Resilient Networking Keeps Critical Sensors Connected

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Abstract

On Monday, December 19th, 2022, a powerful Kona Low storm hit Hawaii, causing widespread power outages and significant damage to infrastructure across the islands. The Maui Ground-Based Electro-Optical Deep Space Surveillance system (GEODSS), a critical Space Surveillance Network (SSN) site atop Haleakalā National Park, experienced a complete loss of legacy communications for 21 days due to a severed fiber cable. This is a key Space Surveillance site responsible for performing ground-based optical tracking of space objects and this outage critically impacted the deep space surveillance mission operations and maintenance performed by the 15th Space Surveillance Squadron (SPSS) for space tracking catalogue updates.

One month prior to the storm, Anduril Industries performed a capstone demonstration under Space Systems Command (SSC) that established a dynamic and operational mesh network layer between key SSN nodes: an optical sensor site (Maui, HI), a radar sensor site (Eglin AFB, FL), and a command and control (C2) site (Dahlgren, VA) while leveraging the Unified Data Library (UDL). This has been an ongoing effort since it was initially presented at Space Pitch Day in 2019. Anduril deployed Flux, a transparent networking layer, to enable secure and resilient transport of SSN legacy data over commercial Starlink satellite communications and Defense Information Systems Agency (DISA) Multiprotocol Label Switching (MPLS) terrestrial circuits. Flux is Anduril's mesh networking protocol designed to work over any network internet protocol (IP) data links and topology. Flux is designed primarily around securely solving edge-node connectivity issues under highly dynamic link environments. Anduril currently uses Flux across all its globally deployed capabilities. A Flux network consists of multiple nodes, each with its own set of neighboring peers within the network. Each node maintains a view of the total network connectivity graph allowing for automated computation of next hops to route messages to their intended destinations. This dynamic routing capability is critical to creating a robust operational mesh network as deployed during the Anduril SSN demonstration.

The evening after the storm, the United States Space Force (USSF) Program Manager informed the Anduril team of the damage and network outage existing at the Maui GEODSS site and asked if it was possible to turn Flux back on for operational use from Maui GEODSS to Dahlgren. The Space Operations Delta 2 Commander provided full approval to use Anduril equipment within 12 hours to support restoring mission operations. Anduril's Flux network was re-enabled between Maui GEODSS and Dahlgren within 24 hours and remained the primary operational communications method until legacy communications were re-established 21 days later. This capability was made possible by Anduril's rapid hardware installation and integration effort that concluded in late October 2022, where the team installed and integrated the hardware and software in less than two weeks that would eventually be utilized during the emergency operational period, including the server hardware and commercial Starlink terminal. Operations were restored in a few hours due to Anduril's swift responsive capabilities and pre-installed system.

1. Introduction

The SSN is a series of globally distributed ground-based sensors the USSF uses to track resident space objects (RSOs) as the primary tool for Space Domain Awareness (SpDA). The mission of the Space Surveillance Network is to detect, track, and identify all artificial objects orbiting the Earth and provide data on them to a range of users. The data maintains unclassified and classified catalogs of location, size, shape, and motion for all known space objects. [1] The sites can be divided into three categories: Optical, Radar, and Command & Control (C2). The sensor network maintains a catalog of known and sensitive space objects and is highly intertwined with critical national defense assets.

Development of the SSN's ground-based sensors began in the late 1950s as a response to the Sputnik-era Soviet Union's increased activity during the Space Race. Some of the earliest sites tasked with tracking Soviet satellites and missile launches have since been decommissioned. Eglin Site C-6, a radar site, has been operational since 1969 and is one of the oldest dedicated SSN sensors. The site houses the AN/FPS-85 phased array radar to conduct near-earth and deep space tracking and characterization. [2] The phased array radar was the first sensor to provide simultaneous detection and tracking of objects beyond 6,000 miles and below orbital inclinations of 30 degrees. The site is currently responsible for tracking a large percentage of resident space objects within Low-Earth Orbit (LEO).

Additional SSN sites were established over the course of the next three decades. In 1976, the Perimeter Acquisition Radar Attack Characterization System (PARCS) began operations at Cavalier Air Force Station in North Dakota. PARCS was primarily leveraged for detecting sea-launched and intercontinental ballistic missiles but also provided data regarding launches and orbiting objects to the SSN. The system is still operational today as part of both the Missile Warning and SpDA missions [3]. A year later, in 1977, another phased array called COBRA DANE was built in Shemya, Alaska, to collect data on foreign missile launch events. This radar, which is similar to the AN/FPS-85 at Eglin, can track many objects simultaneously and still contributes to the SSN today. [4]

In the early 1980s, a total of four optical sites were established. The Ground-based electro-optical deep space surveillance (GEODSS) sites were established in Diego Garcia, Maui, New Mexico, and South Korea to track objects between 6,000 and 28,000 miles. Each site has three individual telescopes that can operate both individually and in coordination with each other. The systems combine highly sensitive digital cameras and a complex mission system. These components determine orbital location by analyzing streaks presented by moving satellites within the images of the night sky. The sites can track objects as small as a basketball more than 20,000 miles away and are critical to the SSN. [5] All of the sites except the South Korea location are still in use today. [1]

Over the next 20 years, many additional sensor sites were established to increase the coverage and capabilities of the SSN as space activity continued to increase steadily. There are currently three C2 centers that coordinate sensor taskings and maintain the space data catalog, with the oldest being in Colorado Springs, Colorado. The Colorado Springs location is currently supported by C2 centers in Vandenberg, CA, and Dahlgren, VA. These sites are responsible for issuing taskings to the remote sensor sites while aggregating and characterizing data from their observations to maintain an accurate space object catalog.

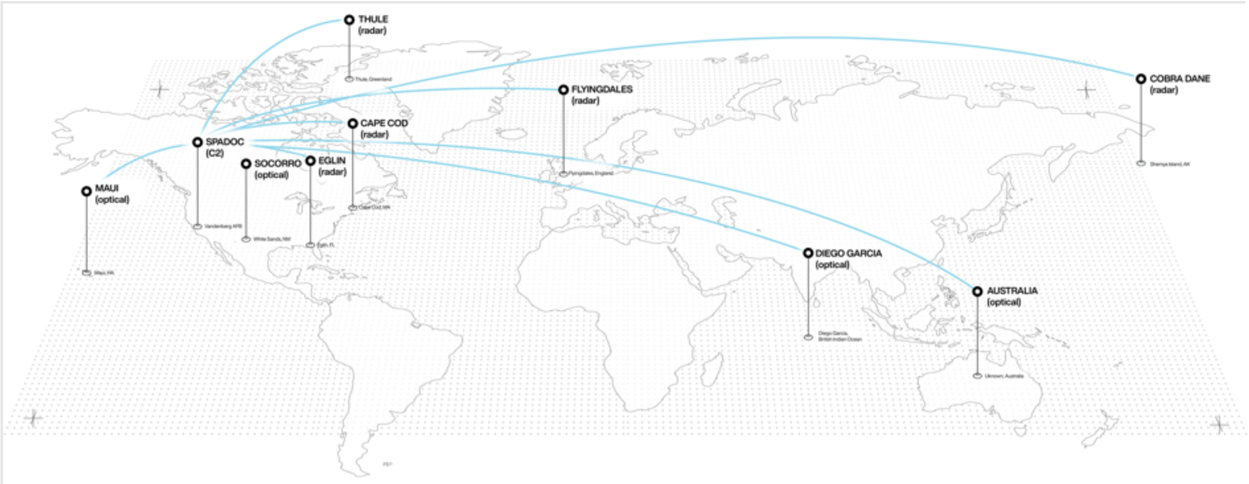

Figure 1: A visual representation of the existing Space Surveillance Network communications architecture.

The SSN relies on the Space Command Digital Integrated Network (SDIN) to facilitate data transfer between the C2 and sensor sites. This network uses a "hub-and-spoke" architecture that leverages legacy equipment to transfer data. [6] While many sites' physical infrastructure has been upgraded over the last three decades, the communications backbone that connects the sites remains largely unchanged. The basic operations consist of C2 sites requesting observations of specific resident space objects from specific sensor sites. Upon request, the sensors execute and return summarized data directly to the requesting C2 site. The C2 site will then characterize this data and distribute the data to other sensor sites.

The last 20 years of space activity have resulted in an ever-increasing count of resident space objects such as space debris, expended rocket boosters, and active or inactive satellites. The barrier to entry in the space domain has never been lower thanks to commercial companies like SpaceX, RocketLabs, and others. These commercial launch providers allow for rapidly increased access to space for meteorology, climate research, commercial telecommunication, navigation, and space exploration. Roughly 24% of all cataloged objects are satellites, and an additional 11% of objects are mission-related (i.e., lens covers or spent upper stages). [7]

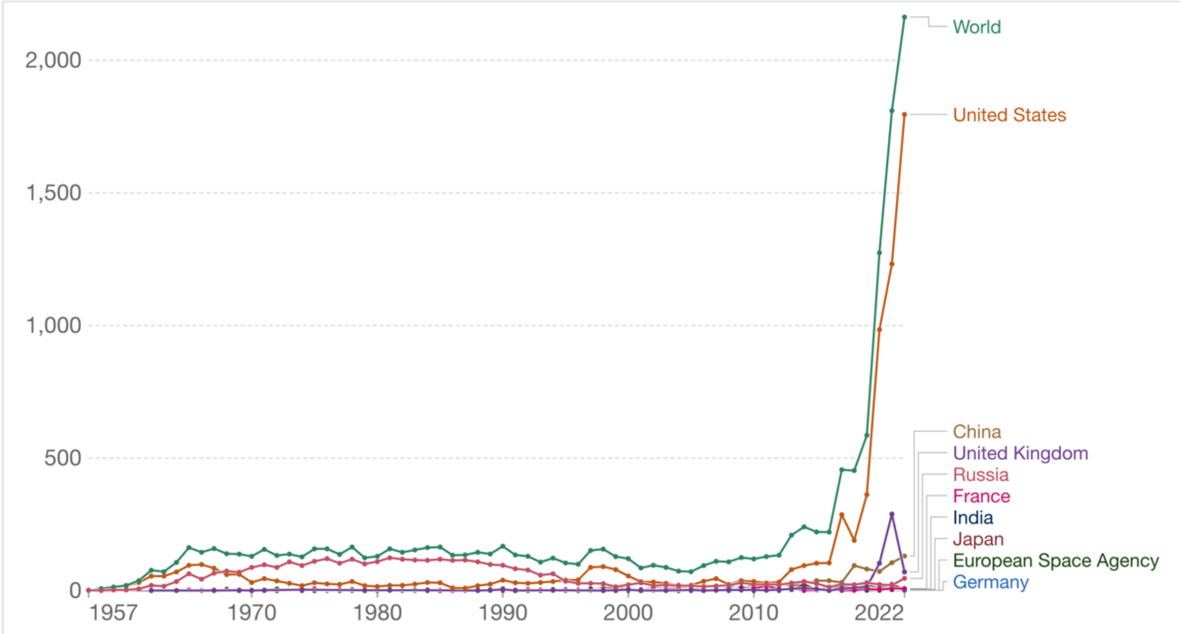

Figure 2: Annual number of objects launched into space (Source: United Nations Office for Outer Space Affairs)

The rapid increase of space objects over the last decade has changed the overall debris-to-spacecraft ratio. The ratio decreased from 75% debris vs. 25% active spacecraft in 2016 to 62% debris vs. 38% active spacecraft in late 2022. [8] The changing mix of debris to spacecraft has resulted in an increased need for space traffic management to prevent collisions that would result in potentially catastrophic consequences across the globe. Collisions are still considered a very low-probability event, but the recent increase of spacecraft continues to present new challenges for the SpDA mission.

As a critical component to maintaining SpDA, the SSN must evolve to distribute data related to the ever-increasing number of resident space objects. One method for modernizing the SSN is to introduce a resilient mesh networking capability that enhances the existing communications infrastructure of extremely capable sensors and allows the network to scale with the rest of the space industry. The capability should leverage commercial and government communications methods to enable resilient, high-throughput, and machine-machine dataflows across the SSN. A modern network architecture will allow for minute-by-minute re-tasking of sensor sites and rapid distribution of real-time data for third-party analysis.

2. Resilient Networking

Maintaining operational communications within dynamic network conditions has been one of the highest priorities and most demanding challenges for any network operator. A common methodology in United States Department of

Defense (DoD) warfighting units is expressed in an order of communication precedence called primary, alternate, contingency, and emergency (PACE). A PACE plan is primarily based on establishing multiple viable communications methods from a data publisher to a data subscriber to maintain full mission capabilities. [9] There are numerous advancements in commercial and government networking capabilities that can be deployed to establish resilient and reliable operational communications.

Anduril leverages its core operating system, called Lattice, to perform a variety of missions across various DoD organizations. Lattice acts as a command-and-control platform that establishes unique operational dataflows in dynamic networks, orchestrates autonomous aerial, terrestrial, maritime and submersible vehicles, and enables rapid integration with third-party systems. The software suite streamlines decision making and routes data to assets in seconds with its mesh networking capability, called Flux.

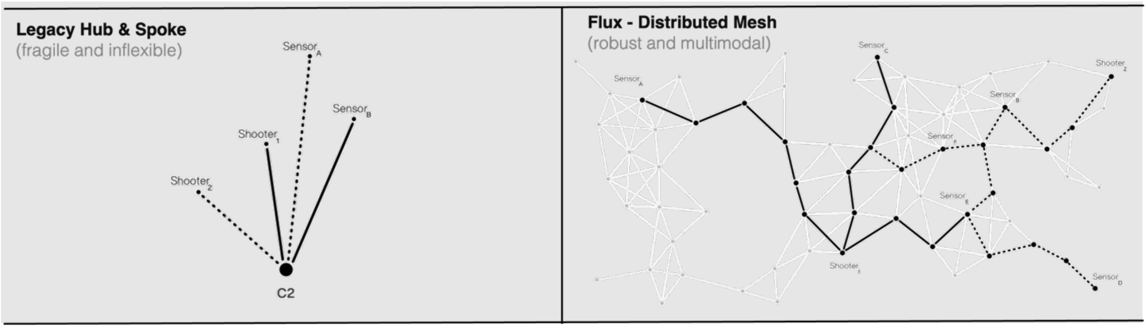

Figure 3: Anduril's Lattice mesh networking layer enables modern machine-machine dataflows.

Anduril's Flux enables machine-to-machine dataflows within contested networks by leveraging ad-hoc routing technology. Mobile ad hoc networks provide resilient communications by implementing a multi-hop topology within dynamic environments that frequently change. These networks leverage efficient routing protocols to effectively maintain and re-establish communication paths between various assets without requiring any input from an end-user. [10]. These networks eliminate the need for legacy "hub-and-spoke" architectures that induce single points of failure and allow for complete disconnection of distributed assets.

Another useful capability within operational communications networks is the implementation of a publish-subscribe (pub/sub) architecture. Pub/sub networks are commonly implemented in distributed, real-time systems due to their versatility and capability to scale. Pub/sub-networks consist of "publishers" that produce data to be consumed by "subscribers" who intend to receive and process that data. The architecture allows for efficient management of network overhead by only distributing data to users that require it and is implemented across many large systems like Google Cloud, Microsoft Azure, and Amazon Web Services. [11]

In the Space Surveillance Network example, a C2 site would be a "publisher" of sensor taskings and a "subscriber" to metric observations published by one of the distributed sensor sites. If an end-user desired to enable sensor-to-sensor workflows, they could implement more specific data topics such as "radar observation" and "electro-optical observation." This added granularity of data specification would enable sensor systems to subscribe to observations directly produced by companion sites for sensor-to-sensor tasking or tipping and cueing.

3. Space Surveillance Network Modernization

In November 2022, Anduril conducted a capstone demonstration across multiple SSN sites, including the GEODSS site in Maui, HI. The demonstration, presented to SSC, leveraged Lattice to bi-directionally transport legacy data between sites via commercial SATCOM and DoD networks while posting specific messages to the UDL. The Anduril capability leveraged commercial-off-the-shelf (COTS) hardware at each site to implement a modern mesh networking capability for legacy communications in just three months to provide increased throughput, resiliency, and insights into the real-time status of assets throughout the demonstration network. The extensive integration effort can be distilled into two separate lines of effort: integrating with each site's local mission systems and establishing multiple, resilient communications methods.

The integration was enabled by Lattice's unique ability to integrate with various mission systems across multiple SSN sites. As detailed previously, these sites were established between the 1960s and early 2000s. While all sites leverage the same messaging formats, the prolonged timespan of implementation ensured that the SSN sites were rarely designed or maintained to the same operational hardware baseline. As a response, Anduril engineers deployed COTS hardware to establish various local data connections for bidirectional dataflow between legacy systems and Lattice. These connections ranged from industry standard (i.e., a Network File System (NFS) or TCP/IP connection) to bespoke or proprietary signaling mechanisms. To decrease the impact to ongoing operations, the Anduril deployment effort leveraged a physical A/B switch to allow for manual switching between a legacy configuration and the Anduril demonstration. Once the local integrations were successfully completed, Anduril was capable of transparently distributing legacy datatypes such as taskings, observations, and catalog updates between the local mission system and Lattice hardware.

After completing the local integrations, Anduril engineers leveraged DoD terrestrial networks and commercial SATCOM to establish multiple communications pathways between the Space Surveillance Network sites. Anduril personnel physically installed commercial SATCOM terminals and connected them to DoD terrestrial networks at each of the demonstration sites. The new communications methods were routed to the COTS hardware running Lattice. Once fully integrated, Lattice provided a transparent mesh networking capability with modern throughput that did not change the end-user's workflow. The integration could distribute legacy data such as taskings, observations, and catalog updates directly between all the demonstration sites via either communication method.

During the demonstration, the Anduril team intentionally introduced a “blended communications” scenario by disabling individual communications methods at specific sites to prohibit a direct connection between a publisher and its subscriber. As operators continued to distribute mission data via their standard workflows, Lattice autonomously routed the data through a common peer of the two sites to ensure delivery. The real-time status of each network connection, including latency, bandwidth, and dataflow path, was visually displayed for end-users to monitor. This visualization of real-time status enables current operators to view specific local and distributed metrics to diagnose and troubleshoot network connectivity issues or optimize operational workflows.

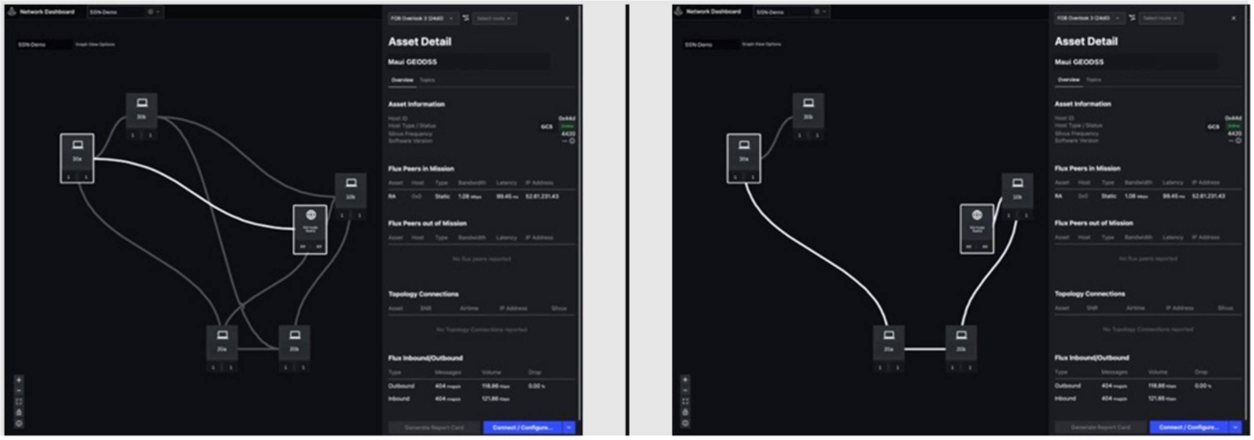

Figure 4: Anduril’s Lattice displays real-time status of a fully connected network (left) and an end-to-end dataflow during a “blended communications” scenario (right).

At a specific site, Anduril provided the connection to the UDL which hosts SpDA data from commercial, academic, and government organizations and presents it to mission partners via a digital storefront. The open architecture repository is critical to enabling mission workflows that aggregate various sources of orbital data. [12] While only a specific site was directly connected to the UDL, Lattice enabled brand new postings of multiple datatypes from all SSN sites used during the demonstration.

4. Maui Storm Response

In December 2022, the Hawaiian Islands were hit by a severe Kona Low storm that resulted in widespread power outages and damage to infrastructure across the islands. The storm produced winds above 100 mph atop Haleakalā National Park. As a result, the GEODSS site experienced severe degradation of legacy communications. Any sustained outage of the Maui GEODSS site dramatically impacts the deep space surveillance mission and maintenance of the space catalogue; a similar storm occurred in 2021 and took the site offline for an extended period.

The USSF program manager informed the Anduril team of the damage to Maui GEODSS and asked if it were possible to implement the capabilities Anduril had demonstrated in November to bolster resilient communications. While local site personnel verified that the physical SATCOM installation withstood the storm, Anduril was quickly able to determine that the commercial SATCOM installation still had connectivity. Within 24 hours, the team received emergency authorization to proceed and deployed to another site within the Anduril demonstration network to enable the integration at Maui GEODSS remotely. The team verified critical bidirectional dataflow and restored operational communications until legacy communications were re-established 21 days later.

5. Future Expansion / Conclusion

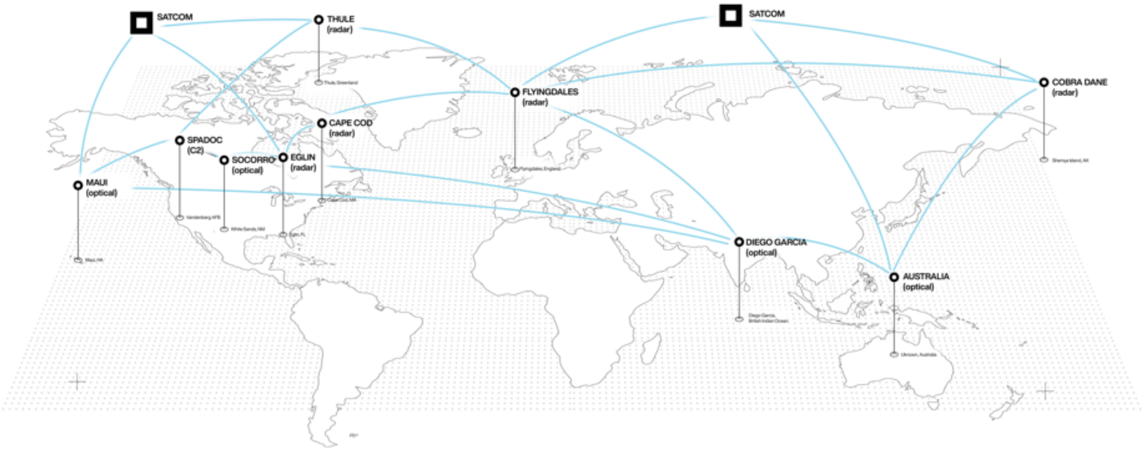

Figure 5: A visual representation of a resilient Space Surveillance Network

To scale with the increased space activity over the last decade, the SSN must implement a resilient mesh networking capability that enables modern dataflows for capable legacy sensor systems. The primary benefit of a mesh network is that as the number of nodes increases, the resiliency of the overall network also increases. A full-scale, modern mesh network would enable two important capabilities for the SSN: the ability to distribute sensor data and status to mission partners in real-time, and the ability to process this data for advanced analytics such as predictive analysis, sensor-to-sensor communications, and other machine learning workflows.

The ability to distribute sensor data and status to mission partners in real-time must also include the ability for local sensors to visualize status across the SSN. Network operators must be able to view metrics such as point-to-point latency, bandwidth, message counts and link status to enable efficient local troubleshooting and optimal operational workflows. The visualization tool should display the full state of the distributed network to include active connected or disconnected status of the SSN sites. The network should allow for real-time modification of data distribution topics to adapt to SpDA mission threats.

A modern mesh networking capability should be resilient against varying network *and* mission parameters. To constantly adapt to evolving threats within the space domain, a modern networking capability must enable machine to machine communication amongst SSN sites. Example workflows include tipping & cueing across different types of sensors, automatically leveraging the UDL, and enabling standalone operations in times of severe communications disruptions.

Once complete, this mesh network provides the opportunity to enable advanced SpDA concepts necessary to address emerging threats from congestion, debris, and deliberate acts of aggression. The underlying technology being deployed by Anduril in partnership with the USSF will provide resilient, high-bandwidth communication required for an ecosystem of sensemaking capabilities necessary for the successful execution of future national security and commercial missions. The capability will provide a modern endpoint for future integrations by various third parties to continuously adapt to the evolving threat within the space domain.

Anduril is currently under contract for fielding a latticed mesh network to additional SSN sites.

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