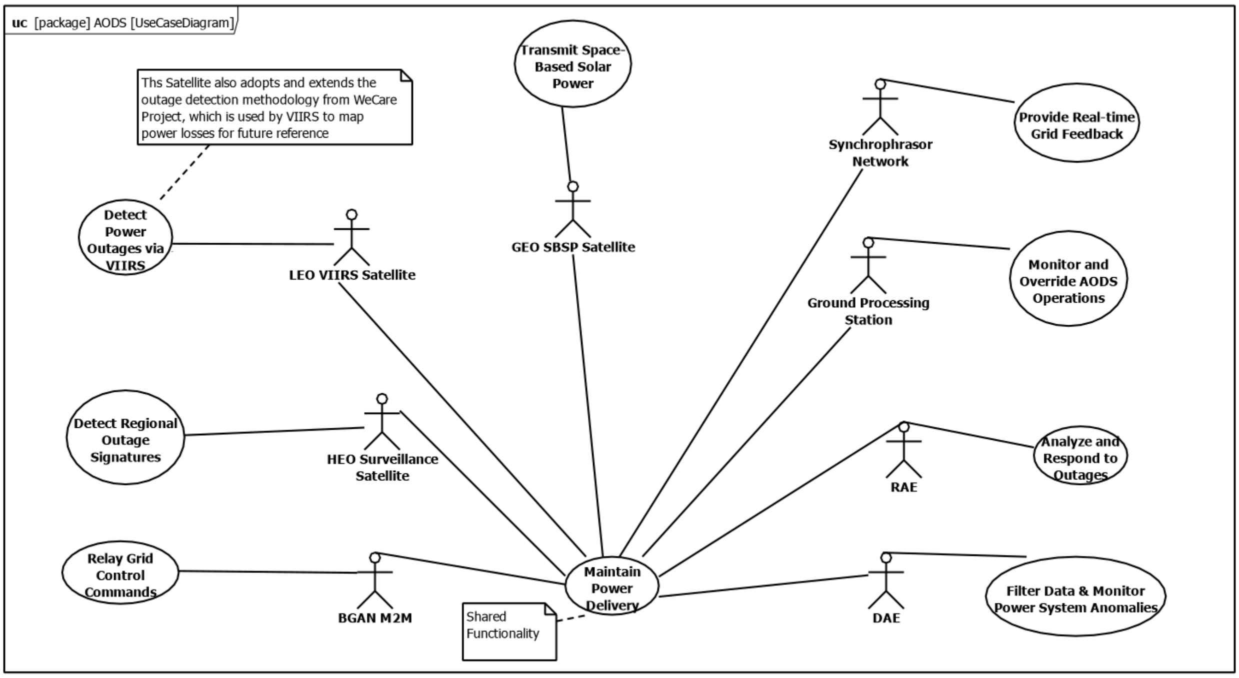
- LEO VIIRS Satellite: Uses VIIRS technology to detect outages.This satellite also contains WeCare prediction model with ST GNNs that allows it to find outage prone areas and identify patterns for future predictions.
- GEO SBSP Satellite: Collects Solar energy via space based solar panels and beams back power to ground stations
- Synchrophrasor Network: Provides real time feedback allowing rapid response to outages
- Ground Processing Station: Coordinates ground teams and satellite grid to restore power grids and ensure balanced supply of power (AODS operations)
- RAE: Analyses outages and responds based on training datasets
- DAE: Filters data and looks for power system anomalies
- BGAN M2M: Relays Grid Control Commands to ground teams and satellites.

● HEO Surveillance Satellite: Detects regional Outage signatures in higher latitudes/remote regions. It also supports persistent monitoring. [60][61]

The key functions (Primary Use cases) carried out through the interaction of these subsystems are:

1. Detect Power Outage via VIIRS: Performed by VIIRS Satellites — Collect night-time light data to monitor grid status to capture radiance anomalies.
2. Detecting Regional Outage Signatures: Performed by HEO satellites — Persistent monitoring over high-latitude and remote regions — critical for continuous situational awareness. Provides wide-area monitoring to complement LEO data.
3. Filtering Data and Monitor Power System Anomalies: Performed by DAE — Filters Noisy Telemetry Data from Satellites and checks if there is a problem with the data received to scan power system anomalies.
4. Analyze and Respond to Outages: Performed by RAE — Evaluate severity and prioritize response actions autonomously.
5. Monitor and Override AODS Operations: Performed by Ground Station — Supervises satellite control, data aggregation, and overall system management.
6. Transmit Space-Based Solar Power: Performed by GEO SBSP Satellite — Delivers space-based solar power to restore affected grid regions.
7. Relay Grid Control Commands: Performed by Inmarsat's BGAN M2M — Transmits detection data and commands in near-real-time across the system.
8. Provide Real time Grid Feedback: Performed by Synchrophrasor — Integrates real-time grid measurements with satellite data for comprehensive outage confirmation.
9. Maintain Power Delivery: The task that every actor needs to satisfy — Giving support to maintain undisrupted power delivery.

Figure 8: SysML Use Case diagram illustrating the functional scope of AODS. The system boundary encompasses all the internal devices and subsystems like LEO VIIRS DNB satellite used in radiance image capture, DAE used in the detection of anomalies, the RAE in autonomous measurement of outages, the HEO Surveillance Satellite for larger monitoring scope, the GEO SBSP satellite for emergency power supply, the Ground Station for the handling and coordination of the system, the BGAN M2M network in real-time data communication, and the Synchrophasor Network for the correlation of real-time grid measures. Each device is simulated as an internal actor running distinct use cases collaboratively for actual-time outage discovery, assessment, communication, and recovery assistance.



The system features of this model are inferred and assumed through critical examination of available research and tried methodologies in satellite-enabled outage detection and power grid management. The crucial functional components, such as radiance anomaly detection based on VIIRS data, onboard decision-making through locally implemented agents, and real-time communication through satellite networks, have been evidenced in [22][9][48][49][50][51][33]. These sources provide theoretical foundations and empirical facts validating the design hypotheses and operational characteristics employed in this model.

2.7.2 Structural Composition

This section explains the functional interactions of AODS in the form of a SysML Internal Block Diagram (IBD). The IBD captures the internal connectivity of subsystems, illustrating how data, commands, and resources flow between them to enable coordinated detection, verification, and mitigation of power outages. By defining the interfaces and interaction pathways, the diagram reflects the operational cohesion necessary for synchronized satellite-ground performance.

The system is conceived as an integrated whole made up of a multitude of interacting subsystems and devices. By describing each device as a composite part of the system, the BDD clearly delineates the system boundary and emphasizes the modularity and scalability of the design. This hierarchical decomposition allows us to grasp the system's complexity by breaking it up into manageable, well-known pieces.

The internal components, which act simultaneously as actors in system use cases and as entities in the system’s structural hierarchy, include:

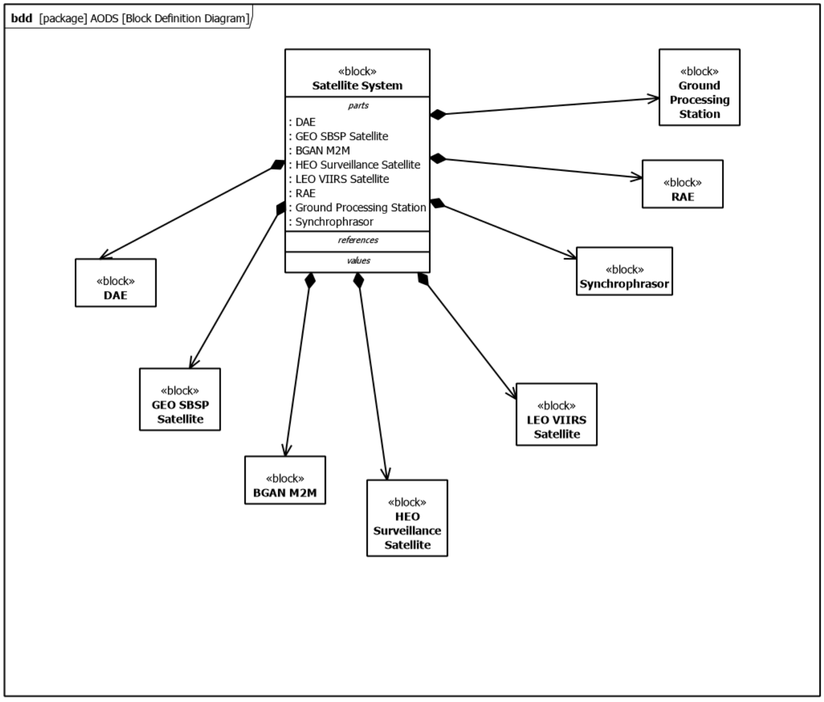
- VIIRS DNB Satellite
- Remote Agent Experiment (RAE)
- Denoising Autoencoder (DAE)
- HEO Surveillance Satellite
- GEO SBSP Satellite
- Ground Station
- BGAN M2M Communication Network
- Synchrophasor Network

Each composite link (Diamond arrows) in the BDD is a whole-part relationship, i.e., they are inseparable and non-divisible parts of the system as a whole. This structural representation not only delineates system boundaries but also allows for:

- Explicit ownership and responsibility: Each entity's intent and contribution towards system behavior is explicitly stated
- Modularity: The system can be understood, analyzed, and built piecewise by dealing with each piece separately.
- Scalability and maintenance: New components can be added or existing ones swapped out without disrupting the entire system architecture.

This approach enables a whole and consistent system design that possesses good outage detection and response characteristics.

Figure 9: SysML Block Definition Diagram depicting the structural elements of the integrated satellite-based power outage detection and response system. The diagram represents the system as a top-level block containing all essential internal elements, specifically the VIIRS DNB Satellite, Remote Agent Experiment (RAE), Denoising Autoencoder (DAE), HEO Surveillance Satellite, GEO SBSP Satellite, Ground Station, BGAN M2M, Synchrophasor Network, and Electrical Grid. These elements are connected to the system block through composite associations, indicating relationships from whole to part and signifying that they function as both actors and structures in the system. This hierarchical decomposition defines system boundaries, promotes modularity in development, and may simplify the integration and maintenance of subsystems, while also indicating ownership and composition.



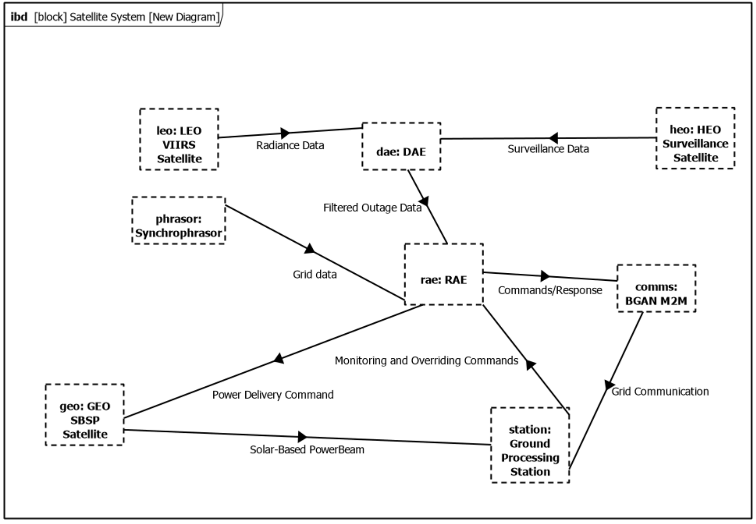
2.7.3 Internal Interactions

The design components of AODS are described in terms of functional interactions in the form of a SysML Internal Block Diagram (IBD). The IBD illustrates the internal connectivity of the subsystems and the flow of data, commands, and resources in the detection, verification, and mitigation of power outages. The IBD will define the interface and interaction pathways between major components of the design, reflecting the operational unity required for coordinated satellite-ground region engagements.

The AODS communicates with other systems in the following manner:

1. LEO VIIRS DNB and HEO Surveillance Satellite simultaneously send high-resolution radiance data and comprehensive surveillance data to DAE respectively for advanced processing and anomaly detection.
2. The Denoising Autoencoder (DAE)filters and cleanses the incoming noisy data streams, identifying and isolating any irregularities or distortions that may indicate anomalies within the power system. After processing, this data is sent to RAE for decision making.
3. The Sychrophrasor Network will also share its data with RAE to cross check with the data of satellites
4. RAE makes the decision if there is an outage and sends it to BGAN M2M which has real time grid control and sends commands to Ground Station. BGAN M2M is a communication line between RAE and the grids.
5. Ground Station will verify these commands to check if they are valid and give control if they are accurate. If not, the Ground station will override the RAE.
6. Then a Power delivery Command from RAE is sent to GEO SBSP which will beam the power towards the ground station and ground station will supply the power to the grids to ensure that there is continuous power delivery

Figure 10: SysML Internal Block Diagram (IBD) illustrating the functional connectivity of the integrated satellite-based power outage detection and response system. The diagram depicts internal data flows, command exchanges, and resource interfaces between subsystems, enabling coordinated operations from anomaly detection to mitigation. Interaction links highlight both direct and intermediary communication pathways essential for synchronized performance across space- and ground-based assets.



By structuring these interactions into a seamless operational loop, the system sustains situational awareness, accelerates anomaly detection, and maintains a synchronized response capability across all connected platforms.

2.7.4 Operational Sequence

This section details the internal operational workflow of the integrated satellite-based power outage detection and response system. With the SysML activity diagram, we modeled the sequential and concurrent processes triggered upon detection of a power outage, outlining the system's automated response cycle.

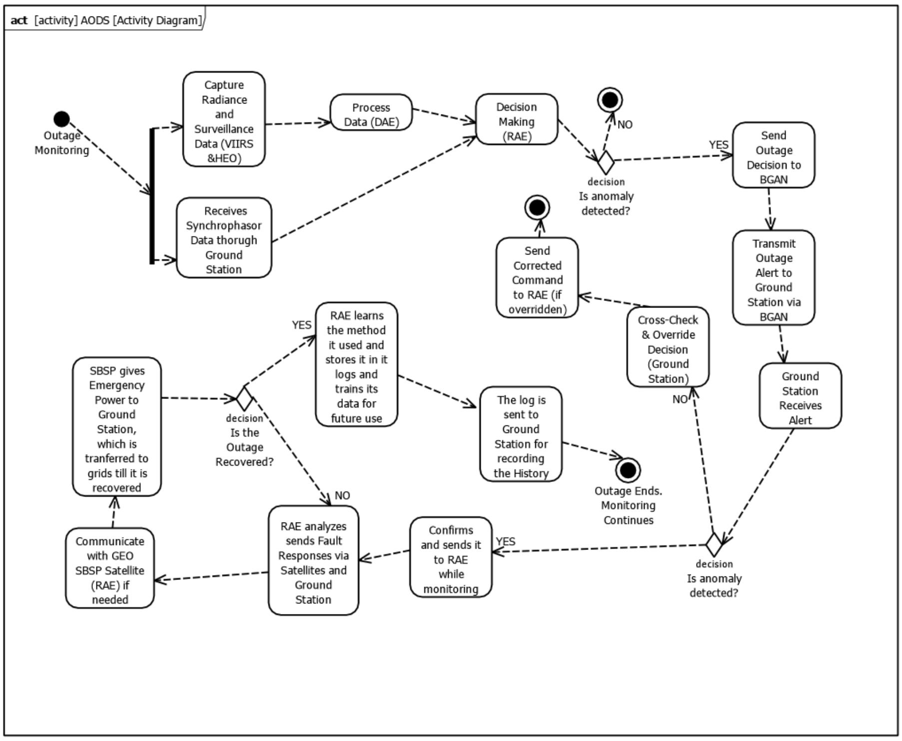
The system process of the integrated satellite-based power outage detection and response system defines the sequence of internal processes initiated on power disruption detection. It explains the activities of subsystem-to-subsystem autonomous interactions responsible for anomaly detection, outage assessment,

communication between components, and power restoration. This sequence is critical to evaluate the system's capability for timely and coordinated outage mitigation.
The workflow is as follows:

1. Outage Monitoring and Data Collection: The system initiates real-time outage monitoring, logging radiance and monitoring data from Low Earth Orbit (LEO) satellites such as VIIRS (Visible Infrared Imaging Radiometer Suite) and High Earth Orbit (HEO) monitoring satellites. Simultaneously, it logs synchrophasor data from the ground station, providing real-time values of electrical grid metrics.
2. Data Processing and Decision Making: The satellite data is initially processed through the Data Analysis Engine (DAE), which filters and cleanses the raw surveillance and radiance data. At the same time, ground station synchrophasor data is aggregated to provide an overall situational awareness. The processed data is then fed into the Remote Agent Experiment (RAE), which is an independent decision module responsible for analyzing potential anomalies in power supply. RAE performs an initial anomaly detection test to determine whether the received data indicates a power fault or outage.
3. Anomaly Alerting and Detection for Transmission: Should the RAE determine that there is no anomaly, ongoing monitoring follows. When an anomaly is found, however, the system triggers sending an outage decision to the BGAN communications system. BGAN M2M facilitates secure real-time transmission of the outage alert messages from the satellite system to the ground station. The ground station receives the alerts and triggers a secondary decision point to confirm the anomaly.
4. Cross-Verification and Override of Ground Station: The ground station, in the decision for anomaly, cross-verifies and checks the same. Operators may override the autonomous decision, if required. When the ground station confirms the anomaly, the outage process proceeds. If no anomaly is confirmed, the outage process is cancelled and RAE is overridden by the system. It then continues to monitor.
5. Fault Response and Communication: Upon confirmation of an outage, the RAE computes the fault analysis and initiates correct fault response commands through satellite and ground station communication links. These responses can be in the form of modification of grid control parameters or invoking recovery procedures.
6. Emergency Power Supply and Rebound: Should the interruption not be addressed promptly, the system sends a signal with the Geostationary Earth Orbit (GEO) Satellite carrying the Space-Based Solar Power (SBSP) platform. The SBSP satellite provides emergency power to the ground station, which subsequently transmits power to affected grid segments. The emergency power supply lasts until the grid is fully restored, as solved from ongoing observation
7. Learning and Logging: After the power outage is over, the RAE records the event parameters, including the fault detection method and remedial action. The logged parameters are stored at the ground station for subsequent analysis and system training. The RAE uses the recorded data to reprogram its anomaly detection algorithm and improve decision-making performance during future events.
8. Continuous Monitoring: After the grid is restored and emergency measures are concluded, the system switches back to continuous monitoring mode with its eye always open for new anomalies to provide continued power grid reliability. This cycle of an outage concludes and reverts back to monitoring from scratch

Figure 11: Activity diagram of AODS operational sequence. The diagram depicts the sequential processes involved in satellite-enabled outage detection, decision-making, and recovery. Operations progress through six functional categories: Outage Monitoring and Data Acquisition (Radiance Capturing from VIIRS and HEO satellites; Synchrophasor Data Reception via ground station), Data Processing and Decision Making (Data Analysis Engine filtering and integrating inputs; RAE evaluating anomalies), Anomaly Detection and Alert Transmission (decision points for anomaly identification; BGAN transmission of alerts to ground station), Cross-Verification and Override (ground station operator validation and possible override of RAE

decisions), Fault Response and Emergency Power Management (RAE dispatching fault mitigation commands; GEO SBSP satellite delivering emergency power until recovery), and Learning and Logging (archiving incident data; RAE retraining with recovery methods). The diagram highlights both autonomous functions and human-in-the-loop safeguards to ensure timely and reliable grid outage response.



2.7.5 Operational Feasibility, Expected Performance, and Model Conclusion

2.7.5.1 Integration Rationale

These SysML models, when collectively considered, outline a comprehensive picture of the satellite-based power outage detection and response structure proposed. The use case diagram defines the functional scope and key system operations; the block definition diagram defines the structural configuration and ownership relationships among constituent subsystems; the internal block diagram defines the logical and physical interfaces that provide information and control flow; and the activity diagram defines the procedural sequence governing the system's autonomous response to outage events. All these models together provide a homogeneous design specification that serves as the foundation for subsequent implementation planning, simulation-based verification, and performance evaluation.

The architecture utilizes the complementary capabilities of different subsystems to attain a synergistic operating scenario. VIIRS DNB and HEO Surveillance Satellites provide high-resolution radiance anomaly detection on large geographic scales and latitudinal extremes with continuous coverage. Denoising Autoencoder cleans raw satellite input to remove sensor noise and environmental interference, enhancing the fidelity of outage indicators prior to analysis.

The core of the autonomous system is the Remote Agent Experiment (RAE), which employs onboard decision logic to determine outage gravity and appropriate response actions without the need for human involvement. This significantly reduces the response latency associated with ground-based systems involving manual interpretation of data and dispatch.

Communication integrity is provided by the Inmarsat BGAN M2M, which provides reliable, low-latency data communication among orbital assets and terrestrial control nodes. Concurrently, the synchrophasor network provides accurate, time-synchronized grid state messages, enabling dynamic recovery procedure optimization as a function of real-time operating conditions.

These components together form a closed-loop, fault-tolerant system designed to operate seamlessly under a wide range of outage conditions and environmental states.

2.7.5.2 Performance Expectations

Performance estimates are derived from empirical data and operational history recorded in pertinent satellite-based sensing and autonomous control research [22][9][48][49][50][51][33][60][61]. Merging high-sensitivity radiance measurement with advanced noise suppression and onboard decision should be able to achieve outage detection-to-response times on the order of minutes, subject to environmental conditions such as cloud cover and communicational availability.

Geographically, the multi-orbit constellation allows near-global coverage, and it is possible to monitor large grid segments simultaneously with the ability to quickly detect cascading failures. The low-latency communication paths within the architecture enable real-time dispatch of restoration commands, which coupled with the synchrophasor feedback loop guarantees optimized and adaptive power re-allocation.

These functions significantly surpass existing ground-based detection systems that tend to have long delays in identifying anomalies, lack full spatial coverage, and require human intervention.

2.7.5.3 Reliability and Resilience

Every facet of AODS in question is imbued with reliability problems. Sensor redundancy is achieved by overlapping orbital paths and using both low Earth orbit (LEO) and highly elliptical orbit (HEO) platforms. The redundancy will minimize coverage gaps caused by orbital shadows or sensor outages.

Redundancy of communication is provided by the use of both the geostationary and mobile satellite communications networks, in such a manner that important data and commands can be rerouted in the event of link failure. The autonomous decision-making system incorporates fail-safe systems and backup protocols whereby service can continue under partial subsystem failures or degraded data quality.

Together, these design aspects present a solid system architecture that has the ability to sustain credible outage detection and response even under uncooperative operating conditions, hence enhancing grid stability and reducing downtime.

2.7.5.4 Scalability

Layered and modular architecture of AODS facilitates simple scalability to accommodate grids of varying size, complexity, and technological sophistication. The platform-independent communication and processing modules at the heart of the system make it simple to integrate with other satellite constellations or terrestrial sensor networks as necessary.

In addition, the architecture enables dynamic reconfiguration of sensing and communication resources to match changing grid requirements or geographical priorities. This flexibility supports deployment in a broad spectrum of regional environments—spanning from highly urbanized power networks to remote and rural electrical systems—without underlying redesign.

2.7.5.5 Constraints, Assumptions and Model Conclusion

The AODS model assumes the availability of multiple orbital platforms (LEO, GEO, and HEO) equipped with complementary outage detection capabilities, as well as ground infrastructure for decision support and grid management. Each technology's role is adapted from prior research papers and case studies, with minor modifications made for integration within a synchronized architecture. While specific implementations may vary by deployment context, the primary functions, such as sensing, communication, decision making etc. The power outage detection and response system described here combines multi-orbit sensing, autonomous decisioning logic, and satellite-earth communication networks into a harmonized and fault-tolerant infrastructure. These functions are assumed through critical examination of available research and tried methodologies in satellite-enabled outage detection and power grid management. This converged framework enables real-time detection, precise evaluation, and coordinated restoration of power outages beyond the limitations of conventional ground-based monitoring systems.

This research proposes a novel, SysML-modeled satellite-based system for power outage detection and response, addressing the latency, coverage, and reliability shortcomings of traditional terrestrial approaches. By integrating diverse sensing modalities, autonomous decision frameworks, and resilient communication pathways into a tightly coupled operational cycle, the model offers a scalable and high-resilience solution capable of near-real-time grid situational awareness and intervention.

While initial performance estimates are supported by existing literature and engineering principles, further work is required to simulate, prototype, and field-validate the model under realistic environmental and operational constraints. Nonetheless, the architecture represents a promising pathway toward globally synchronized, satellite-supported power grid resilience and paves the way for future innovations in outage management and the future growth of SysML

3.RESULTS & DISCUSSION

Throughout this research, it is evident how satellites impact society when correlated with power grids. Additionally, the research also mentions how SysML is frequently used to support these missions. The satellites provide a variety of benefits, including coverage (through the use of various types of satellites), efficiency, power grid management, and safety, which can be seen through various instances of how they directly affect society. A couple of these instances are when satellites effectively communicate with grids, which can enable economic growth, higher living conditions, and provide safety through detection of natural disasters and outages. A lot of this help with satellites cannot be done with poor maintenance and energy efficiency, so various advancements in technology help guide through better satellite uses. A technology that is used with satellites includes their capabilities to use solar power and transmit it to Earth. However, this does come with flaws, but further enhancements can boost precision and synchronization for better and more accurate power distribution. Additional technologies that boost satellites include their variety and the VIIRS DNB technology. Various satellites can be defined by their trajectories. There are GEO, LEO, and HEO satellites. These trajectories, achieved with various advancements, favor communications, coverage, or utilities, and as a whole, can compensate for their flaws. Also, another technology mentioned before that is used is VIIRS DNB, which captures light emissions and is used to help detect fluctuations in brightness of a particular area. This can detect outages and provide autonomous maintenance. On another note, SysML, through the use of MBSE, plays a huge part throughout these missions, as its goal is to organize, gather data, and simplify complicated missions. Without proper use of this, all the benefits previously mentioned could have been halted since these missions would have been drastically more difficult to keep track of and maintain. This research contains several methods of satellite usage and how they have an effect on several regions of power grids across the world. Systems such as the MBSE do provide collection and analysis of data but require sufficient latency and bandwidth from the satellite itself, as space debris does affect satellites on a daily basis. Furthermore, in this research, we are introduced to AEDP, which analyzes data from an SP and provides possible situations and risks with the given inputs. This can provide fast and efficient detection of power outages in a power grid, but would require tons of data training for the AI to work with. In comparison, these methods are extremely conventional and efficient to work with, although there are many risks that can go into these systems. Overall, despite the limitations, the satellite applications and tools are suited for success in transforming outage detections and maintenance in power grids. These systems and tools have consistently achieved their effectiveness in real-world conditions: SysML has been proven to be an easier tool to design system models; Inmarsat's BGAN M2M satellite continues to offer energy support through remote and disaster zones; RAE has shown great potential to be the future of satellite communications through its autonomous missions and reduced labor costs, VIIRS DNB and WeCare models have been evolving and making significant progress in the satellite industry. SBSP, still emerging, shows enormous support to supplement ground-level grids—particularly in regions prone to natural or political instability. Different types of satellites, such as LEO satellites, are cheaper and could be used for rapid data refresh due to their proximity to the ground. GEO satellites are used for continuous coverage, and HEO satellites are used for high-latitude visibility, which has the potential for having VIIRS DNB. Though these systems face known limitations, such as high deployment costs, latency in data transmission, orbital congestion, and energy demands from AI models, they have still achieved high operational impact by filling the major gaps that terrestrial infrastructure cannot.

Despite their growing effectiveness, satellite-based systems for outage detection and grid maintenance face notable limitations. SysML does come with some consequences: it is expensive, time-consuming, and requires other tools for it to work. SBSP has high initial costs and needs safe wireless power transmission (although it has been noted, it must remain adaptive to unprecedented changes), managing space debris, and navigating international regulatory frameworks. Technical complexity remains high, requiring accurate integration across satellite orbits (LEO, GEO, HEO), ground sensors, and predictive platforms. Latency and bandwidth constraints, especially during high-resolution data transmission or AI model inference, can delay timely responses. Data limitations can reduce the accuracy of predictive systems like WeCare tools, like VIIRS DNB are obstructed by weather interference and low spatial resolution in rural zones. Environmental concerns also persist, such as orbital congestion, risk of debris, and emissions from launches, and the heavy energy requirements of AI systems raise sustainability questions.

To overcome some of the listed limitations above—most importantly those relating to latency, bandwidth, system integration, and autonomous decision-making—this paper proposes a holistic, satellite-aided outage detection and response model. The system makes use of different satellite orbits (LEO, GEO, and HEO) to ensure complementary coverage and reliability and function in close cooperation with power grids. Using a model-based systems engineering approach based on SysML, the design involves well-structured subsystems' interactions and autonomous decision-making. The model combines satellite radiance monitoring, anomaly identification from artificial intelligence-based processing, real-time communication between the network, and self-adjusting outage evaluation. Operations are tracked by ground facilities, satellite measurements compared with measurements on the grid, and recovery guidance. Space solar power elements can provide emergency backup energy to the stricken areas when needed. Through integrating all elements as subsystems in one system instead of isolating external players, the system seeks to maximize responsiveness, minimize latency, and improve resilience in detecting and recovering from outages .By taking an integrated approach directly to many of the issues raised above, the system meets its goals of alleviating delays in data transfer, facilitating better coordination among satellites and grids, and improving the reliability of autonomous decision-making, thereby showing the capability of satellite-based systems to revolutionize global power outage management.

Advances in AI efficiency, hybrid cloud-edge computing, and optical satellite links will most likely reduce latency and improve system responsiveness. SysML modeling continues to guide complex system design, making integration more accessible. Innovations like SBSP and autonomous satellite control could extend operational independence and energy reliability. Collaboration across governments, utilities, and aerospace firms will be pivotal. With improved data-processing standards and sustainable practices, these technologies are made to enable global, adaptive, and highly resilient energy infrastructures.

4.CONCLUSION

This paper aims to analyze the capabilities of satellites to make power grids more efficient and prevent outages by using SysML, MBSE and AI models. Satellites ensure real time, resilient and flexible monitoring of power grids which enable cost savings and reliability even in the most remote areas. Despite clear cut benefits there are some limitations including environmental challenges, technological complexity, space debris, high initial costs and the potential of cyber-attack. We developed models which helped us identify the best possible satellites for this mission while also analyzing the various power sources which could be used [62] along with technologies and a conceptual satellite-based outage detection system that could be used for future missions for aiding minimized disruption of global power delivery.

This study has a few limitations. Due to the proprietary nature of satellite technology, the study was unable to access live industry data; therefore, it relied primarily on publicly available information, which may not have fully reflected the current state of technological capabilities. In addition, there was a large amount of focus on a few areas, such as Japan, Australia, and parts of Africa, so the results obtained may not fully reflect the applicability of this technology in other regions of the world, like Asia or North America. Also, in the programmed model, some assumptions were made regarding the weight of equipment and orbital paths for simplicity. Finally, the study made some assumptions about the cost and scalability of this project. We hope in the future, with access to better technology and data, power grids can be improved considerably using more autonomous edge-based AI technologies, leading to a more innovative, more reliable, and more sustainable planet [63]. Some future steps could be developing hybrid ground-satellite systems like AODS, improving AI training data, and reducing launch emissions.

Acknowledgment

This research was supported by Incognito Blueprints Pvt. Ltd.

Author contributions

R.S.A. conceptualization, data curation, formal analysis, visualization, methodology, writing—original draft, writing—review & editing, investigation, supervision, and project administration. A.S. data curation, formal analysis, investigation, methodology, writing—original draft. A.P. conceptualization, methodology, writing—original draft, investigation, supervision, and project administration. N.A. methodology, writing—original draft, writing—review & editing, formal analysis, data curation. D.J. conceptualization, methodology, writing—original draft, writing—review & editing, formal analysis, data curation

Competing financial interests

The authors declare no competing financial interests.

REFERENCES:

1. Sourmehi, C. EIA Projects Nearly 50% Increase in World Energy Use by 2050, Led by Growth in Renewables - Today in Energy - U.S. Energy Information Administration (EIA). www.eia.gov. https://www.eia.gov/todayinenergy/detail.php?id=49876.
2. Group, W. B. Energy Access Has Improved, Yet International Financial Support Still Needed to Boost Progress and Address Disparities. World Bank. https://www.worldbank.org/en/news/press-release/2025/06/25/energy-access-has-improved-yet-international-financial-support-still-needed-to-boost-progress-and-address-disparities.
3. TDT. Electricity reaches 92% of world population, 666M still lack access. Daily Tribune. https://tribune.net.ph/2025/06/29/electricity-reaches-92-of-world-population-666m-still-lack-access (accessed 2025-07-06).
4. Author. Satellite Communication for Smart Grids: How Satellites Support the Management and Operation of Smart Electrical Grids. Diverse Daily. https://diversedaily.com/satellite-communication-for-smart-grids-how-satellites-support-the-m anagement-and-operation-of-smart-electrical-grids/ (accessed 2025-07-01).
5. Crawford, I. A. The Long-Term Scientific Benefits of a Space Economy. Space Policy 2016, 37, 58–61. https://doi.org/10.1016/j.spacepol.2016.07.003.

6. 10 ways that satellites helped you today. Government of Canada. https://www.asc-csa.gc.ca/eng/satellites/everyday-lives/10-ways-that-satellites-helped.asp.
7. Disaster response. Viasat.com. https://www.viasat.com/about/sustainability-impact/disaster-recovery/ (accessed 2025-06-27).
8. (1)Lee, H.; Tushar; Cui, B.; Mallikeswaran, A.; Banerjee, P.; Srivastava, A. K. A Review of Synchrophasor Applications in Smart Electric Grid. WIREs Energy and Environment 2016, 6 (3). https://doi.org/10.1002/wene.223.
9. Cui, H.; Qiu, S.; Wang, Y.; Zhang, Y.; Liu, Z.; Karila, K.; Jia, J.; Chen, Y. Disaster-Caused Power Outage Detection at Night Using VIIRS DNB Images. Remote Sensing 2023, 15 (3), 640. https://doi.org/10.3390/rs15030640.
10. Guest Contributor. Grid operators: Wide grid monitoring using satellite time synchronisation. Smart Energy International. https://www.smart-energy.com/industry-sectors/energy-grid-management/wide-grid-monitorin g-using-satellite-time-synchronisation-grid-operators/ (accessed 2025-07-01).
11. Mann, M.; Melaas, E.; Malik, A. Using VIIRS Day/Night Band to Measure Electricity Supply Reliability: Preliminary Results from Maharashtra, India. Remote Sensing 2016, 8 (9), 711. https://doi.org/10.3390/rs8090711.
12. Ropp, T. It's a Liftoff: NASA Embraces MBSE With SysML. Tonex Training. https://www.tonex.com/its-a-liftoff-nasa-embraces-mbse-with-sysml/ (accessed 2025-06-26).
13. Parametric Diagrams | Enterprise Architect User Guide. Sparxsystems.com. https://sparxsystems.com/enterprise_architect_user_guide/16.0/modeling_languages/parametric_diagrams.html/ (accessed 2025-06-26).
14. SysML Example Tutorial: Griffin Space Vehicle Project. SysML.org. https://sysml.org/tutorials/sysml-example-tutorial/ (accessed 2025-06-26).
15. Madariaga, C.; Bashir, A.; Swickline, C. Applying MBSE in Space Based Systems Development. INCOSE International Symposium 2023, 33 (1), 584–600. https://doi.org/10.1002/iis2.13040.
16. Model Based Space Systems and Software Engineering ~ MBSE2021. Indico at ESA / ESTEC (Indico). https://indico.esa.int/event/386/timetable/?print=1&view=standard_numbered_inline_minutes (accessed 2025-06-26).
17. MBSE Consultants. Exploring the Role of MBSE in NASA's Artemis Lunar Exploration Program - MBSE Consultants. MBSE Consultants - Your ultimate blog for all things Model-Based Systems Engineering (MBSE). Dive into in-depth content crafted for engineers, systems designers, and industry professionals who want to enhance their projects with MBSEprinciples. https://mbseconsultants.com/exploring-the-role-of-mbse-in-nasas-artemis-lun ar-exploration-program/ (accessed 2025-06-26).
18. JAXA | Data Acquisition on the Lunar Surface with a Transformable Lunar Robot, Assisting Development of the Crewed Pressurized Rover. JAXA | Japan Aerospace Exploration Agency. https://global.jaxa.jp/press/2021/05/20210527-1_e.html (accessed 2025-06-26).
19. Careers at Northrop Grumman Corporation. Northropgrumman.com. https://jobs.northropgrumman.com/careers.
20. Kaslow, D.; Soremekun, G.; Kim, H.; Spangelo, S. Integrated Model-Based Systems Engineering (MBSE) Applied to the Simulation of a CubeSat Mission. 2014 IEEE Aerospace Conference 2014. https://doi.org/10.1109/aero.2014.6836317.
21. SysML Open Source Project: What is SysML? Who created it? SysML.org. https://sysml.org.
22. Gerrity, S.; Wood, D. Space-Based Solar Power. Energy.gov. https://www.energy.gov/space-based-solar-power .

23. ESA. Space-Based Solar Power overview. www.esa.int. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/SOLARIS/Space-Based_Solar_Power_overview.
24. Keeter, B. New Study Updates NASA on Space-Based Solar Power - NASA. NASA. https://www.nasa.gov/organizations/otps/space-based-solar-power-report/.
25. Sood, B. Achieving Improved Reliability with Failure Analysis Bhanu Sood Reliability and Risk Assessment Branch NASA Goddard Space Flight Center Bhanu.sood@Nasa.gov ; 2018 . https://ntrs.nasa.gov/api/citations/20180003067/downloads/20180003067.pdf.
26. Chinchali, S. P.; Eyal Cidon; Pergament, E.; Chu, T.; Sachin Katti. Neural Networks Meet Physical Networks. 2018. https://doi.org/10.1145/3286062.3286070.
27. United States Patent Bearman et Al. https://ntrs.nasa.gov/api/citations/20010008193/downloads/20010008193.pdf (accessed 2025-07-03)
28. Ogungbemi, E.; Ukomi, U.; Udoh, R. (PDF) Comparative coverage and horizon plane analysis for LEO, MEO, and GEO AND HEO Satellites. ResearchGate. https://www.researchgate.net/publication/366204569_Comparative_coverage_and_horizon_plane_analysis_for_LEO_MEO_and_GEO_AND_HEO_Satellites (accessed 2025-07-03)
29. “Power from the Sun: Its Future.” Science, vol. 162, no. 3856, 1968, pp. 857–861. JSTOR, https://www.jstor.org/stable/1725510.
30. “Space Solar Power: An Update.” Science, vol. 162, no. 3856, 1968, pp. 862–868. Science, https://www.science.org/doi/10.1126/science.162.3856.857.
31. A Survey on Satellite Communication System Security. PMC, 2023, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11086249/.
32. Congressional Budget Office. Large Constellations of Low-Altitude Satellites: A Primer. 2022, https://www.cbo.gov/publication/59175.
33. D'amico, S.; Carpenter, J. 50 Satellite Formation-Flying and Rendezvous. https://ntrs.nasa.gov/api/citations/20190001374/downloads/20190001374.pdf (accessed 2025-08-21).
34. *Satellites help power grid keep its balance - NASA Science*. science.nasa.gov. https://science.nasa.gov/earth/climate-change/satellites-help-power-grid-move-as-is-its-balance/.
35. Sah, R.; Srivastava, R.; Das, K. *Constellation Design of Remote Sensing Small Satellite for Infrastructure Monitoring in India*. arXiv.org. https://arxiv.org/abs/2107.09253?context=cs.RO (accessed 2025-08-12).
36. Yusef Kheyruri; Sharafati, A. Spatiotemporal Assessment of the NASA POWER Satellite Precipitation Product over Different Regions of Iran. *Pure and Applied Geophysics* 2022, *179* (9), 3427–3439. https://doi.org/10.1007/s00024-022-03133-6.
37. Miller, S.; Straka, W.; Mills, S.; Elvidge, C.; Lee, T.; Solbrig, J.; Walther, A.; Heidinger, A.; Weiss, S. Illuminating the Capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band. *Remote Sensing* 2013, *5* (12), 6717–6766. https://doi.org/10.3390/rs5126717.
38. Crisp, N. H.; Roberts, P. C. E.; Livadiotti, S.; Oiko, V. T. A.; Edmondson, S.; Haigh, S. J.; Huyton, C.; Sinpetru, L.; Smith, K. L.; Worrall, S. D.; Becedas, J.; Domínguez, R. M.; González, D.; Hanessian, V.; Mølgaard, A.; Nielsen, J.; Bisgaard, M.; Chan, Y.-A. .; Fasoulas, S.; Herdrich, G. H. The Benefits of Very Low Earth Orbit for Earth Observation Missions. *Progress in Aerospace Sciences* 2020, *117*, 100619. https://doi.org/10.1016/j.paerosci.2020.100619.
39. Flores, R.; Burhani, B. M.; Fantino, E. A Method for Accurate and Efficient Propagation of Satellite Orbits: A Case Study for a Molniya Orbit. *Alexandria Engineering Journal* 2021, *60* (2), 2661–2676. https://doi.org/10.1016/j.aej.2020.12.056.

40. Skoulidou, D. K.; Rosengren, A. J.; Kleomenis Tsiganis; Voyatzis, G. Dynamical Lifetime Survey of Geostationary Transfer Orbits. *Celestial Mechanics and Dynamical Astronomy* 2018, *130* (11). https://doi.org/10.1007/s10569-018-9865-1.
41. Osedlo, V. I.; Kalegaev, V. V.; Rubinshtein, I. A.; Tulupov, V. I.; Shemukhin, A. A.; Pavlov, N. N.; Abanin, O. I.; Zolotarev, I. A.; Barinova, V. O.; Bogomolov, V. V.; Vlasova, N. A.; Myagkova, I. N.; Ginzburg, E. A. Monitoring the Radiation State of the Near-Earth Space on the Arktika-M No. 1 Satellite. *Cosmic Research* 2022, *60* (6), 406–419. https://doi.org/10.1134/s0010952522060089.
42. Wade, M. *Molniya-1*. In *Encyclopedia Astronautica* (archived at web archive), originally online at astronautix.com; archived July 16, 2008.https://web.archive.org/web/20080516082459/
43. Jedlovec, G.; Molthan, A. *Use of VIIRS DNB Data to Monitor Power Outages and Restoration for Significant Weather Events*. Nasa.gov. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130013872.pdf (accessed 2025-08-12).
44. Ajay Palanisamy Research-Project-2025. Satellite_grid.java. GitHub, 27 June 2025, https://github.com/Research-Project-2025/Remote-Satellite/blob/main/Satellite_grid.java.
45. Ajay Palanisamy Research-Project-2025. PowerGridDetectionSimulation.java. GitHub, 27 June 2025,https://github.com/Research-Project-2025/Remote-Satellite/blob/main/PowerGridDetectionSimulation.java.
46. Cole, T.; Wanik, D.; Molthan, A.; Román, M.; Griffin, R. Synergistic Use of Nighttime Satellite Data, Electric Utility Infrastructure, and Ambient Population to Improve Power Outage Detections in Urban Areas. *Remote Sensing* 2017, *9* (3), 286. https://www.mdpi.com/2072-4292/9/3/286?utm
47. What Causes Electrical Outages? | American Public Power Association. Publicpower.org. https://www.publicpower.org/periodical/article/what-causes-electrical-outages (accessed 2025-06-07).
48. Power-Outage-Detection, W. WeCARE - Power-Outage-Detection. Ucfwecare.org. https://www.ucfwecare.org/power-outage-detection (accessed 2025-06-07).
49. Case study: Ergon Energy. Inmarsat Corporate Website. https://www.inmarsat.com/en/insights/enterprise/2015/case-study-ergon-energy.html (accessed 2025-06-07).
50. Jin, W.; Sun, B.; Li, Z.; Zhang, S.; Chen, Z. Detecting Anomalies of Satellite Power Subsystem via Stage-Training Denoising Autoencoders. Sensors 2019, 19 (14), 3216. https://doi.org/10.3390/s19143216.
51. Bernard, D.; Dorais, G.; Gamble, E.; Kanefsky, B.; Kurien, J.; Millar, W.; Muscettola, N.; Nayak, P.; Rouquette, N.; Rajan, K.; Smith, B.; Taylor, W.; Tung, Y.-W.; Bernard@lpl, D.; Gov). https://ntrs.nasa.gov/api/citations/20000116204/downloads/20000116204.pdf.
52. None Nneka Adaobi Ochuba; Favour, N.; Stefano, E.; None Olatunji Akinrinola; None Olukunle Oladipupo Amoo. PREDICTIVE ANALYTICS in the MAINTENANCE and RELIABILITY of SATELLITE TELECOMMUNICATIONS INFRASTRUCTURE: A CONCEPTUAL REVIEW of STRATEGIES and TECHNOLOGICAL ADVANCEMENTS. *Engineering science & tecnology journal* 2024, *5* (3), 704–715. https://doi.org/10.51594/estj.v5i3.866.
53. Fourati, F.; Alouini, M.-S. Artificial Intelligence for Satellite Communication: A Review. *Intelligent and Converged Networks* 2021, *2* (3), 213–243. https://doi.org/10.23919/ICN.2021.0015.
54. Tuia, D.; Schindler, K.; Demir, B.; Zhu, X. X.; Mrinalini Kochupillai; Sašo Džeroski; Jan; Hoos, H. H.; Frate, F. D.; Mihai Datcu; Markl, V.; Bertrand Le Saux; Schneider, R.; Gustau Camps-Valls. Artificial Intelligence to Advance Earth Observation: A Review of Models, Recent Trends, and Pathways Forward. *IEEE Geoscience and Remote Sensing Magazine* 2024, 2–25. https://doi.org/10.1109/mgrs.2024.3425961.

55. G. Fontanesi; F. Ortíz; Lagunas, E.; V. Monzon Baeza; Vázquez, M. Á.; Vásquez-Peralvo, J. A.; Minardi, M.; Vu, H. N.; Honnaiah, P. J.; Lacoste, C.; Y. Drif; Abdu, T. S.; G. Eappen; Rehman, J.; Luis Manuel Garcés-Socorrás; Martins, W. A.; P. Henarejos; H. Al-Hraishawi; Carlos, J.; Vu, T. X. Artificial Intelligence for Satellite Communication and Non-Terrestrial Networks: A Survey. arXiv (Cornell University) 2023. https://doi.org/10.48550/arxiv.2304.13008.
56. Algorithm Theoretical Basis Document for NOAA NDE VIIRS I-Band (375m) Active Fire Compiled by the SPSRB Common Standards Working Group; 2020. https://www.star.nesdis.noaa.gov/jpss/documents/ATBD/ATBD_Iband_ActiveFires_v1.0.pdf (accessed 2025-08-21).
57. Frank, J.; Iverson, D.; Knight, C.; Narasimhan, S.; Swanson, K.; Scott, M.; Windrem, M.; Pohlkamp, K.; Mauldin, J.; Mcguire, K.; Moses, H. *Demonstrating Autonomous Mission Operations Onboard the International Space Station*. https://ntrs.nasa.gov/api/citations/20190000220/downloads/20190000220.pdf (accessed 2025-08-12).
58. Nrel.gov. https://docs.nrel.gov/docs/fy23osti/86593.pdf (accessed 2025-08-12).
59. Boukabara, S.-A.; Krasnopolsky, V.; Stewart, J. Q.; Maddy, E. S.; Shahroudi, N.; Hoffman, R. N. Leveraging Modern Artificial Intelligence for Remote Sensing and NWP: Benefits and Challenges. https://journals.ametsoc.org/view/journals/bams/100/12/bams-d-18-0324.1.xml (accessed 2025-06-07).
60. Department of Defense. FY 2013 Annual Report: Space-Based Infrared System (SBIRS). Office of the Director, Operational Test & Evaluation. 2013. https://www.dote.osd.mil/Portals/97/pub/reports/FY2013/af/2013sbirs.pdf?ver=2019-08-22-111347-550 (accessed August 14, 2025).
61. Department of Defense. FY 2012 Annual Report: Space-Based Infrared System (SBIRS). Office of the Director, Operational Test & Evaluation. 2012. https://www.dote.osd.mil/Portals/97/pub/reports/FY2012/af/2012sbirs.pdf (accessed August 14, 2025).
62. Depuru, S. S. S. R.; Wang, L.; Devabhaktuni, V. Smart Meters for Power Grid: Challenges, Issues, Advantages and Status. Renewable and Sustainable Energy Reviews 2011, 15 (6), 2736–2742. https://doi.org/10.1016/j.rser.2011.02.039.
63. Chichilnisky, G. What Is Sustainable Development? Man-Made Climate Change 1999, 42–82. https://doi.org/10.1007/978-3-642-47035-6_4.