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U.S. Space-Based Nuclear Command and Control: A Guide

BY Marie Villarreal Dean

The United States has long depended on a vast array of complex sensing and communications infrastructure to receive warning in the event of a nuclear attack and to execute nuclear orders. This command and control network is highly reliant on space-based assets to operate and provide dependable information to decision makers in the event of a nuclear crisis. This paper aims to provide a comprehensive outline of the contribution of satellites in the U.S. nuclear command and control network, analyze space assets in the nuclear modernization process, explore vulnerabilities and the risks they face as the space environment becomes more contested, and propose policy solutions to strengthen and protect this vital infrastructure. This information should serve as a resource for scholars, practitioners, and decisionmakers to better understand this complex system and the unique challenges it faces in today's space environment.

The U.S. Nuclear Command and Control Network

The U.S. nuclear command, control, and communications (NC3) network is a complex system

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composed of many critical parts designed to support the United States' nuclear deterrent. The Department of Defense defines NC3 as the facilities, equipment, communications, procedures, and personnel that enable the President to exercise nuclear authority.[1] The graphic below shows a simplified rendering of the components of this network, including the nuclear platforms themselves, sensors, communications infrastructure, and the decision-makers.

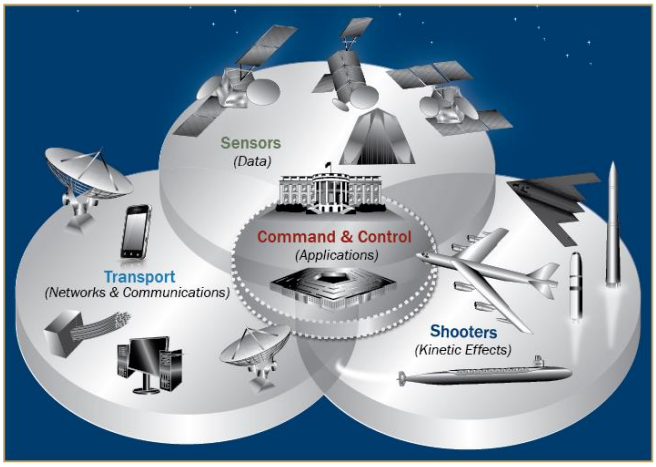

Figure 1: Space-Based Nuclear Command & Control.

Source: "Nuclear Matters Handbook 2020 [Revised]," Chapter 2, https://www.acq.osd.mil/ncbdp/nm/NMHB2020rev/chapters/chapter2.html.

The Nuclear Posture Review (NPR) is the guiding document for U.S. nuclear policy for each administration. The latest NPR was published in 2022 and outlines the five critical functions of the nuclear command and control system: detection, warning and attack characterization; adaptive nuclear planning; decision-making conferencing; receiving and executing Presidential orders; and enabling the management and direction of forces.[2] These functions are carried out through a system of interconnected elements that include warning satellites and radars, communication satellites, aircraft and ground stations, fixed and mobile command posts, and control centers for nuclear systems. The current system is often referred to as having two layers: a "thick-line," which consists of both standard operational and crisis architectures, and a "thin-line," which provides survivable, secure, and enduring connectivity to the president, secretary of defense, and combatant commanders. NC3 serves as the link between the nuclear forces and presidential authority.[3]

The nuclear command and control network requires a high degree of survivability to continue performing even in a worst-case nuclear war scenario. It has been designed to be survivable to various extreme conditions and has incorporated hardening, mobility, redundancy, and concealment measures.[4]

Space-Based Assets in NC3

The space-based component of NC3 is integral to the defense of the United States because it is "the preferred means to transmit a presidential order to use nuclear weapons and would provide the first warning of an incoming nuclear attack."[5] Satellites provide secure communications; intelligence, surveillance, and reconnaissance (ISR); missile launch early warning; and positioning, navigation, and timing (PNT) functions as well as the synchronization of NC3 systems and networks. These systems consist of a satellite or constellation of many satellites, ground stations,

[1]Deputy Assistant Secretary of Defense for Nuclear Matters. "Nuclear Matters Handbook 2020 [Revised]," 2020. https://www.acq.osd.mil/ncbdp/nm//NMHB2020rev/chapters/chapter2.html.

[2] U.S. Department of Defense. "2022 Nuclear Posture Review," October 2022. https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF.

[3] Claeys, Suzanne. "NC3: Challenges Facing the Future System," 2020. https://www.csis.org/analysis/nc3-challenges-facing-future-system.

[4] Critchlow, Robert. "Nuclear Command and Control: Current Programs and Issues." CRS Report, 3 May 2006, https://apps.dtic.mil/sti/pdfs/ADA453640.pdf.

[5] Acton, James, and Thomas McDonald. "Nuclear Command-and-Control Satellites Should Be Off Limits." Defense One, 2021. https://www.defenseone.com/ideas/2021/12/nuclear-command-and-control-satellites-should-be-limits/187472/.

sensors, and uplink/downlinks for transmitting and receiving data, and terminals for the end-users.[6] Additionally, earth observation, electronic intelligence, and meteorological forecasting are also space-based functions that contribute to NC3. According to Lt. Gen. Jack Weinstein, Air Force deputy chief of staff for strategic deterrence and nuclear integration, "we need an unblinking eye to find out what is going on. That unblinking eye is provided by space…[the NC3 network] is entirely dependent on space."[7]

Communications

The primary NC3 satellite communications (SATCOM) infrastructure is the geosynchronous Advanced Extremely High Frequency (AEHF) constellation of six satellites, which is the follow-on to the 1990s MILSTAR program. AEHF is supported by additional protected SATCOM units in polar orbit, which currently consists of two Enhanced Polar System (EPS) hosted payloads and supporting systems providing coverage above 65 degrees latitude.[8] AEHF is a multi-service communications constellation that is designed to be protected against certain forms of counterspace attack. AEHF provides jam-resistant communications for the NC3 network, as well as other land, sea, and air assets.

Notably, AEHF serves latitudes located within 65 degrees north and 65 degrees south latitude, which covers everything from the base of the Arctic Circle to northern Antarctica. AEHF communications are also shared with select allies and partners. AEHF provides assured communications for the President, senior national security leaders, and military tactical and strategic forces throughout a nuclear war.[9] AEHF is one of a few publicly acknowledged avenues through which executive authorization orders can be transmitted. The AEHF constellation provides support across land, air and naval warfare; special operations; strategic nuclear operations; strategic defense; theater missile defense; and space operations and intelligence.[10] The six aging MILSTAR satellites, the first of which launched in 1994,[11] have since been supplemented by the newer AEHF constellation and are now retired and well out of the way of the geostationary plane.[12] The final AEHF payload was launched in March 2020 as the first Space Force mission, with the total program cost for six satellites at $15 billion.[13]

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[6] Lt Gen Deptula, David, William LaPlante, and Robert Haddick. "Modernizing U.S. Nuclear Command, Control, and Communications." Mitchell Institute for Aerospace Studies, February 14, 2019. https://mitchellaerospacepower.org/wp-content/uploads/2021/02/a2dd91_ed45cfd71de2457eba3bcce4d0657196.pdf#page=26.

[7] Erwin, Sandra. "Another Way to Define Nuclear Triad: Three Legs, plus 'Space Capability.'" SpaceNews, May 1, 2018. https://spacenews.com/another-way-to-define-nuclear-triad-three-legs-plus-space-capability/.

[8] Northrop Grumman. "Enhanced Polar System." Northrop Grumman. Accessed October 12, 2022. https://www.northropgrumman.com/space/enhanced-polar-system.

[9] Capt. Elizabeth Forbes, Space Force. "End of an Era: The AEHF Program Comes to a Close." Los Angeles Air Force Base, 2021. https://www.losangeles.spaceforce.mil/News/Article-Display/Article/2485377/end-of-an-era-the-aehf-program-comes-to-a-close/.

[10] Capt. Elizabeth Forbes, Space Force. "End of an Era: The AEHF Program Comes to a Close." Los Angeles Air Force Base, 2021. https://www.losangeles.spaceforce.mil/News/Article-Display/Article/2485377/end-of-an-era-the-aehf-program-comes-to-a-close/.

[11] Air Force. "MILSTAR Satellite Communications System." 2015. https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104563/milstar-satellite-communications-system/.

[12] Benjamin Bahney (Senior Fellow, Lawrence Livermore National Laboratory's Center for Global Security Research), in conversation with the author, July 2022, and analysis from the Satellite Dashboard https://satellitedashboard.org/.

[13] Erwin, Sandra. "Is the Cost of Military Space Programs Going Up or Down? Depends on How You Count." SpaceNews, March 19, 2018. https://spacenews.com/is-the-cost-of-military-space-programs-going-up-or-down-depends-on-how-you-count/.

Missile Warning

Space-Based Infrared System (SBIRS) is the primary early warning satellite constellation. Made up of six satellites with nuclear-hardened components, SBIRS consists of two hosted sensor payloads in a Highly Elliptical Orbit (HEO) and four dedicated payloads in Geosynchronous Orbit (GEO).[14] SBIRS uses infrared sensors that detect thermal signatures to surveil the Earth, providing vast amounts of data used for missile defense, battlespace awareness, missile warning, and tactical intelligence,, sending raw unprocessed data through five separate downlinks to the ground. The follow-on to the Defense Support Program (DSP) constellation, SBIRS is designed to meet system survivability and endurance requirements, and hardened against a nuclear electro-magnetic blast in space.[1516] As of August 4, 2022, all six satellites have been successfully launched into GEO orbit.[17] The original Air Force budget calculations expected SBIRS to cost $5 billion for six satellites– the current numbers place SBIRS at $19.2 billion dollars for six satellites.[18]

Figure 2: Depiction of SBIRS Missile Warning Satellite

Source: Space Force, Lockheed Martin https://www.spaceforce.mil/News/Article/2926454/newest-missile-warning-satellite-accepted-for-operations/

NUDET

While early warning and secure communications satellites are well-known for their role in national security, other satellites fulfilling more mundane tasks receive less attention but are still important to national security operations. These satellite systems and their respective ground stations are integral parts of the larger NC3 system.

Hosted sensors on the Global Positioning System (GPS), Defense Support Program (DSP), and other classified GEO constellations also contribute to NC3.[19] These satellites host the space segment of the United States Nuclear Detonation (NUDET) Detection System (USNDS),[20] which according to the Air Force, "provides a near real-time worldwide, highly survivable capability to detect, locate, and report any nuclear detonations in the earth's atmosphere or in near space."[21] These sensors have been operating since the first GPS launch in 1978, and provide nuclear force management, technical intelligence, and treaty monitoring to the National Command Authority, U.S. Strategic Command, U.S. Space Command, and the Air Force Technical Applications Center, with funding supplied by the Air

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[14] Lockheed Martin. "SBIRS," February 13, 2022. https://www.lockheedmartin.com/en-us/products/sbirs.html.

[15] USAF. Defense Support Program Satellites. 2015. https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104611/defense-support-program-satellites/.

[16] USAF. "Space Based Infrared System." Air Force, 2019. https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104549/space-based-infrared-system/.

[17] Erwin, Sandra. "ULA Launches the Last SBIRS U.S. Space Force Missile Warning Satellite." SpaceNews, August 4, 2022. https://spacenews.com/ula-launches-the-last-sbirs-u-s-space-force-missile-warning-satellite/.

[18] Erwin, Sandra. "Is the Cost of Military Space Programs Going up or down? Depends on How You Count." SpaceNews, March 19, 2018. https://spacenews.com/is-the-cost-of-military-space-programs-going-up-or-down-depends-on-how-you-count/.

[19] USAF. "NUDET Detection System." 2023 Space Procurement Justification Book, 2021, p.135. https://www.saffm.hq.af.mil/Portals/84/documents/FY20/PROCUREMENT/FY20_PB_3021_Space.pdf?ver=2019-03-18-152805-323#page=137.

[20] USAF. "NUDET Detection System." 2020 Space Procurement Justification Book, 2019, p.137. https://www.saffm.hq.af.mil/Portals/84/documents/FY20/PROCUREMENT/FY20_PB_3021_Space.pdf?ver=2019-03-18-152805-323#page=137.

[21] USAF. "NUDET Detection System." 2020 Space Procurement Justification Book, 2019, p.137. https://www.saffm.hq.af.mil/Portals/84/documents/FY20/PROCUREMENT/FY20_PB_3021_Space.pdf?ver=2019-03-18-152805-323#page=137.

Force and the NNSA.[22] The Space Force requested $7 million for continued NUDET system procurement in its FY2023 budget.[23]

NC3 Modernization

The ongoing nuclear modernization process began with the upgrading of the next-generation B2 bomber in the early 2000s[24] and continued more broadly as outlined in the 2012 Nuclear Posture Review under President Obama.[25] The current modernization push was supported by political compromise and was concurrent with the ratification of the New START treaty in 2010. It has been driven by several factors, including an increase of foreign competition with Russia and China as both states modernize their own strategic arsenals, as well as the need to replace an aging arsenal and support infrastructure and upgrade nuclear infrastructure with today's digital technology. Admiral Richard, former commander of U.S. Strategic Command, recently testified that:

The strategic security environment is now a three-party nuclear near-peer reality. Today's nuclear force is the minimum required to achieve our national strategy. Right now I am executing my strategic deterrence mission under historic stress, crisis levels of deterrence, crisis deterrence dynamics that we have only seen a couple of times in our nation's history, and I am doing it with submarines built in the '80s and '90s, and air-launched cruise missile built in the '80s, intercontinental ballistic missiles built in the '70s, a bomber built in the '60s, part of our nuclear command and control that predates the internet, and a nuclear weapons complex that dates back to the Manhattan era.[26]

Having been designed to counter the Soviet missile threat, the NC3 architecture was last significantly updated in the 1980s. In the years since, the US has faced new nuclear threats without advancing the NC3 system to meet them. Advanced technologies also have complicated NC3 requirements by creating new threats to the systems themselves.[27] The modernization process also extends to space-based assets and a space domain that sees increasing congestion and contestation. The national security space enterprise has shifted to adjust architecture and acquisitions practices to an increasingly contested environment. In a memo chartering the establishment of the Space Development Agency (SDA), former acting Defense Secretary Patrick Shanahan wrote that:

A national security space architecture that provides the persistent, resilient, global, low-latency surveillance needed to deter, or if deterrence fails, defeat adversary

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[22] Inspector General, Department of Defense. "Evaluation of the Space-Based Segment of the U.S. Nuclear Detonation Detection System," September 2018. https://media.defense.gov/2019/Nov/12/2002209615/-1/-1/1/DODIG-2018-160.PDF.

[23] U.S. Department of Defense. "Department of Defense Fiscal Year 2023 Budget Estimates, Space Force Procurement," April 2022, p.133. https://www.saffm.hq.af.mil/Portals/84/documents/FY23/PROCUREMENT_/FY23%20Space%20Force%20Procurement.pdf?ver=vMyfar1xW31ifPHFc-mz6A%3d%3d#page=133.

[24] Klotz, Frank, and Alexandra Evans. "Modernizing the U.S. Nuclear Triad: The Rationale for a New Intercontinental Ballistic Missile." RAND, January 2022, Figure 1, p.4. https://www.rand.org/content/dam/rand/pubs/perspectives/PEA1400/PEA1434-1/RAND_PEA1434-1.pdf.

[25] White House: Office of the Press Secretary. "Fact Sheet: An Enduring Commitment to the U.S. Nuclear Deterrent." whitehouse.gov, November 17, 2010. https://obamawhitehouse.archives.gov/the-press-office/2010/11/17/fact-sheet-enduring-commitment-us-nuclear-deterrent.

[26] "Testimony on United States Strategic Command and United States Space Command in Review of the Defense Authorization Request for Fiscal Year 2023, Senate Armed Services Committee," March 8, 2022. https://www.spacecom.mil/Newsroom/News/Testimony/SASC-Hearing-Transcript/.

[27] Lt Gen Deptula, David, William LaPlante, and Robert Haddick. "Modernizing U.S. Nuclear Command, Control, and Communications." Mitchell Institute for Aerospace Studies, February 14, 2019. https://mitchellaerospacepower.org/modernizing-u-s-nuclear-command-control-and-communications/.

action is a prerequisite to maintain our long-term competitive advantage. We cannot achieve these goals, and we cannot match the pace our adversaries are setting, if we remain bound by legacy methods and culture.[28]

Modernization includes upgrading and replacing satellites to reduce obsolescence and removing aging systems, equipping new payloads with more advanced sensors, expanding capacity, and designing systems for survivability and resiliency. Specific systems in need of modernization include various missile launch early warning and communications satellites, including SBIRS and AEHF. Along with developing new constellations to keep pace with missile technologies, additional modernization is likely to include upgrades in sensors, ground stations, terminals, and resiliency, survivability and hardening of the entire network.

The latest projections from the Congressional Budget Office estimate that approximately 15% of the requested budget for nuclear modernization from 2021-2030 is dedicated to command, control, communications, and early warning systems.[29]

NextGen OPIR

SBIRS will be supplemented and eventually replaced by the Next Generation Overhead Persistent Infrared (Next Gen OPIR) constellation. The first block of this constellation will consist of three satellites in GEO covering mid-latitudes and two satellites in polar highly elliptical orbits for upper latitude coverage.[30] Lockheed Martin was awarded the non-competitive, sole-source contract worth $2.9 billion to develop the three Next Gen OPIR geosynchronous satellites in 2018 with a follow-on contract of $4.9 billion. The first GEO satellite is planned for initial launch in 2025, while the first polar satellite, built by Northrop Grumman, will likely launch in 2028.[31] Delivery of the full constellation is expected by 2028. Another initiative, the Future Operationally Resilient Ground Evolution (FORGE), will modernize the ground station segment of this system and process data from both SBIRS and Next Gen OPIR.[32] The 2023 Fiscal Year budget research and development request for this system was $3.5 billion for the total ground, GEO, and polar components,[33] with total projected program costs estimated at $14.4 billion.[34]

In 2017, General John Hyten, former vice chairman of the Joint Chiefs of Staff, called the aging SBIRS satellites "big juicy targets," referring to their lack of defenses against anti-satellite weapons, and criticized the timeline for the development of the next-generation replacement. This invigorated the Air Force to speed up

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[28] Krzyzaniak, John. "'Big, Fat, Juicy Targets'— the Problem with Existing Early-Warning Satellites. And a Solution." Bulletin of the Atomic Scientists, September 30, 2019. https://thebulletin.org/2019/09/big-fat-juicy-targets-the-problem-with-existing-early-warning-satellites/.

[29] Congressional Budget Office. "Projected Costs of U.S. Nuclear Forces, 2021 to 2030." May 24, 2021. https://www.cbo.gov/publication/57240.

[30] U.S. Government Accountability Office, and John Ludwigson. "Space Acquisitions: Changing Environment Presents Continuing Challenges and Opportunities for DOD," April 2022. https://www.gao.gov/assets/gao-22-105900.pdf.

[31] Space Systems Command. "Next-Generation Overhead Persistent Infrared Program Selects Mission Payload Suppliers." March 2022. https://www.ssc.spaceforce.mil/Portals/3/Documents/PRESS%20RELEASES/Next-Generation%20Overhead%20Persistent%20Infrared%20Program%20Selects%20Mission%20Payload%20Suppliers%20v4.pdf?ver=7qUXGXb35DOGSCh2uAQEGw%3D%3D.

[32] U.S. Government Accountability Office, and John Ludwigson. "Space Acquisitions: Changing Environment Presents Continuing Challenges and Opportunities for DOD," April 2022. https://www.gao.gov/assets/gao-22-105900.pdf.

[33] Office of the Under Secretary of Defense (Comptroller). "Department of Defense Budget, Fiscal Year 2023, RDT&E Programs," April 2022. https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2023/FY2023_r1.pdf#page=50.

[34] U. S. Government Accountability Office. "Missile Warning Satellites: Comprehensive Cost and Schedule Information Would Enhance Congressional Oversight." September 2021. https://www.gao.gov/products/gao-21-105249.

the development of the system and integrate more advanced features, from better sensors to resiliency measures.[35] Next Gen OPIR is planned to be more resilient against threats, which were a concern for the SBIRS constellation. According to a Lockheed Martin representative, "a space program of this size — which includes developing two entirely new missile warning payloads — has never moved this fast."[36]

The development of the Next Gen OPIR constellation is being divided between two contractors to reinforce redundancy for sensitive national security payloads. For example, if one of the contractors were to experience a delay or other issue, the entirety of the planned constellation wouldn't be compromised and could continue on schedule. Resilience is being addressed at every step of the development process, from payload requirements to architecture design, with Space Force Colonel Brian Denaro describing Next Gen OPIR as the cornerstone of U.S. integrated missile warning, tracking, and battlespace awareness, saying that, "Next Gen OPIR is designed to provide a resilient space-based global missile warning capability against emerging missile and counter-space threats."[37]

Space Development Agency

The Space Development Agency is also developing a global infrared hypersonic and ballistic missile tracking layer in LEO and MEO as a key component of its National Defense Space Architecture that will be integrated with the broader NC3 network.[38] The first eight satellites will launch in Tranche 0,[39] and the next wave will be composed of 28 additional satellites in LEO launching in 2025.[40] The end goal is an entire constellation in LEO and MEO interfacing with each other seamlessly and capable of boost-phase missile detection and tracking.[41] SDA recently announced that it has awarded L3Harris and Northrop Grumman a total of $1.3 billion in contracts to develop prototype satellites capable of tracking hypersonic missiles in flight.[42] The main motivation behind this larger space missile warning architecture is to have satellites in lower orbits that can provide enhanced tracking capability for hypersonic missiles and gliders, while also having the added benefit of increasing redundancy.

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[35] Erwin, Sandra. "The End of SBIRS: Air Force Says It's Time to Move on." SpaceNews, February 19, 2018. https://spacenews.com/the-end-of-sbirs-air-force-says-its-time-to-move-on/.

[36] SpaceNews. "Lockheed Martin Gets $4.9 Billion Contract to Build Three Missile-Warning Satellites for U.S. Space Force," January 5, 2021. https://spacenews.com/lockheed-martin-gets-4-9-billion-contract-to-build-three-missile-warning-satellites/.

[37] Space Systems Command. "United States Space Force Next Gen OPIR GEO Program Completes Block 0 GEO Space Vehicle C." August 24, 2021. https://www.ssc.spaceforce.mil/News/Article-Display/Article/2744261/united-states-space-force-next-gen-opir-geo-program-completes-block-0-geo-space.

[38] Hitchens, Theresa. "Space Development Agency Missile Tracking Data Will Inform NC3." Breaking Defense, November 11, 2022. https://breakingdefense.sites.breakingmedia.com/2022/11/space-development-agency-missile-tracking-data-will-inform-nc3/.

[39] Space Development Agency. "SDA Awards Contracts for the First Generation of the Tracking Layer – Space Development Agency." https://www.sda.mil/sda-awards-contracts-for-the-first-generation-of-the-tracking-layer/.

[40] U.S. Department of Defense. "Space Development Agency Makes Awards for 28 Satellites to Build Tranche 1 Tracking Layer." July 2022. https://www.defense.gov/News/Releases/Release/Article/3096294/space-development-agency-makes-awards-for-28-satellites-to-build-tranche-1-trac/.

[41] Miller, Amanda. "Emerging Emphasis on Missile Tracking Reflected in Space Force's 2023 Budget Request." Air Force Magazine, April 26, 2022. https://www.airforcemag.com/emerging-emphasis-on-missile-tracking-reflected-in-space-forces-2023-budget-request/.

[42] Williams, Lauren. "Hypersonic Missile-Tracking Satellites Greenlit For Development." Defense One, 2022. https://www.defenseone.com/defense-systems/2022/07/hypersonic-missile-tracking-satellites-greenlit-development/374618/.

Beyond AEHF

The modernization plan for AEHF involves supplementing and then replacing it with the new Evolved Strategic Satellite (ESS) constellation, a Space Force program.[43] It will provide expanded global strategic and secure communications capabilities to support NC3 functions.[44] Lockheed Martin, Boeing, and Northrop Grumman are developing competing designs for the ESS program over the next few years. Contracts for the full ESS system are expected to be awarded in 2025.[4546] AEHF was originally intended to be replaced by the Transformational Satellite Communications System (TSAT) program, but due to cost overruns and delays the program was canceled in 2010 and instead two more AEHF satellites were launched as an interim measure.[47]

The Enhanced Polar System Recapitalization effort, designed as a stopgap between the Enhanced Polar System and the upcoming polar component of the ESS, is currently in development and scheduled to launch in 2022. The $429 million contract for the polar segment was awarded to Northrop Grumman.[48]

AEHF Case Study[49]

Typically, while most of the technical specifications of these satellite systems are highly classified, there is a variety of publicly available information available on the Advanced Extremely High Frequency (AEHF) constellation. Developed as the successor to the MILSTAR communications constellation, the program began in 1999, was developed in 2001, reached its initial operational capability in 2018, and is now operated and maintained by the Space Force. The first of the six satellites launched in 2010, with the final unit launched in 2020. Its operational schedule faced some setbacks, including technical issues with AEHF-1 resulting in it being stranded on-orbit and later recovered, and further delays on AEHF-4.[50] AEHF provides extremely high-frequency (EHF) uplink and crosslink capabilities and super high-frequency (SHF) communications. Its capacity is ten times that of MILSTAR, featuring an increased coverage area. Its anti-jam payload includes onboard signal processing, radio frequency equipment, crossbanded EHF/SHF communication antennas, with a mass of 6,168 kg at launch. Its hardened and survivable mission control and terminal segments are made up of fixed and mobile ground, air, and sea terminals, which facilitate data transfer rates from 75 bps to 8 Mbps.[51] The original Air Force cost estimate for the entire AEHF

[43] Congressional Research Service, and John R Hoehn. "Nuclear Command, Control, and Communications (NC3) Modernization," December 2020. https://apps.dtic.mil/sti/pdfs/AD1146336.pdf.

[44] U.S. Government Accountability Office, and John Ludwigson. "Space Acquisitions: Changing Environment Presents Continuing Challenges and Opportunities for DOD," April 2022. https://www.gao.gov/assets/gao-22-105900.pdf.

[45] Capt. Elizabeth Forbes, and Space Force. "End of an Era: The AEHF Program Comes to a Close." Los Angeles Air Force Base, 2021. https://www.losangeles.spaceforce.mil/News/Article-Display/Article/2485377/end-of-an-era-the-aehf-program-comes-to-a-close/.

[46] "Lockheed Martin Wins $258M US Space Force Contract for ESS Program Prototype," November 11, 2020. https://www.satellitetoday.com/government-military/2020/11/11/lockheed-martin-wins-258m-us-space-force-contract-for-ess-program-prototype/.

[47] Gates, Robert. "Budget Press Briefing as Prepared for Delivery by Secretary of Defense Robert M. Gates," April 2009. https://www.airforcemag.com/PDF/SiteCollectionDocuments/Reports/2009/April%202009/Day07/Gates_budget_040609.pdf.

[48] Strout, Nathan. "Space Force's Stopgap Polar Communications System Passes Another Milestone." C4ISRNet, July 9, 2020. https://www.c4isrnet.com/battlefield-tech/space/2020/07/09/space-forces-stopgap-polar-communications-system-passes-another-milestone/.

[49] Air Force. "Advanced Extra High Frequency (AEHF)," March 13, 2007. http://web.archive.org/web/20070313152253/http://www.losangeles.af.mil/SMC/MC/aehf.htm.

[50] Ray, Justin. "Two U.S. Military Satellite Launches Delayed into Next Year – Spaceflight Now," 2017. https://spaceflightnow.com/2017/08/02/two-u-s-military-satellite-launches-delayed-into-next-year/.

[51] Airforce Technology. "Advanced Extremely High Frequency (AEHF) Satellite System." March 2021. https://www.airforce-

system was $6 billion, while the total cost came out to be $15 billion.[52]

Challenges and Policy Recommendations

As the modernization process continues, there are several challenges to maintaining and developing a strong space-based NC3 capability as the U.S. faces increasing threats in the space domain. Questions around cybersecurity, force design and proliferation, escalation and deterrence, and defenses are driving current policy discussions.

The 2022 National Defense Strategy features the concept of "integrated deterrence" – which, per the deputy undersecretary of defense for policy Sasha Baker, is "a framework for working across warfighting domains, theaters and the spectrum of conflict, in collaboration with all instruments of national power, as well as with U.S. allies and our partners."[53] Space-based assets will be a key part of the United States' ability to continue integrating forces and networks, across both conventional and strategic missions. "Integrated deterrence is about using the right mix of technology, operational concepts, and capabilities—all woven together in a networked way that is so credible, and flexible, and formidable that it will give any adversary pause," according to Secretary of Defense Lloyd Austin. Instead of relying upon sheer military strength to deter adversaries, integrated deterrence envisions pulling on every available lever of influence to achieve the desired foreign policy and military effect. [54]

Cybersecurity

Because of the digital nature of space systems, cyber interference and attacks remain a top concern for the national security space enterprise, and indeed "many of the most daunting challenges for NC3 resilience lie at the intersection of cyberspace and outer space domains, where cyber-attacks are directed at space-based NC3 assets."[55] Vulnerabilities along supply chains and through contractors could also present openings for bad actors or other failures to disrupt the complex network. According to Erin Miller, Executive Director of the Space Information Sharing and Analysis Center (ISAC), "due to the different regulations and requirements used by firms and within the government, it is difficult to ensure that components from all levels of the supply chain have the same quality of cyber protection."[56] A 2019 DOT&E Cyber Assessment report highlighted such concerns and the results of the evaluation of NC3 capability were "briefed to the highest levels of DOD leadership and have resulted in a significant increase in focus in this vital area."[57]

technology.com/projects/advanced-extremely-high-frequency-aehf/.

[52] Erwin, Sandra. "Is the Cost of Military Space Programs Going Up or Down? Depends on How You Count." SpaceNews, March 19, 2018. https://spacenews.com/is-the-cost-of-military-space-programs-going-up-or-down-depends-on-how-you-count/.

[53] Lopez, C. Todd. "Integrated Deterrence at Center of Upcoming National Defense Strategy." U.S. Department of Defense, March 2022. https://www.defense.gov/News/News-Stories/Article/Article/2954945/integrated-deterrence-at-center-of-upcoming-national-defense-strategy/

[54] Osborn, Kris. "What Does the Pentagon's 'Integrated Deterrence' Strategy Mean?" The National Interest. The Center for the National Interest, November 16, 2021. https://nationalinterest.org/blog/reboot/what-does-pentagons-integrated-deterrence-strategy-mean-196372.

[55] Dunnmon, et al. "Nuclear Command and Control in the Twenty-First Century: Maintaining Surety in Outer Space and Cyberspace." Project on Nuclear Issues. Center for Strategic and International Studies (CSIS), 2017. https://www.jstor.org/stable/resrep23162.5.

[56] Gillete, Amber. "From Supply Chains to Spacecraft: Taking an Integrated Approach to Cybersecurity in Space | Wilson Center." Accessed January 8, 2023. https://www.wilsoncenter.org/blog-post/supply-chains-spacecraft-taking-integrated-approach-cybersecurity-space.

[57] Office of Test and Evaluation (DOT&E). "Cyber Assessment," 2019. https://www.dote.osd.mil/Portals/97/pub/reports/FY2019/other/2019cyber-assessments.pdf?ver=2020-01-30-115600-800#page=4.

In terms of acquisition, a 2021 SpaceNews op-ed explained why cybersecurity and supply chain management must go hand in hand: "Given current resource constraints, the leanness of the new U.S. Space Force, and the push for agility and rapid acquisition, commercial reliance is likely to increase. The proliferation of vendors providing data, software, hardware, and services in this environment presents an array of opportunities to adversaries with cascading effects, which punctuates the importance of immediately elevating cyber hygiene and supply chain risk management (SCRM)."[58]

The Space Force is also at the forefront of recognizing these risks and increasing focus on preparing to counter them, with the formation of the Space Delta 6 cybersecurity squadron, as well as the new Space Force Infrastructure Asset Pre-Assessment Program (IA-PRE) that aims to "advance the security posture of current and future commercial satellite communications procurements for the DoD."

To mitigate these challenges, government and industry should continue to focus on designing for resiliency with a focus on cybersecurity at every step of the process, and guard against supply chain interdiction from research and development to launch. Because cyber anti-satellite operations are among the counterspace threats that worry experts the most, building in robust cybersecurity measures for satellite payloads and ground stations during the modernization process and similar efforts should be a priority.[59] Contractors and commercial companies should ensure cybersecurity hardening at every step of the process to help mitigate system weaknesses and vulnerabilities. Furthermore, as the 2022 Russian hack against commercial satellite operator Viasat in Ukraine shows, satellite ground stations are generally a weak link in this system and can be relatively easy targets in a conflict.[60] A key recommendation of the 2020 Cyberspace Solarium Commission report stated that:

Even more concerning is the potential cyber threat to the U.S. nuclear deterrent and the survivability and resilience of NC3 systems and NLCC programs facing the full spectrum of cyber threats. These threats are particularly alarming because they can undermine the stability of nuclear deterrence and create the conditions for inadvertent nuclear war. The greatest risk is that precisely because cyber interactions take place below the threshold of armed conflict, the combination of cyber risks and NC3 systems can, in effect, lower that threshold. With this in mind, Congress should direct DoD to routinely assess every segment of the NC3 and NLCC enterprise for adherence to cybersecurity best practices, vulnerabilities, and evidence of compromise.[61]

Proliferation

Furthermore, shifting space architecture design away from few numbers of expensive satellites that take a long time to build, launch, and position, towards larger constellations of smaller, cheaper satellites could help increase resiliency and protect against common mode failures that occur when one satellite is interfered with, leading to the weakening of the entire constellation. This new infrastructure could also include a streamlined launch program to rapidly replace damaged satellites and investing in air or ground redundancy systems. Because constellations take so long to build, launch,

[58] Pillow, Liz. "Op-Ed | SOS Space: Why Cybersecurity and Supply Chain Risk Management Must Go Hand in Hand." SpaceNews, November 16, 2021. https://spacenews.com/op-ed-sos-space-why-cybersecurity-and-supply-chain-risk-management-must-go-hand-in-hand/.

[59] Erwin, Sandra. "Cyber Warfare Gets Real for Satellite Operators." SpaceNews, March 20, 2022. https://spacenews.com/cyber-warfare-gets-real-for-satellite-operators/.

[60] Erwin, Sandra. "U.S. Space Force to Step up Protection of Satellite Ground Systems in the Wake of Russia's Cyber Attacks." SpaceNews, May 19, 2022. https://spacenews.com/u-s-space-force-to-step-up-protection-of-satellite-ground-systems-in-the-wake-of-russias-cyber-attacks/.

[61] Cyberspace Solarium Commission, Senator Angus King, and Representative Mike Gallagher. "Final Report," March 2020, p.119. https://cybersolarium.org/wp-content/uploads/2022/05/CSC-Final-Report.pdf.

and get into position, many systems won't be operating at full capacity for years, so building in additional air, ground communications or missile warning support is an important consideration. The Space Development Agency is at the forefront of this effort, with proliferation and a spiral mode of architecture development as its two pillars approach to the National Defense Space Architecture, allowing for higher resilience, more flexibility, and the ability to "quickly pivot in response or even preemptively to advances in the threat."[62] Additionally, top officials have stressed the need for a proliferated force design, including former Space Force Chief of Space Operations General Raymond: "We have got to shift our space architecture, if you will, from a handful of exquisite capabilities that are very hard to defend to a more robust, more resilient architecture."[63]

Entanglement, Escalation, & Deterrence

Disruption of space assets could have serious impacts on U.S. nuclear posture and general force readiness by impacting missile warning and secure communications capabilities and the disruption of critical space infrastructure. These effects could be amplified in a conflict scenario where U.S. forces are under attack. If an adversary were looking to undermine U.S. nuclear security, these qualities would make the space-based NC3 segment an attractive target.

Military satellites can be entangled systems, meaning that some fulfill both strategic and tactical missions. While the benefits of entanglement include cost reductions and operational benefits, a concern is the possibility of unintended escalation that could exist if these systems were targeted. An adversary's targeting of U.S. conventional space capabilities in an attempt to gain an advantage in a conventional conflict could have destabilizing effects on U.S. confidence in its nuclear forces if the strategic space-based NC3 capabilities were affected as incidental damage.[64] The variety of possible offensive actions in space also could impact the degree to which certain modes of attack on certain assets would create escalation concerns. The jamming of dual-use satellite communications during a conventional conflict might elicit a different response than the jamming of a missile detection satellite or the detection of a co-orbital vehicle shadowing one of these systems. Both the mode of attack and the target, as well as the context of a possible conflict could impact the degree to which certain attacks would raise strategic concerns.[65] However, some scholars have argued that the entanglement of strategic and tactical functions in NC3 satellites serves as a deterrent against aggressive action, instead of as a potential tripwire.[66] Adversaries may not want to risk targeting these assets for tactical purposes because of the prospect of unintended escalation. Therefore, disentanglement might work counter to deterrence efforts. A strategy of entanglement might be more desirable as a result, and if so, it is also possible that the potential for this type of unintended escalation in space might decrease.

Additionally, because these space systems are a part of the nuclear command and control network, some experts have proposed that countries most dependent on their satellites negotiate "keep-out" zones around

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[62] Space Development Agency. "Introduction," April 2022, p. 5. https://www.sda.mil/wp-content/uploads/2022/04/SDA-About-Us-2020-to-2021_march-2022-1.pdf#page=5.

[63] Erwin, Sandra. "Raymond: Space Force in 2022 to Focus on the Design of a Resilient Architecture." SpaceNews, January 18, 2022. https://spacenews.com/raymond-space-force-in-2022-to-focus-on-the-design-of-a-resilient-architecture/.

[64] Acton, James M. "Escalation through Entanglement: How the Vulnerability of Command-and-Control Systems Raises the Risks of an Inadvertent Nuclear War." *International Security* 43, no. 1 (August 2018): 56–99. https://doi.org/10.1162/isec_a_00320.

[65] Egeli, Sitki. "Space-to-Space Warfare and Proximity Operations: The Impact on Nuclear Command, Control, and Communications and Strategic Stability." *Journal for Peace and Nuclear Disarmament* 4, no. 1 (January 2, 2021): 116–40. https://doi.org/10.1080/25751654.2021.1942681.

[66] Stewart, Brian. "Deterrence Through Entanglement." Georgia Institute of Technology, 2022. https://smartech.gatech.edu/handle/1853/67292.

each other's high-altitude satellites.[67] This type of international norm or treaty creation is promising to mitigate threats, although the willingness of major nuclear powers like the U.S., Russia, and China to join such an agreement is questionable. A potential challenge is that countries signing on to this agreement would have to be willing to disclose which of their satellites perform such operations and their locations in orbit, against concerns that this information sharing would increase the vulnerability of those assets.

According to expert Ankit Panda, "space-based NC3 assets deserve special consideration after the 2018 NPR's widening of the conditions for nuclear use."[68] In the 2018 NPR, the U.S. "would only consider the employment of nuclear weapons in extreme circumstances to defend the vital interests of the United States, its allies, and partners. Extreme circumstances could include significant non-nuclear strategic attacks. Significant non-nuclear strategic attacks include, but are not limited to, attacks on the U.S., allied, or partner civilian population or infrastructure, and attacks on U.S. or allied nuclear forces, their command and control, or warning and attack assessment capabilities."[69] By including "non-nuclear strategic attacks" on NC3 in the list of the circumstances under which the U.S might consider nuclear use, this sent the message that interfering with NC3 may cross a line. It also raised questions as to what types of aggressive activity would qualify as a "non-nuclear strategic attack" – a term which the Trump Administration never fully defined. In the 2022 NPR, the Biden Administration reverted to the more ambiguous language of the Obama-era, simply stating that "the United States would only consider the use of nuclear weapons in extreme circumstances to defend the vital interests of the United States or its Allies and partners."[70] There has been a longstanding understanding that targeting these systems could be highly escalatory and destabilizing, so maintaining robust NC3 capabilities and protecting them from interference is crucial.

Space Defenses

NC3 satellites can also benefit from both passive and active protective measures. Passive measures include disaggregated, distributed, and proliferated constellations, creating larger groups of smaller satellites that perform critical functions. A disaggregation strategy could help mitigate the problem of entanglement in dual-use infrastructure – for example, "the Evolved Strategic SATCOM (ESS) system will support strategic users for missions such as nuclear command and control, whereas the Protected Tactical Service (PTS) system will support tactical SATCOM users that need a high level of jam resistance. This could reduce the potential for unintentional escalation by forcing an adversary to be explicit about the capabilities it is targeting in an attack."[71] However, a strategy of disaggregation may not be feasible or the best option for some space systems, depending on technical or budgetary limitations or strategic concerns. And of course, "an adversary may not be able to distinguish between satellites that are intended for different missions, and even if such differences are disclosed, an

[67] Acton, James, and Thomas McDonald. "Nuclear Command-and-Control Satellites Should Be Off Limits." Defense One, December 2021. https://www.defenseone.com/ideas/2021/12/nuclear-command-and-control-satellites-should-be-limits/187472/.

[68] Panda, Ankit. "Space-Based Nuclear Command and Control and the 'Non-Nuclear Strategic Attack.'" The Diplomat, April 2020. https://thediplomat.com/2020/04/space-based-nuclear-command-and-control-and-the-non-nuclear-strategic-attack/.

[69] Department of Defense. "2018 Nuclear Posture Review," February 2018. https://media.defense.gov/2018/Feb/02/2001872886/-1/-1/1/2018-NUCLEAR-POSTURE-REVIEW-FINAL-REPORT.PDF.

[70] U.S. Department of Defense. "2022 Nuclear Posture Review," October 2022, p.9. https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF.

[71] Harrison, Todd. "Defense Against The Dark Arts In Space: Protecting Space Systems from Counterspace Weapons." CSIS, 2021. https://www.csis.org/analysis/defense-against-dark-arts-space-protecting-space-systems-counterspace-weapons

adversary may not trust this distinction and attack both anyway."[72]

Other passive measures include redundant, mobile, and hardened ground stations, wherein satellite operations are not dependent on a single, fixed, and vulnerable ground station to receive and transmit key data but can be supported by other ground stations or air receivers. Defenses like advanced space situational awareness, electromagnetic shielding, rapid deployment, and reconstitution of satellite payloads, and using encrypted and air-gapped systems are among the additional ways that NC3 space systems can protect themselves from accidents or interference. Active satellite defense measures can take the form of jamming and spoofing, lasers, targeting counterspace systems with cyberattacks, or firing projectiles or physically seizing threatening objects. While some of these defensive options add to the cost or weight of a satellite payload, a mixture of these has the potential to provide important nuclear command and control satellites with a robust defense.[73]

International options to reduce the impacts of a congested and contested orbital environment also exist. Creating a strong global space traffic management system would contribute to the ability of all countries to obtain strong space situational awareness, and reduce the risks posed by accidental collisions. Recent initiatives have also promoted the creation of international norms around responsible behavior in space, with the end goal of guiding conduct and creating a safe and sustainable space environment. The first meeting of the UN Open-Ended Working Group On Reducing Space Threats in May 2022 discussed these norms, and future meetings show promise of beginning discussions around space security.[74] The US-led moratorium on destructive kinetic ASAT testing was recently adopted into a UN resolution by a 154-8 vote. Nine states have committed to the unilateral moratorium, while China and Russia voted against the resolution and India abstained. The U.S., Russia, China, and India are the only states to have tested an ASAT weapon. This resolution could signal a degree of momentum on policy options that could work to reduce risks in space.[75] One future possibility could see nations with strong national security interests in space begin talks to negotiate the terms of a treaty banning purposeful interference with or targeting of critical satellites, to include those involved in each other's strategic forces.[76] However, any such diplomatic efforts must work towards solution that all countries can agree to and navigate sensitive national security concerns inherent to space assets, which has so far proved challenging.

Summary

The space leg of the U.S. nuclear command and control network is a highly complex system, with the nature of the orbital environment presenting unique challenges to its security. The open-source nature of this project naturally imposes limits on what it can answer on highly sensitive national security infrastructure, but it will

[72] Harrison, Todd. "Defense Against The Dark Arts In Space: Protecting Space Systems from Counterspace Weapons." CSIS, 2021. https://www.csis.org/analysis/defense-against-dark-arts-space-protecting-space-systems-counterspace-weapons

[73] Harrison, Todd. "Defense Against The Dark Arts In Space: Protecting Space Systems from Counterspace Weapons." CSIS, 2021. https://www.csis.org/analysis/defense-against-dark-arts-space-protecting-space-systems-counterspace-weapons.

[74] Hitchens, Theresa. "UN Talks on Space Norms Surprisingly Collegial, but Fireworks to Come: Sources." Breaking Defense, May 31, 2022. https://breakingdefense.sites.breakingmedia.com/2022/05/un-talks-on-space-norms-surprisingly-collegial-but-fireworks-to-come-sources/.

[75] Foye, Heather, and Gabriela Rosa Hernández. "UN First Committee Calls for ASAT Test Ban." Arms Control Association. December 2022. https://www.armscontrol.org/act/2022-12/news/un-first-committee-calls-asat-test-ban.

[76] Hitchens, Theresa. "At Home and Internationally, 'governance' Is the Space Watchword: 2023 Preview." Breaking Defense, December 28, 2022. https://breakingdefense.sites.breakingmedia.com/2022/12/at-home-and-internationally-governance-is-the-space-watchword-2023-preview/.

hopefully provide a resource for researchers, analysts, and policymakers on this important topic. The next phase of research on this topic should include questions on the role of the National Reconnaissance Office and other intelligence community architecture in the NC3 system, how the military is altering capability and survivability requirements in the next 10-20 years given the rapidly changing space threat environment, how tradeoffs between the increased need for survivability and resulting increases in payload complexity and costs are being decided, and the potential impacts on international security as other nuclear powers invest in their own advanced space nuclear command and control assets. In conclusion, developing strong successors to NC3 space programs and adapting new systems are critical to staying abreast of the rapidly changing and increasingly dangerous space environment.

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