Research Report

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The Effects of High-Altitude Nuclear Explosions on Non-Military Satellites

HOMELAND SECURITY OPERATIONAL ANALYSIS CENTER

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About This Report

The Cybersecurity and Infrastructure Security Agency (CISA) serves as the U.S. Department of Homeland Security's (DHS's) planning, analysis, and collaboration center, bringing together the private sector, government agencies, and other key stakeholders to identify, analyze, prioritize, and manage the most significant risks to the country's critical infrastructure sectors and national critical functions. In September 2023, CISA's National Risk Management Center engaged the Homeland Security Operational Analysis Center (HSOAC) to help inform CISA's efforts in identifying, understanding, and assessing emerging risks through several related tasks as part of the National Critical Function Emerging Issue Risk Analysis project. Emerging risks may include developments in technology, novel and emerging hazards and threats, infrastructure vulnerabilities, and changing market conditions, as well as the intersection of different emerging risks.

This report presents a summary of the publicly available literature on the effects produced by high-altitude nuclear explosions in the space and near-space environments on satellites. The purpose is to aid the understanding of the potential risks to satellites from nuclear explosions, with an emphasis on low Earth orbit, where most satellites reside. The target audience is the public and elected officials with some physics background.

This research was sponsored by CISA and conducted in the Infrastructure, Immigration, and Security Operations Program of the RAND Homeland Security Research Division, which operates HSOAC.

About the Homeland Security Operational Analysis Center

The Homeland Security Act of 2002 (Public Law 107-296, § 305, as codified at 6 U.S.C. § 185) authorizes the Secretary of Homeland Security, acting through the Under Secretary for Science and Technology, to establish one or more federally funded research and development centers (FFRDCs) to provide independent analysis of homeland security issues. RAND operates HSOAC as an FFRDC for DHS under contract 70RSAT22D00000001.

The HSOAC FFRDC provides the government with independent and objective analyses and advice in core areas important to the department in support of policy development, decisionmaking, alternative approaches, and new ideas on issues of significance. HSOAC also works with and supports other federal, state, local, tribal, and public- and private-sector organizations that make up the homeland security enterprise. HSOAC's research is undertaken by mutual consent with DHS and organized as a set of discrete tasks. This report presents the results of research and analysis conducted under task order 70RCSJ23FR0000076, National

Critical Function Emerging Issue Risk Analysis. The results presented in this report do not necessarily reflect official DHS opinion or policy.

For more information on the RAND Homeland Security Research Division, see www.rand.org/hsrd. For more information on this publication, see www.rand.org/t/RRA3028-3.

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Summary

The United States has become increasingly dependent on space for communications, remote sensing, weather, navigation, and science and technology development. If a nuclear weapon were to be detonated in space or near space, these capabilities would be placed at great risk. This report summarizes the effects of space and near-space nuclear detonations on nonmilitary satellites, based on publicly available information.

We discuss two illustrative cases: a hypothetical nuclear detonation at 400 km altitude and a detonation at 30 km altitude. The former is in the low Earth orbit (LEO) band, where most satellites orbit. The latter is at an altitude suitable for generating electromagnetic pulse. We examined the effects from prompt radiation (i.e., immediate radiation effects), delayed radiation effects, and effects on the atmosphere.

A 400-km detonation would place many satellites at risk. Although satellites as far as geosynchronous orbit (35,786 km) will not be significantly affected by a nuclear detonation in LEO, a detonation of 110 kilotons or greater will place at risk up to about 20 percent of the satellites in LEO from prompt radiation. Detonations larger than 110 kilotons will expose the same number of satellites to greater radiation, but no additional satellites will be exposed because Earth shields those at greater distance from prompt radiation. However, a detonation of any considerable yield will place an additional large fraction of LEO satellites at risk from delayed effects of trapped electrons for months to potentially years. Thus, relaunching and quickly reconstituting a satellite constellation might not be feasible. Exactly how many satellites will be at risk and for how long depends on the details of where those electrons would be concentrated relative to the satellites' orbits (including their inclinations) and the degree of hardening of those satellites. The detonation would interfere with radio communications between the ground and satellites locally for minutes to hours. Because LEO is the most populated orbital band, a 400-km detonation or any detonation within LEO will significantly degrade space-based communications, remote sensing, and weather services.

A 30-km nuclear detonation can place systems on the ground at risk by generating electromagnetic pulse. It is not expected to have significant, direct effects on satellites from prompt radiation. For large bursts (hundreds of kilotons), some LEO satellites could be exposed to trapped electron radiation for weeks, perhaps up to months, but this exposure would be less than in the 400-km case. The detonation would interfere with radio communications between the ground and satellites locally for minutes to hours.

To some degree, satellites can be hardened to X-rays and electrons. But the costs of doing so to the levels required to protect against the impacts of a nuclear weapon are not commercially practical. There is no practical shielding for satellites to neutrons and gamma rays. Although damaged satellites can be replenished by new ones, if the desired orbits pass through shells of

high-energy trapped electrons, replenishment must wait until the electron density decays to safe levels.

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Chapter 1. Introduction

Many modern services are provided in part or in whole by satellites. The number of active satellites has increased considerably in the past few years, and the public's daily dependence on satellites increased along with it. So, too, has the possibility of the detonation of a nuclear weapon in space. Concurrently, in the past few years, multiple adversarial countries have emphasized the capabilities of nuclear weapons and forces. During the war in Ukraine, Russia has repeatedly threatened to use nuclear weapons. China has been building up its nuclear forces. And North Korea has performed underground nuclear tests and multiple tests of missiles it claims can carry nuclear weapons.

Historically, during high-altitude nuclear tests performed from 1958 to 1962, nuclear tests damaged and destroyed some satellites (Conrad et al., 2010; Gombosi et al., 2017; Wenaas, 1978). During this early period of the space age, the number of satellites in orbit was few, and very few functions on the ground depended on space capabilities. Today, satellite-provided services permeate nearly every aspect of government and civilian life. They provide global communications, weather monitoring, navigation, remote sensing, and many other capabilities underpinning modern life. Even the timing used for the cryptography of bank transactions often uses space-based assets. A loss of a significant fraction of satellites could have significant disruptive effects on the day-to-day life of the public.

Importantly, because most satellites have orbits that are not fixed above a specific location on Earth, a high-altitude nuclear explosion (HANE) need not occur directly over the United States to have long-range and long-duration effects to the constellations of satellites on which the United States (or any country) depends. Indeed, a HANE could occur far away—even on the other side of Earth—and still harm many satellites that service U.S. customers. Although a detonation can be an outcome of war, nuclear detonations could also arise from testing, accident, or demonstration to others of capability or willingness to use nuclear weapons (see, for example, Dupont, 2004). Whatever its intent, a HANE could have significant effects on the many satellites on which the United States depends domestically.

Chapter 2. Methodological Approach

The purpose of this report is to provide a brief review of a HANE's general effects on nonmilitary satellites and the capabilities they provide. To understand what would happen if a nuclear weapon were detonated in space, we performed a structured literature review of peer-reviewed journal articles and publicly available research and analysis on HANE, general nuclear weapon effects, satellite design, and the usage and distribution of satellites in various orbits. We did not attempt to predict the exact consequences of nuclear detonations in space and near space. To estimate the detailed effects, specific calculations would need to be performed that are beyond the scope of this report. The analysis and discussion are necessarily simplified, and the results should be read as approximative. This work simplifies the problem by treating each type of effect in isolation. We did not attempt to establish thresholds for satellite exposure considering how a satellite would be affected by simultaneous exposure to multiple effect types. And for simplicity, we treated the detonation of a single weapon. We explored different yields of that weapon but did not consider the effects of detonation of multiple weapons.

Chapter 3. General Effects of Nuclear Explosions

When a nuclear weapon detonates, an enormous amount of energy is released from nuclear reactions.[1] For a simple weapon, the energy comes from nuclear fission alone, which is the splitting of heavy nuclei. For more-complex weapons, the energy comes from a combination of nuclear fission and nuclear fusion, which is the combination of light nuclei. In either case, in an extremely short time, the weapon and its immediate surroundings are elevated to temperatures above 1 million kelvins. At these temperatures, the atoms are stripped of their electrons, forming a plasma. This plasma is so hot that it glows in the X-ray region of the electromagnetic spectrum. Hence, upon detonation, the weapon immediately emits X-rays (which are most of the energy output) and by-products of the nuclear reactions—mainly, gamma rays (more energetic than X-rays), neutrons, electrons, and heavier ions. There is also residue from the burst that is radioactively unstable and continues to fission. This delayed radioactive decay is the dangerous aspect of "fallout" from surface bursts. The main fission by-product of interest in space from this residue is free electrons (those not bound to atoms) of high energy.

Four parameters are the most important factors for how a HANE might affect a satellite and its functions:

- location of the HANE (altitude and position in Earth's magnetic field)
- yield of the weapon
- location of the satellite (distance to the HANE, and orbital altitude and inclination)
- robustness of the satellite design to various hostile environments.

One of the most important aspects of the location of a HANE is its altitude. The density of Earth's atmosphere decreases exponentially with altitude, so the density of atmosphere surrounding a HANE changes significantly with altitude. In this report, we focus on hypothetical detonations at two altitudes: 30 km (19 miles) above Earth's surface and 400 km (249 miles) above Earth's surface. Thirty kilometers is a plausible altitude at which to detonate a nuclear weapon to generate an electromagnetic pulse (EMP), and, as we argue below, to reduce—but not eliminate—the magnitude of the effects on satellites. A 30-km altitude is also a plausible altitude to perform some kind of demonstration burst. A burst altitude of 400 km is within the band of low Earth orbits (LEOs) and is the average orbital altitude of the International Space Station. It is also an altitude that might be selected to attack satellites in LEO. Of note is that the United States detonated a 1.4-megaton weapon at 400 km in 1962 (Starfish Prime) and collected and analyzed many empirical observations of the resulting effects (Dyal, 2006; Hess, 1963; U.S. Department of Energy, 2000). In discussing the effects of the density of the atmosphere, it is useful to begin with the more familiar detonations near Earth's surface.

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[1] For a more detailed description of a nuclear detonation than that summarized here, see Glasstone and Dolan (1977).

A detonation near Earth's surface is surrounded by air dense enough to absorb most of the X-rays (and therefore most of the energy) within just a few meters of the burst point. This absorption of X-rays forms the much larger fireball familiar in photographs and films of many nuclear tests. The formation of the fireball converts much of the X-ray energy into a shock wave that can destroy structures and a thermal pulse that can ignite mass fires and severely burn humans. Gamma radiation and neutrons from the immediate detonation will travel much farther than the X-rays and can sicken or kill humans. The radioactive decay from the residue can be distributed great distances from the burst point by a thermal plume that disperses the fallout over a large area and can sicken or kill humans for a considerable time after the detonation.

At altitudes high enough for satellites to orbit, however, the density of air is too thin to appreciably absorb the radiation and particles emitted from a HANE. The electromagnetic radiation (X-rays and gamma rays) and uncharged particles (neutrons) move away from the burst point unimpeded and strike any satellite within line of sight. No shock wave or strong thermal pulse is formed, so no satellites are destroyed by blast. The electrons have an electrical charge, however, and are therefore deflected by Earth's magnetic field. Trapped electrons from both those emitted from the initial burst and those from the radioactive decay of the residue follow paths along Earth's magnetic field lines. They become trapped in Earth's magnetic field, bouncing back and forth along north- and south-oriented field lines. As is described in more detail below, the electrons are initially confined to a tube along the field lines near the detonation point. Over a period of hours, the trapped electrons drift eastward, smearing the tube into a shell around Earth consisting of electrons bouncing back and forth from north to south at nearly the speed of light. Through many complicated mechanisms, over a longer period of time, the electron population decays. Therefore, the location of a HANE in Earth's magnetic field is a second aspect of location that is important because it governs where the electrons are trapped.

With respect to a satellite, there are three categories of effects that we discuss below in more detail. First, the immediate radiation from the HANE, mostly in the form of intense X-rays, gamma rays, and neutrons will expose all satellites within line of sight to ionizing radiation.[2] Second, the trapped electrons will expose satellites whose orbits pass through those shells of electrons to moderate- to high-energy electrons for prolonged periods of time. Third, the gamma rays, X-rays, and some ultraviolet rays from a HANE will be absorbed by the atmosphere below the HANE, with consequences in the form of interference with radio communications and EMP. We elaborate below on the degree of these effects on satellites.

A HANE detonated at 30 km is intermediate between the near surface and the LEO cases. The atmosphere at 30 km is too rarified for commercial aircraft to fly but too dense for a sustained orbit of a satellite. The air at 30 km is low-enough density that some of the gamma radiation and neutrons will travel upward and strike any satellites within line of sight. However, the air is dense enough to absorb electrons and X-rays locally. This absorption forms a local

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[2] Ionizing radiation is radiation of sufficiently high energy to knock electrons out of their atomic orbits.

fireball and a shock wave. The shock wave cannot travel to the near vacuum of LEO and therefore does not affect satellites. The X-rays from a HANE at 30 km, therefore, will not reach LEO and not directly affect satellites. Because the X-rays are absorbed locally, however, they will warm a volume of air that contains the radioactive residue that rises because of buoyancy. If the yield of the HANE is sufficiently large, this buoyant volume of air can rise high enough (above about 64 km, or about 40 miles) to inject electrons from the radioactive residue into trapped shells in Earth's magnetic field (Glasstone and Dolan, 1977; Liu et al., 2022). Such an effect was observed in some U.S. high-altitude tests (Hoerlin, 1976).

To summarize, most of the energy of a nuclear weapon is emitted in the form of X-rays. Near the surface of Earth, the X-rays cause a strong shock wave and thermal pulse. At 30 km, the X-rays form a weaker shock and warm a volume of radioactive air that rises buoyantly and may inject electrons into trapped shells in Earth's magnetic field. Some of the gamma radiation and neutrons travel by line of sight to satellites. At 400 km, X-rays, gamma rays, and neutrons travel to satellites by line of sight, and electrons get trapped in shells in Earth's magnetic field. In the rest of this report, we discuss in more detail the ramifications of these effects on satellites.

Chapter 4. Nuclear Explosions at 400 Kilometers

We divide the discussion of a HANE at 400 km into three categories: the immediate effects (called *prompt effects*), delayed effects, and effects on the atmosphere below the HANE.

Prompt Effects

X-rays, gamma rays, and neutrons from a nuclear explosion are of high-enough energy to create two effects on materials:

- The first effect is for the radiation to lose energy in the material by knocking electrons away from atoms. This effect can cause electric currents to flow and build up charges in semiconductors.
- The second effect is for the radiation to displace atoms in the material, creating holes in the atomic lattice. This effect can degrade or destroy the performance of semiconductors, which, in turn, can degrade the performance of a satellite.

Collectively, these are called *transient radiation effects on electronics* (TREE). The word *transient* refers to the radiation, not the effects, which can be permanent.

The exact nature of TREE depends on the specific materials and electronics targeted, as well as the intensity and energy spectrum of the radiation (which depend on weapon yield and design) and the susceptibility of the satellite to ionizing radiation (e.g., the degree of shielding).[3] For these reasons, the summary of effects below simplifies many of the details. Predicting the exact effects on a particular satellite requires detailed knowledge of both the weapon and the satellite and is beyond the scope of this report.

X-Rays

Roughly 70 to 80 percent of the energy of a nuclear weapon is released in the form of X-rays. Less than 1 percent of the energy is released as gamma radiation, and the energy released as neutrons is also small compared with the X-ray output (Glasstone and Dolan, 1977). Although the X-rays are not as penetrating into materials as gamma rays and neutrons and therefore are more amenable to shielding, the larger proportion of energy in the form of X-rays makes X-rays the largest source of concern from prompt effects of a HANE.

X-rays can affect satellites in one or more of these ways:

- First, when they are absorbed, some of the energy is converted to heat, which raises the temperature of the surface where they are absorbed, creating damage in numerous ways. If the energy is absorbed fast enough, the heating can create a shock wave in the material, causing fractures. This temperature rise can damage materials throughout the satellite,

[3] The effects also depend on the rate of exposure to radiation (radiation dose per unit time), but we do not go into this level of detail.

including surface treatments. Solar panels—the power source to most satellites—are of particular susceptibility from thermal effects (Conrad et al., 2010). Satellites are at risk from thermal effects for X-ray fluences greater than about 400 joules per meter squared (J m^{-2}) 400 J m^{-2} (Conrad et al., 2010).

- Second, the absorption of X-rays in conductors in the satellite, including metal shielding, can knock electrons from atoms, inducing a high-voltage and electrical current surge in the satellite. This effect is called *system-generated electromagnetic pulse* (SGEMP) but should not be confused with EMP, which is a different effect (and is discussed briefly below). SGEMP can damage electronic components. Most SGEMP is caused by X-rays rather than gamma rays or neutrons. Satellites are at risk for SGEMP for X-ray fluences greater than about 4 J m^{-2} (Conrad et al., 2010).
- Third, higher-energy X-rays can cause damage to electronics via ionization. Semiconductors are particularly susceptible to ionization. Ionization can temporarily upset or permanently damage electronics and electronic memory. Satellites are at risk for X-ray fluences greater than about 0.4 J m^{-2} (Conrad et al., 2010).

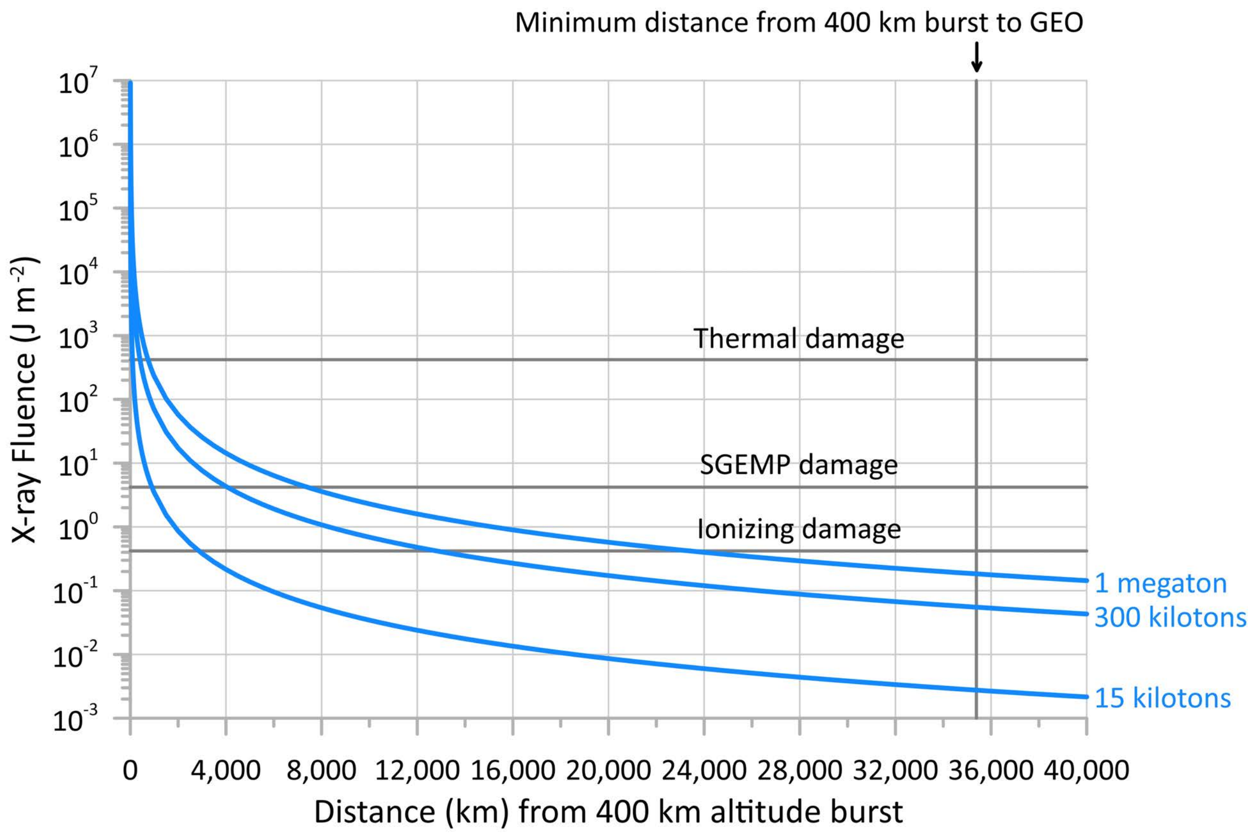
Different materials (e.g., coatings on solar panels, metals, semiconductors) are not equally at risk to all three damage mechanisms. Thresholds given are for the most susceptible materials. Whether a satellite is damaged or destroyed by X-rays depends on the X-ray exposure, which is, in turn, dependent on whether the satellite is within line of sight of the burst point, the weapon's X-ray yield, and the distance from the burst point to the satellite. Assuming a conservative lower estimate of about 70 percent of the yield in the form of X-rays (Glasstone and Dolan, 1977), the X-ray fluence $F_{\text{x-ray}}$ from a nuclear explosion, in joules per meter squared, is

$$F_{\text{x-ray}} = 2.3 \times 10^{11} \frac{Y}{r^2},$$

where Y is the total yield in kilotons and r is the distance from the burst point, in meters. For example, a nuclear burst equivalent to the weapon dropped on Hiroshima (15 kilotons) at a distance of 100 km exposes a satellite to approximately 345 J m^{-2}, which is below the thermal threshold but well above the thresholds for the other two mechanisms discussed above.

Figure 1 shows the effects that X-rays from a HANE at 400 km (within LEO) can have on satellites at geosynchronous orbit (GEO) (35,786 km altitude). The *x*-axis of the figure is the distance from a 400-km HANE. The vertical line on the plot shows the minimum distance to GEO. The *y*-axis gives the X-ray fluence for nominal weapons of three different total yields. The figure shows that a burst of even a 1-megaton weapon at 400 km is not expected to have any significant X-ray–related effects on satellites in GEO.

Figure 1. X-Ray Fluence from a 400-Kilometer Burst

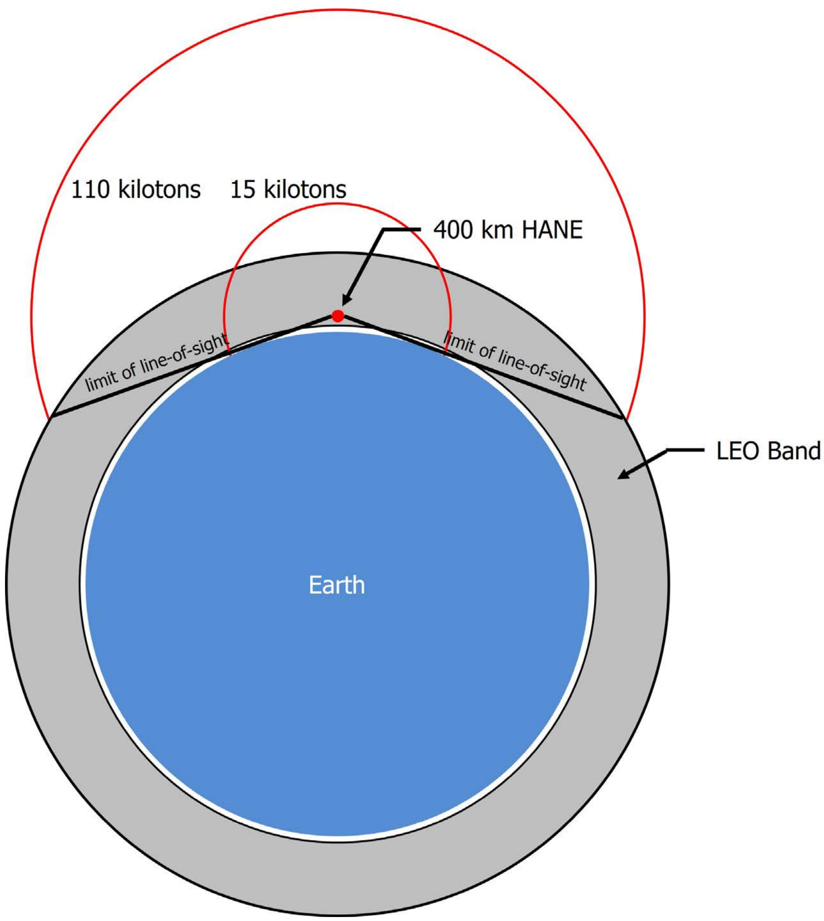


Although X-ray emission from a HANE at 400 km is not expected to affect satellites in GEO, it will affect satellites in LEO. Using the thresholds above, satellites are at risk for X-ray fluences in excess of about 0.4 J m^{-2} (Conrad et al., 2010). This number should be taken as an approximation. Satellites can be shielded to some extent from X-rays. Tantalum is a common material used but is heavy and adds a weight penalty to satellite design. But some components, such as the solar panels for power, cannot be readily shielded. Because neutrons and gamma rays deeply penetrate materials, no shielding can be practically used on satellites for neutron and gamma rays (Nordin and Kong, 1999). Therefore, even when a satellite is heavily shielded for X-rays, there is no point in shielding beyond the thresholds for neutron and gamma radiation. For all these reasons, the threshold of 0.4 J m^{-2} is a rough estimate for the satellites at risk and should be used for illustrative purposes, not an exact quantitative value.

Figure 2 shows the distances for this level of X-ray fluence from a 400-km HANE on the LEO band of satellites (roughly from 160 km to 2,000 km). The 400-km burst point is shown as a red dot, which is low in the LEO band. A weapon with a 15-kiloton total yield exposes satellites within roughly 2,900 km to 0.4 J m^{-2} or higher X-ray fluences. This range is depicted in Figure 2 by the inner red arc. This volume is approximately 4 percent of the LEO volume. A weapon with a 110-kiloton total yield places all satellites within line of sight in the LEO band to

X-ray fluences in excess of the 0.4 J m^{-2} threshold. Greater total yields expose the same volume to higher X-ray fluences but do not expand the volume exposed because of the shielding of Earth. This range is depicted in Figure 2 by the outer red circle. This volume is approximately 20 percent of the LEO volume.

Figure 2. X-Ray Exposure of Satellites in Low Earth Orbit



In summary, although some X-rays can be shielded, the large amount of energy that a nuclear weapon produces in the form of X-rays puts satellites at risk for great distances from the burst point. But the relatively narrow altitude band occupied by LEO and the geometry of the shadowing of Earth combine to restrict the exposure of satellites to prompt X-rays to a fraction of satellites.

Neutrons

A weapon's neutron radiation (both intensity and energy spectrum) is dependent on the proportion of yield the weapon produces from fission versus fusion and other details of the design. We used a generic weapon for which the neutron fluence F_{neutron} in neutrons per square meter, n m^{-2}, is approximately

$$F_{\text{neutron}} = 1.6 \times 10^{22} \frac{Y}{r^2},$$

where *Y* is the total yield in kilotons and *r* is the distance from the burst in meters (Conrad et al., 2010). Neutrons largely create atomic displacements in materials and secondary ionization, and the susceptibilities of materials to these effects vary. As a generalization, neutron fluences of greater than about 10^{16} n m^{-2} can upset electronics (Nordin and Kong, 1999). We used this value as a threshold for neutron exposure.

Figure 3 shows the effects that neutrons from a HANE at 400 km (within LEO) can have on satellites at GEO and reads similarly to Figure 1. The figure shows that the neutrons from a burst of even a 1-megaton weapon at 400 km are not expected to have any significant effect on satellites in GEO.

Although neutron emission from a HANE at 400 km is not expected to affect satellites in GEO, it will, to some extent, affect satellites in LEO. It is not practical to shield satellites from neutron radiation because of the penetration capabilities of high-energy neutrons. The distance from the burst that places satellites at risk is small compared to that for X-rays, so it is less informative to show neutron effects at the scale shown for X-rays in Figure 2. Instead, Figure 4 shows the approximate distance from the burst at which satellites are at risk as a function of the total yield of a weapon. Each curve shows the approximate threshold for damage to satellites, and the area shaded beneath each curve indicates the region at risk. For a 15-kiloton burst, satellites are at risk from neutrons at distances up to about 5 km from the burst point. For a 300-kiloton burst, satellites are at risk from neutrons at distances up to about 22 km from the burst point. For a 1-megaton burst, satellites are at risk from neutrons at distances up to about 40 km from the burst point.

Figure 3. Neutron Fluence from a 400-Kilometer Burst

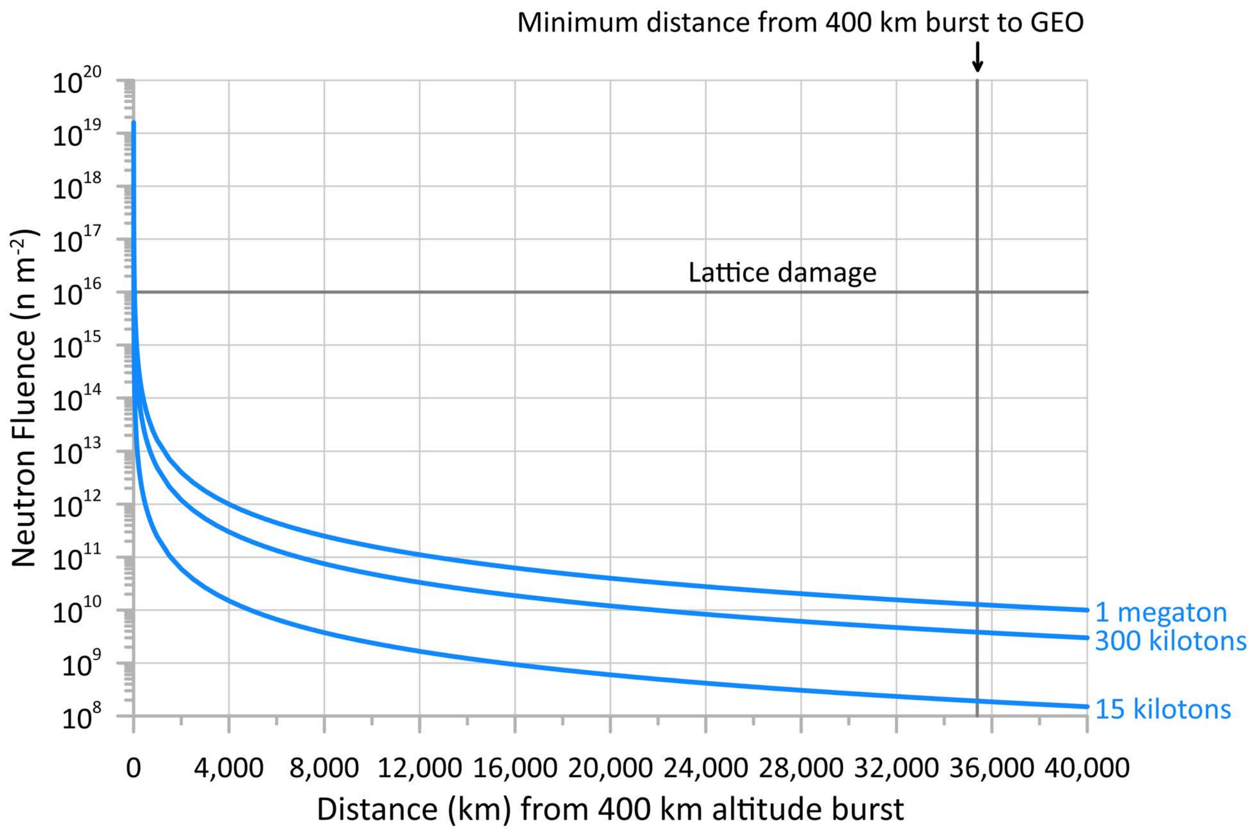
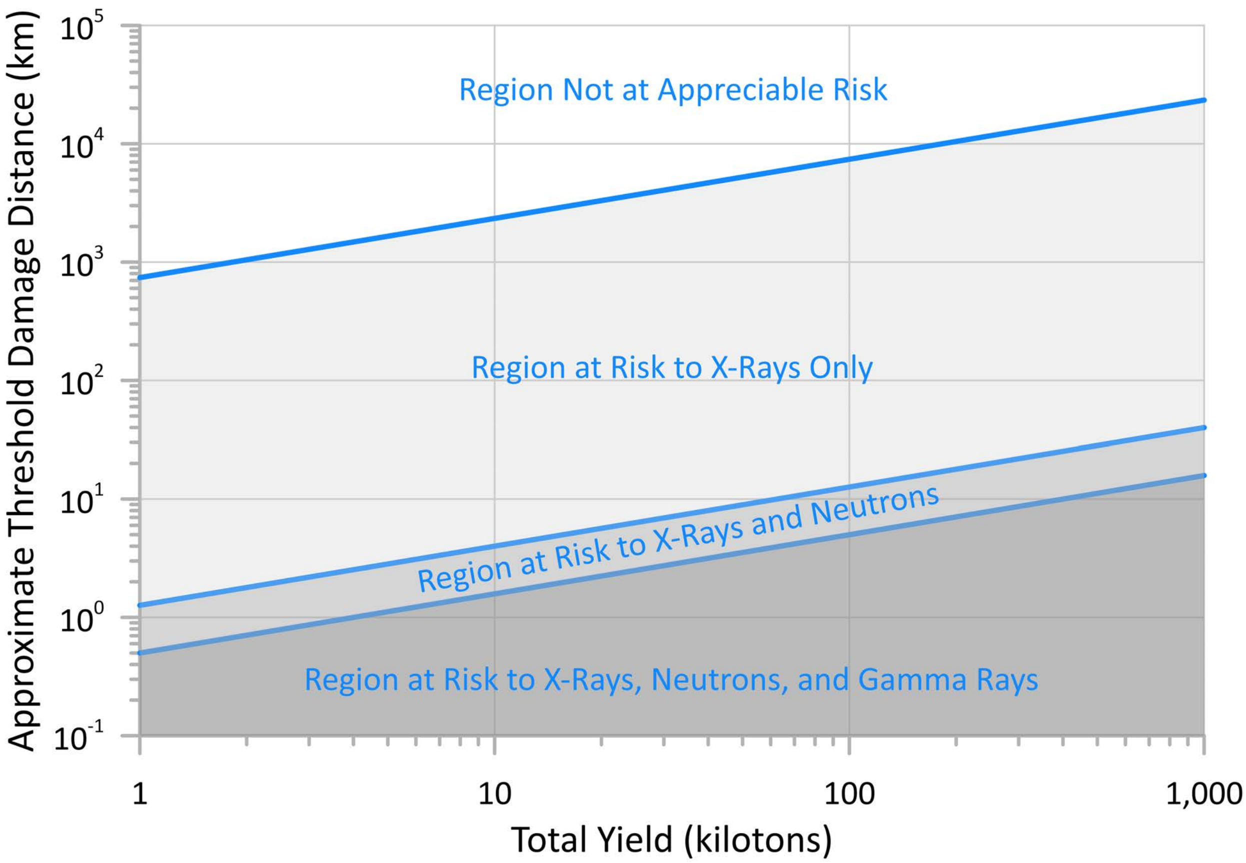


Figure 4. Approximate Prompt Radiation Threshold Damage Distances from the Burst Point



Gamma Rays

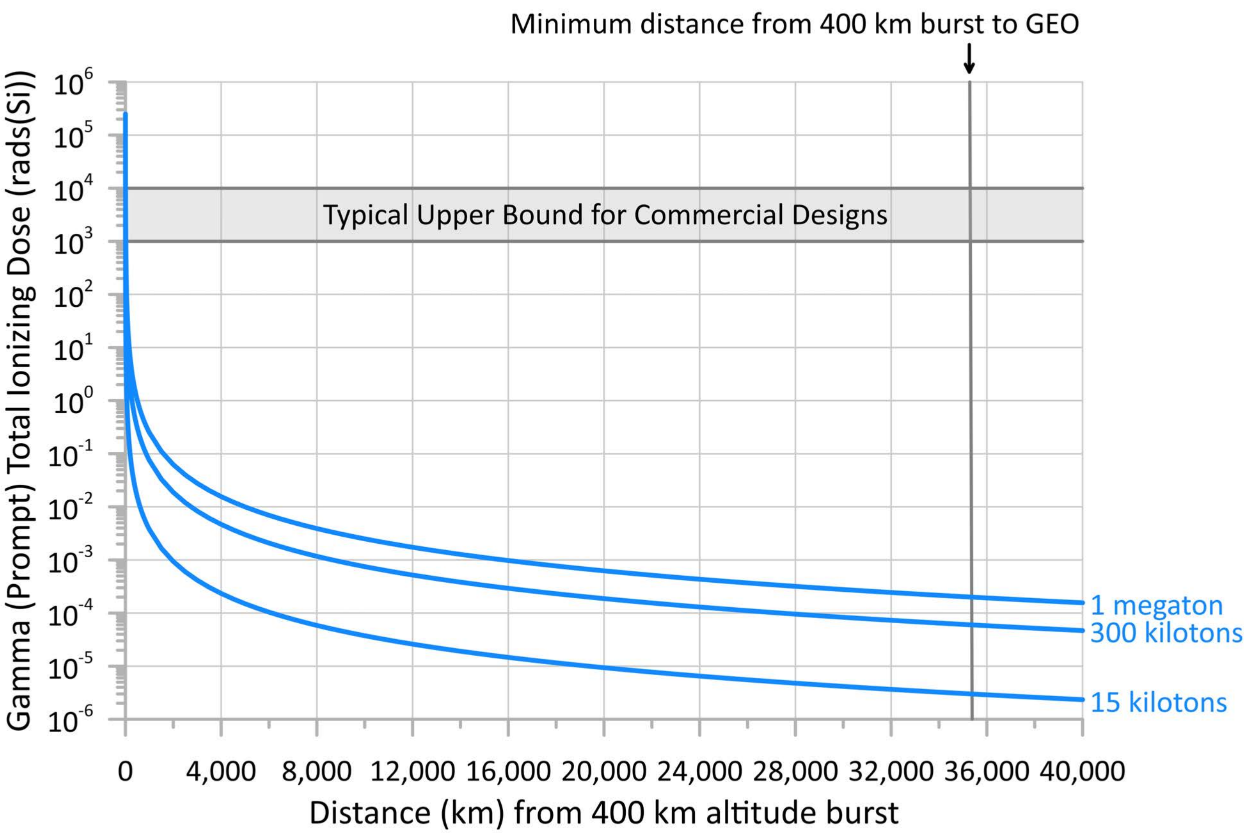
The amount of gamma radiation released from a weapon depends on weapon design. Both the gamma dose and the dose per unit time determine the damage to materials. Here, we focus on the total ionizing dose from gamma radiation F_{gamma} from a generic weapon in terms of total absorbed dose. The appropriate measure is the amount of energy absorbed by a material per unit mass. This unit is rads (or grays in the International System of Units), and rads vary according to material. For damage to electronics, the energy absorbed per unit mass of silicon (Si) is normally used, which is denoted by rads(Si). F_{gamma} in rads(Si) is approximately

$$F_{\text{gamma}} = 2.5 \times 10^8 \frac{Y}{r^2},$$

where *Y* is the total yield in kilotons and *r* is the distance from the burst in meters (Conrad et al., 2010). (We focus here only on prompt gamma radiation, which does not include exposure to delayed gamma radiation produced from fissioning of bomb residue.) Gamma rays largely create atomic displacements in materials, and materials' susceptibilities to these effects vary. Commercial satellites in LEO are typically designed to withstand about 10^3–10^4 rads(Si) (Hands et al., 2018; Nordin and Kong, 1999), which is the threshold that we used. Like with neutrons, there is no effective way to shield satellites from gamma radiation.

Figure 5 shows the effects that gamma radiation from a HANE at 400 km (within LEO) can have on satellites at GEO and reads similarly to Figures 1 and 2. The figure shows that a burst of even a 1-megaton weapon at 400 km is not expected to have any significant effect from gamma rays on satellites in GEO.

Figure 5. Prompt Gamma Ray Total Ionizing Dose from a 400-Kilometer Burst



However, satellites closer in LEO will be affected. The lower curve in Figure 4 shows the approximate threshold damage distance for gamma radiation as a function of total yield. For a 15-kiloton burst, satellites are at risk from gamma rays at distances up to about 2 km from the burst point. For a 300-kiloton burst, satellites are at risk from gamma rays at distances up to about 9 km from the burst point. For a 1-megaton burst, satellites are at risk from gamma rays at distances up to about 16 km from the burst point.

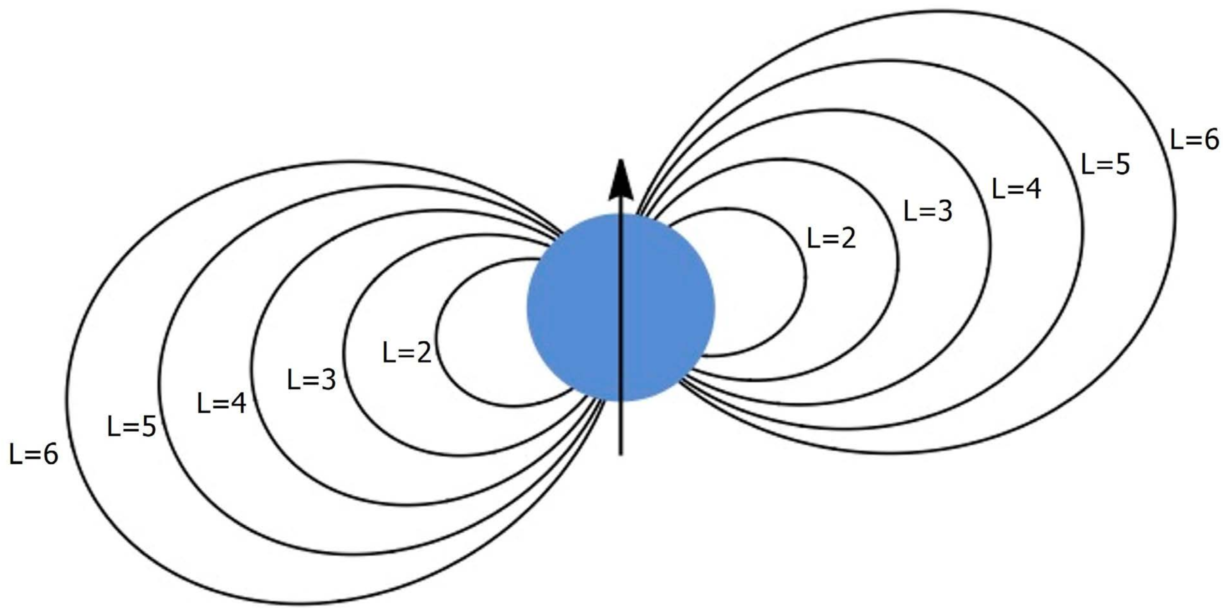
Delayed Effects

The residue from a nuclear burst contains dozens of radioactive isotopes with half-lives ranging from about an hour to years (Teller et al., 1968). As a generalization, the shorter-half-life isotopes emit higher-energy electrons than the longer-half-life isotopes. Overall, radioactive decay of this residue emits a spectrum of electrons, many of which are high energy (Bendel, 1982; Cross, 2007; Griffin, 1964; Van Allen, Frank, and O'Brien, 1963). At 400 km, some of these electrons are captured in Earth's magnetic field in a phenomenon called the *Argus effect*.[4] These electrons can stay trapped in the magnetic field for weeks, months, or even years, depending on their energies and burst location.

Because electrons are trapped in magnetic field lines, then migrate eastward in hours to occupy a two-dimensional blanket around Earth (Hess, 1964), a coordinate system was developed to describe the shapes and locations of trapped electrons (McIlwain, 1961). The coordinates are called *L-shells* and are shown schematically in Figure 6. An L-shell is a set of magnetic field lines that, at any common magnetic longitude, are the same distance from the center of Earth. We can label these L-shells by the number of Earth radii (approximately 6,371 km) they are from the center of Earth at Earth's magnetic equator. L = 2, for example, is the shell formed by rotating around Earth the magnetic field line that is, at the magnetic equator, 2 Earth radii from the center of Earth (or 1 Earth radius from the surface) (the rotation is around the magnetic dipole, not the rotational axis of Earth). L-shells are closer to Earth's surface as they approach the northern and southern magnetic poles. The figure shows selected L-shells to scale. An equatorial LEO orbit at 550 km, such as Starlink, is at L = 1.09. A satellite in equatorial GEO is at L = 6.6.

[4] It is also known as *pumping up the Van Allen belts*, *belt pumping*, and the *Christofilos effect*.

Figure 6. Illustration of L-Shells



For a burst in an L-shell, most of the trapped electrons will be confined to a distribution around a range of L-shells slightly greater than the L-shell where the nuclear weapon detonates. Electrons bounce back and forth along the magnetic field lines, being "reflected" at northern and southern points called *conjugate points* or *mirror points*. The location of the conjugate points depends on the angle between the electron's velocity and the local direction of the magnetic field lines. If the conjugate points are in the atmosphere, the electrons collide with atmospheric atoms and are absorbed rapidly. If not, electrons can persist for days, weeks, or years, their population decaying by a set of complicated phenomena (Claudepierre et al., 2020).

Satellites that cross the shells of trapped electrons are exposed to the electrons over prolonged periods of time. There are three effects these electrons have on satellites:

- The lower-energy electrons can deposit on the surfaces and exterior shielding of the satellite. This can lead to electrical charging of the surfaces and give rise to charge differences in the satellite. These charges can build up over time to a point when they suddenly discharge, causing a high current flow in the satellite that can damage electronics. Most fission electrons are not low energy, and surface charging can generally be mitigated by grounding, so we do not discuss this effect further (Garrett, 1981; National Aeronautics and Space Administration, 2022).
- Intermediate-energy electrons can penetrate exterior shielding and deposit their energy in interior parts of a satellite. This effect is often called *deep dielectric charging* (Baker et al., 1987; Denig and Frederickson, 1985; Lai et al., 2018; Zuo et al., 2021). It can also cause a charge buildup that is later discharged rapidly, causing a damaging current flow.

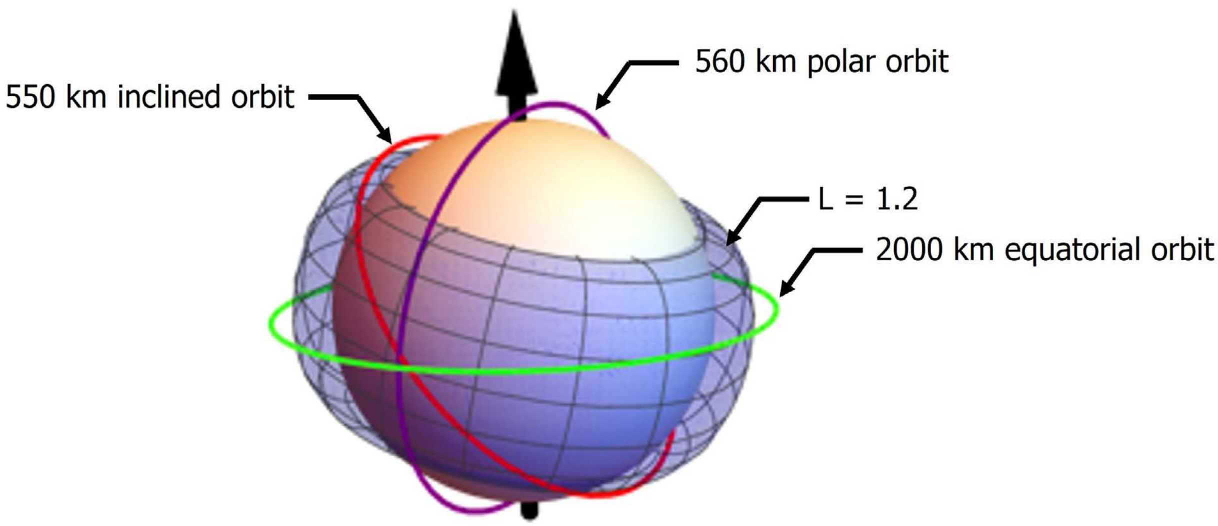
- High-energy electrons can cause ionization or atomic displacements, giving rise to effects similar to those of high-energy X-rays, gamma rays, and neutrons, thereby damaging or destroying electronics.

There is a natural background electron radiation around Earth. Natural background electron densities can vary by orders of magnitude in response to space weather conditions, with much greater variations at GEO than at LEO. There is a statistically significant correlation between satellite anomalies and the levels of free electrons to which satellites are exposed from this background radiation (Iucci et al., 2005). Earth's magnetic field captures electrons from solar and cosmic processes in a region called the Van Allen belts (Kanekal and Baker, 2016; Li and Hudson, 2019). These particles are concentrated in inner ($L \approx 1.5 – 2.5$) and outer belts ($L \approx 4 - 6$), with a lower-density zone in between called the *slot* ($L \approx 2.5 - 4$). Electrons populate both belts, but the inner belt is dominantly protons. Because of the damaging effects these electrons (and protons) can have on satellites, orbits are generally chosen to avoid the Van Allen belts to reduce exposure to high-energy electrons and protons and, when traversing the Van Allen belts to get to higher orbits, to do so rapidly. Nevertheless, any satellite is exposed to some degree to electron radiation during its lifetime and is designed accordingly.

A HANE can considerably boost the electron densities in Earth's magnetic field, and the electrons that are produced by HANE tend to be at the higher-energy range, where deep dielectric charging and lattice damage are important effects. Exactly how much the background electron density will be enhanced by a nuclear explosion depends on the weapon and location of burst and is difficult to calculate precisely. In general, electrons with high energy have longer decay times (last longer), and ones closer to Earth (around LEO) persist longer than those at GEO (35,786 km altitude) (Claudepierre et al., 2020). As researchers learned from the experience of the Starfish Prime nuclear test in 1962, LEO electron densities can be boosted by many orders of magnitude, and the electrons can take years to decay back down to background levels (van Allen, 1966). Starfish Prime was a 1.4-megaton total yield burst at 400 km, detonated at L = 1.12. The electrons were trapped dominantly between about L = 1.2 and 1.6 (Cladis, Davidson, and Newkirk, 1977), but with most of the electrons in a narrow set of shells centered at L = 1.2 (Reeves et al., 2005). The Starfish Prime trapped electrons had a mean lifetime of about 1.5 years (van Allen, 1966).

The exposure of a satellite to trapped electrons depends on its orbit relative to the populated L-shells. The orbit of a particular satellite is highly confined to a narrow band around Earth, and the trapped electrons are confined to a relatively narrow band of L-shells. The more time that a satellite spends within the populated L-shells, the more at risk it is. Some satellites can have orbits that largely avoid the populated L-shells. Figure 7 depicts this geometry schematically for a few illustrative cases. The blue sheet shows one L-shell, the L = 1.2 shell. Three orbits are also shown: an inclined orbit at 550 km (red), a polar orbit at 560 km (purple), and an equatorial orbit at 2,000 km (green). Each orbit has different exposure to electrons concentrated at L = 1.2. The 2,000-km orbit avoids the trapped-electron shell, while the other two spend varying times inside the shell. Reality would be more complicated because the electrons would be dispersed across a range of L-shells and vary in energy. But the broader point is that some satellites will be at great risk, and others may escape significant damage depending on their hardening and the orientation of their orbits relative to the populated L-shells.

Figure 7. Schematic Diagram of Argus Effect Geometry



As noted above, commercial satellites in LEO are typically designed to withstand about 10^3–10^4 rads(Si) (Hands et al., 2018; Nordin and Kong, 1999). There is some evidence that commercial satellite designs have become less robust to radiation exposure over time (Baker, 2000).[5] If a satellite has a design life of five years when exposed to 10^3 rads(Si), and a HANE exposes it to three orders of magnitude more than that (10^6 rads[Si]), its design life would be reduced by roughly a factor of 1,000, which means that its expected design life would be reduced to just several days.[6] The Starfish Prime event damaged several satellites shortly after the burst, but there were few satellites in orbit at the time, and designs were different in 1962 both because of different technologies and because knowledge of the space environment and the response of materials to it was in its early stages (Gombosi et al., 2017).

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[5] Discussions with satellite design experts indicate that this has not improved in the past 25 years.

[6] Five years is a typical planned lifespan for LEO satellites (Congressional Budget Office, 2023).

Effects on the Atmosphere

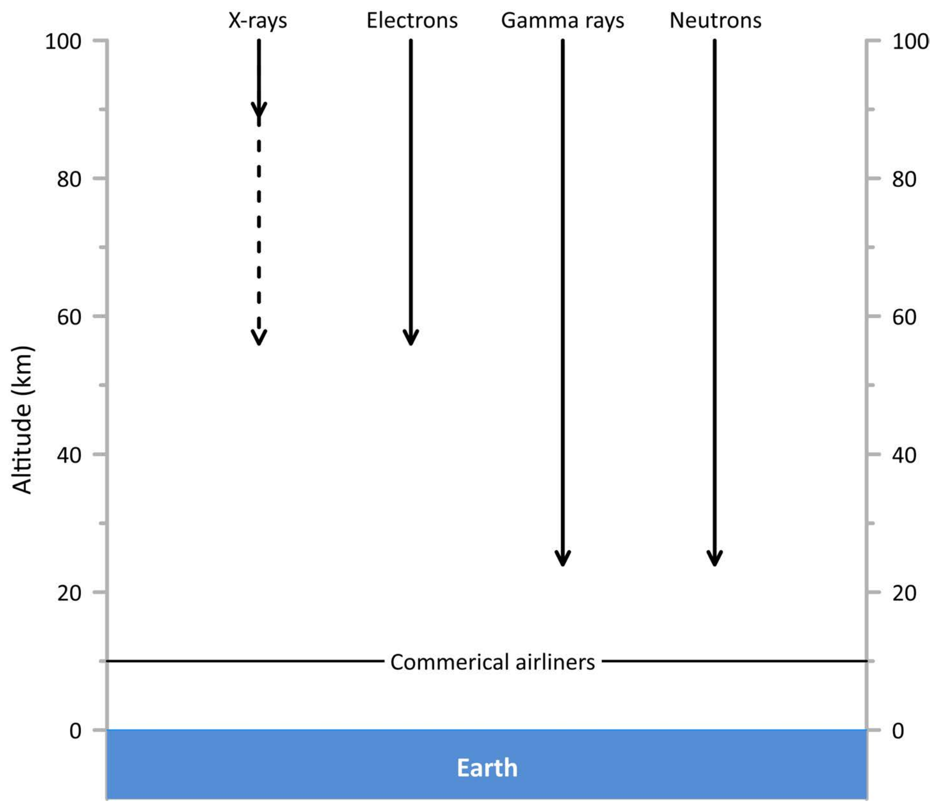
The radiation from a HANE at 400 km will travel outward in all directions, including downward where the radiation will be absorbed in the atmosphere. This absorption will give rise to additional effects that can indirectly affect the functioning of satellites. The radiation would be absorbed at different altitude ranges depending on radiation type and energy. Because Earth's atmosphere's density increases exponentially as the radiation approaches Earth, the radiation would be stopped within a relatively narrow zone. Figure 8 shows the approximate altitudes beyond which the various forms of radiation are stopped (Glasstone and Dolan, 1977).

The X-rays will be absorbed highest in the atmosphere, many being absorbed by about 90 km, and some making their way to about 55 km altitude (shown by the dashed arrow). The most-penetrating radiation, the gamma rays and neutrons, will be absorbed by about 25 km. No substantial radiation will penetrate to the level of commercial airline traffic, much less make it to the surface of Earth.

The gamma radiation will create early-time EMP (see text box). This EMP will affect some unprotected electronics on the ground over a region roughly within line of sight of the burst but will have little effect on satellites overhead. Because the X-rays would make up most of the energy released from the burst, their absorption will warm the atmosphere. If the yield of the weapon is high enough, this warmed layer of atmosphere will rise buoyantly. Because it is electrically charged, the movement of this charge through Earth's magnetic field will induce a current in Earth, which is another form of EMP, called the *heave component* of late-time EMP. Another form of late-time EMP will be caused by the bomb debris's expansion in Earth's magnetic field, called the *blast component*. These two forms of late-time EMP will not affect satellites directly, but all forms of EMP could affect satellites indirectly by damaging their ground support systems or ground systems that use the satellites' services.

All these forms of radiation will ionize the atmosphere. Some of this ionization arises from the prompt radiation, and some from the trapped electrons whose conjugate points are in the atmosphere, which will persist longer. Both sources of ionization will cause the atmosphere to be temporarily locally electrically charged and interfere with some radio communications. The frequencies used for the command and control of satellites and for satellite services (e.g., communications, transmitting imagery) fall toward the higher-frequency end of the radio frequency spectrum. Frequency bands used by satellites are in the ultrahigh-frequency range and above (more than 0.3 GHz) (Dietrich and Davies, 1999). This frequency range will be affected by the ionization of the atmosphere in a local region for minutes to hours (Defense Atomic Support Agency, 1961; Glasstone and Dolan, 1977; Holland, 1977; Jusick et al., 1964; Jusick and Furman, 1969; Kownacki, 1963; Ouyang et al., 2014; Williams, 1962; Xu et al., 2019). There is also the possibility of some interference of radio communications briefly from radio waves emitted by the trapped electrons in Earth's magnetic field (called *synchrotron radiation*), but this effect, if it occurs, will be localized as well (Defense Atomic Support Agency, 1961; Peterson and Hower, 1963).

Figure 8. Approximate Stopping Altitudes of Radiation



SOURCE: Data extracted from Glasstone and Dolan (1977, Table 10.29, p. 469).
NOTE: The figure shows the approximate distances at which various forms of radiation can penetrate Earth's atmosphere from 400 km above. X-rays stop over a broader region than other radiation forms, which is reflected by the dashed line. The horizontal line at 10 km is the approximate altitude at which commercial airliners cruise and is provided for a reference scale.

High-Altitude Electromagnetic Pulse

A nuclear detonation at high altitude can generate EMPs by several mechanisms. These EMPs are grouped by time after burst and duration. *Early-time EMP* occurs within about one-millionth of a second after burst. *Intermediate-time EMP* occurs up to about a second after burst. *Late-time EMP* occurs up to a few minutes after burst.

Early- and intermediate-time EMPs arise from the same phenomena: gamma radiation ejecting electrons from atoms in the atmosphere and the deflection of those electrons in Earth's magnetic field. The air must be dense enough to provide enough atoms for significant electrons to be ejected but not so dense that those electrons would be absorbed by atomic collisions before they are significantly deflected in Earth's magnetic field. This region includes 30 km altitude. Early- and intermediate-time EMPs place electronics not adequately protected at potential risk below the burst point over a wide region. Satellites above are at minimal risk, but ground systems supporting, controlling, or using the satellites could be at risk.

Late-time EMP arises from two distinct mechanisms, called *blast* and *heave*. Blast is formed by the deflection of Earth's magnetic field from the charged particles expanding away from the burst point. The distortion of the magnetic field induces an electric current in Earth. Heave is formed by the buoyant rise of a sheet of air heated by the burst's X-ray and ultraviolet radiation. That ionized sheet also distorts Earth's magnetic field and induces a current in Earth's crust. Late-time EMP places terrestrial systems grounded over long distances (such as the power grid) at risk if they do not have adequate mitigation. Satellites are not at risk, but ground systems supporting, controlling, or using the satellites could be at risk.

Chapter 5. Nuclear Explosions at 30 Kilometers

A HANE at 30 km is substantially different from one at 400 km. The main difference is that the X-rays and electrons are absorbed locally. Again, we divide the discussion into prompt effects, delayed effects, and effects on the atmosphere.

Prompt Effects

The X-rays from a 30-km burst will form a fireball similar to what is seen in atmospheric detonations, but the fireball will be much larger than at sea level and not as hot because the radiation travels farther before being absorbed. The prompt X-rays and electrons will, therefore, not reach satellites in LEO. The atmosphere is thin enough above 30 km, however, for some gamma radiation and neutrons to reach LEO. But because the distance is hundreds of kilometers to LEO, the radiation will not be intense enough to place satellites at risk (Figure 4).

Delayed Effects

The Argus effect for the 30-km case is more complicated than for the 400-km HANE case. At 30 km, the prompt electrons are absorbed by the atmosphere locally and do not reach LEO. However, the large fireball caused by the absorption of the X-rays forms a buoyant cloud containing radioactive debris. If the weapon yield is large enough, this radioactive cloud can rise high enough that the electrons can travel freely without collision, which is roughly above 55 km (see Figure 8). That altitude requires the buoyant cloud to rise more than 25 km from the burst point. Detonations somewhere in the range of low hundreds of kilotons to 1 megaton can achieve those rise heights. A 15-kiloton detonation is unlikely to rise sufficiently (Liu et al., 2022). Once that happens, electrons produced by the radioactive decay of debris can be trapped in Earth's magnetic field, creating an Argus effect. For any given yield, the Argus effect will be less for the 30-km case than for the 400-km case. This is for two reasons:

- First, many of the electrons will be absorbed before the cloud rises to an altitude above which electrons can travel unimpeded.
- Second, as time progresses, the residue becomes depleted in isotopes with short half-lives, and those with longer half-lives are more abundant. Isotopes with longer half-lives emit electrons that are a bit lower in energy. The net result is that the trapped electron densities are much less for the 30-km case than for the 400-km case, and trapped electrons remain trapped in the magnetic field for less time.

U.S. high-altitude weapon tests confirm these calculations. Teak was a 3.8-megaton detonation at 77 km altitude in 1958. It was detonated just above the altitude above which most electrons can move freely without collision, producing a minor Argus effect. The altitude and latitude of detonation corresponded to L = 1.1. The Argus effect was maximal at about L = 1.14, with measured enhancement out to at least L = 1.2. The Teak electron density decayed in days (Cladis, Davidson, and Newkirk, 1977; Hoerlin, 1961; Steiger and Matsushita, 1960; U.S. Department of Energy, 2000; van Allen, 1966). Another test in 1958, called Orange, had a smaller effect than Teak's. Orange was a 3.8-megaton detonation at 43 km altitude, below the zone of unimpeded electron movement. Electrons from the Orange test were injected at about L = 1.1. Orange's radioactive cloud did rise high enough to inject some trapped electrons into Earth's magnetic field, but the effect was not well monitored and did not appear to lead to a significant Argus effect (Cladis, Davidson, and Newkirk, 1977; U.S. Department of Energy, 2000; van Allen, 1966).

Effects on the Atmosphere

The gamma radiation from a 30-km burst will create considerable early-time EMP. This burst altitude is too low to create much late-time EMP. The early-time EMP will affect some unprotected electronics on the ground over a region roughly within line of sight of the burst but will have little effect on satellites overhead. The X-rays will create a fireball that ionizes the atmosphere locally. This ionization will cause the atmosphere to be temporarily electrically charged and interfere with some radio communications. The frequencies used for the command and control of satellites and for satellite services (e.g., communications, transmitting imagery) fall toward the higher-frequency end of the radio frequency spectrum. Frequency bands used by satellites are in the ultrahigh-frequency range and above (more than 0.3 GHz) (Dietrich and Davies, 1999). This frequency range will be affected by the ionization of the atmosphere in a local region for minutes to hours (Defense Atomic Support Agency, 1961; Glasstone and Dolan, 1977; Holland, 1977; Jusick et al., 1964; Jusick and Furman, 1969; Kownacki, 1963; Ouyang et al., 2014; Williams, 1962; Xu et al., 2019).

Chapter 6. Nuclear Explosions' Effects on Nonmilitary Satellites

Summary of a 400-Kilometer Altitude High-Altitude Nuclear Explosion

The detonation of a nuclear weapon at 400 km altitude will damage or destroy a significant number of satellites, depending on the location of the detonation. The effects arise from both prompt radiation and delayed effects from weapon debris called the *Argus effect*. Neither will significantly affect satellites as distant as GEO.

Prompt radiation will damage the largest number of satellites through X-rays. Earth will shadow most LEO satellites from direct line of sight. A 15-kiloton detonation will place roughly 4 percent of LEO band (160 to 2,000 km) of satellites at risk from prompt radiation. Any detonation of about 110 kilotons or greater will place roughly 20 percent of LEO band of satellites at risk from prompt radiation, which is all those in LEO within line of sight. Higher yields will expose this same volume to greater X-ray fluences. Greater fractions of the LEO band of satellites cannot be affected by prompt effects because of the shadowing of Earth (Figure 2). Although satellites can be shielded to some degree from X-rays, subject to weight and cost constraints, they cannot practically be shielded from gamma rays or neutrons. Any satellite within a distance that places it at risk to gamma rays or neutrons will be destroyed, but this zone is only kilometers to tens of kilometers from the burst point, depending on weapon yield.

Although prompt effects are confined to a local zone around the HANE, the Argus effect is global. Within hours of detonation, electrons circle Earth in a band of L-shells. Any satellites whose orbits cross those L-shells and that are not adequately hardened will have their lifespans greatly shortened. Depending on burst location and yield, these electrons can remain trapped for weeks to years. Without detailed calculations, it is not possible to estimate how many satellites are at risk. It is certain that some fraction of satellites would be significantly damaged or destroyed. It is also possible that—depending on weapon yield and position of burst—a single detonation might not be sufficient to populate enough L-shells with enough electrons to damage or destroy all LEO satellites.

Some EMP will be generated, but the EMP would only place at risk systems on the ground that support or use the satellites' services. Some communications to and from the satellites will be diminished or obstructed completely over local areas for minutes to potentially hours.

This assessment is for satellites of nominal hardening and does not apply to military satellites that may have significant hardening. The assessment is also for the detonation of a single weapon. The detonation of multiple weapons at different times and locations can have compounding affects that are greater than the sum of individual detonations. Also, if a significant number of satellites are damaged to the extent that command and control of station-keeping is lost, the risk of conjunctions (collisions) will increase.

Summary of a 30-Kilometer Altitude High-Altitude Nuclear Explosion

A detonation at 30 km will form a fireball that absorbs most of the prompt radiation. Neutrons and gamma rays that can travel farther will be diminished in fluence sufficiently not to place LEO satellites at significant risk. Except for detonations with hundreds of kilotons of yield, the Argus effect will be suppressed; for those detonations that do inject trapped electrons into Earth's magnetic field, the effect will be much smaller than that of a LEO burst and persist for a much shorter time. The main effect will be early-time EMP. Early-time EMP will affect some electronics on a broad region of the ground beneath the burst point, but it will not have a significant effect on most satellites. It might, however, place at risk some ground systems supporting, controlling, or using satellites.

Functions of Satellites

Nuclear explosions can place satellites at great risk. Which functions will be affected by a detonation depends on a satellite's orbit relative to the location of the burst. Satellites can be grouped by orbit type: LEO (160 to 2,000 km), medium Earth orbit (MEO) (2,000 to 35,786 km), highly elliptical orbit (HEO), and GEO (35,786 km). MEO orbits are used mostly by navigation satellites. HEO orbits are strongly elliptical (their orbits range widely in altitude) and are used because they preferentially cover certain parts of the world well for a given function or observe parts of Earth at the same time of day. Satellites in GEO revolve around Earth at the same speed as Earth rotates and therefore remain stationary over a region on Earth's surface.

A detonation in LEO is threatening to more satellites than detonations in the other orbits. As shown in the table, roughly 90 percent of satellites are in the LEO band (this number is somewhat distorted by the enormous number of Starlink satellites placed in LEO in the past few years, but, even excluding the Starlink constellation, most satellites are in LEO). And because the orbital diameter of LEO is much smaller than in GEO, the satellites are more densely concentrated in LEO. Therefore, for any detonation, a greater number of satellites would be in lethal range to a nuclear burst. The dominant function of satellites in LEO is communications (SAIC, 2023; Union of Concerned Scientists, 2023), which means that communications would be most at risk of all the functions that satellites provide. Roughly 98 percent of remote-sensing satellites are also in LEO. These monitor Earth and contribute to many activities on the ground, including managing agricultural decisions, water management, and disaster relief. Roughly 89 percent of weather satellites also orbit in LEO.

Satellite Functions, by Orbit

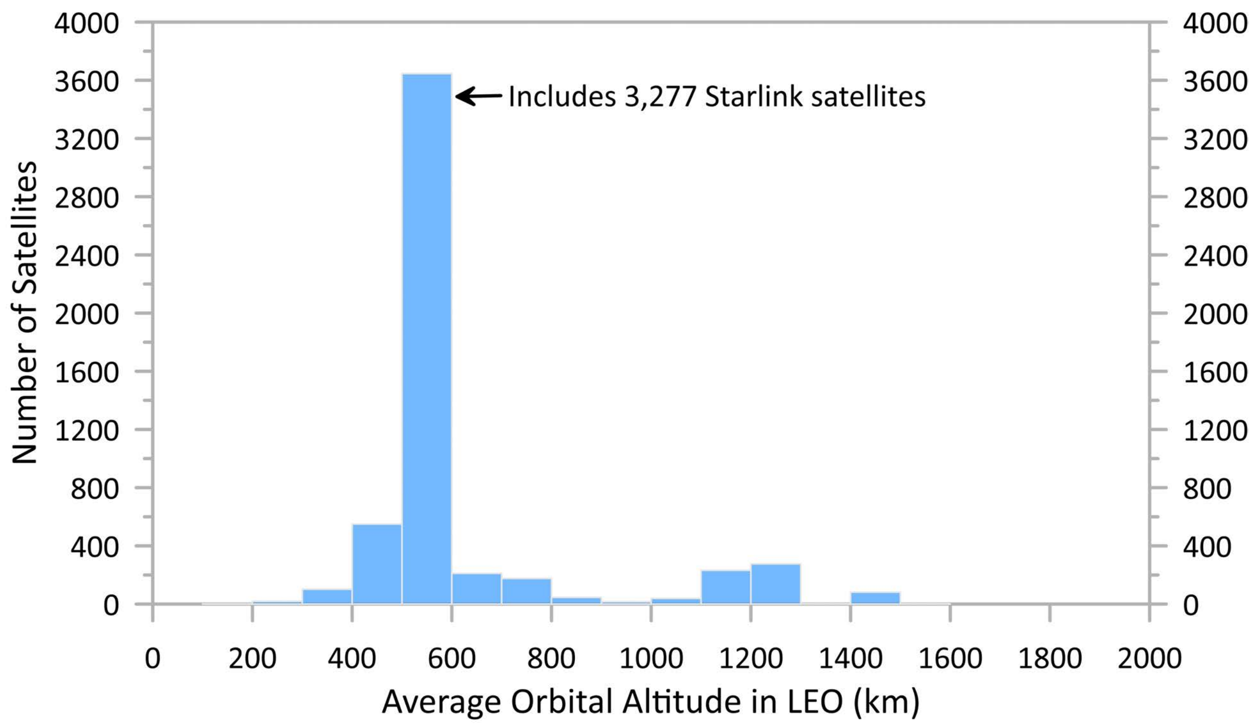
Function	LEO	MEO	HEO	GEO	Total
Communications	4,250	0	6	449	4,705
Science	155	0	20	18	193
Navigation	38	95	0	29	162
Weather	152	0	6	13	171
Remote sensing	717	0	2	12	731
Technology development	279	0	1	11	291
Total	5,591	95	35	532	6,253

SOURCES: Analysis of data from SAIC (2023) and Union of Concerned Scientists (2023) as of January 2023. We have included only satellites that were found in both datasets, which excludes anything launched in 2023 because Union of Concerned Scientists (2023) data were last updated January 1, 2023. Additionally, those satellites that had decayed before 2023, as determined from SAIC (2023), have been removed.

If we look more closely at how satellites are distributed in LEO, Figure 9 shows that, within the LEO band, most satellites are between 400 and 800 km and between 1,100 and 1,300 km. The Starlink constellation, which is at roughly 550 km, dominates the LEO population. This concentration of orbits makes the estimates of the volume of satellites affected by a 400-km burst in the LEO band to be lower bounds because few satellites are in the upper orbits, near 2,000 km.

Additionally, the International Space Station orbits at about 400 km, so humans live in this part of LEO. Any event that places the International Space Station itself at risk places the humans onboard at risk. Humans are more sensitive to radiation than hardware is (Simon et al., 2022). Even extreme variations in the normal space environment at 400 km can cause humans aboard the International Space Station to seek shelter in a more highly protected section of the station (Klotz, 2007). Standards for humans' exposure in space are low and can be easily exceeded by a HANE in LEO (Klotz, 2007; National Aeronautics and Space Administration, 2023; Ueno et al., 2020).

Figure 9. Histogram of Satellites in Low Earth Orbit



SOURCES: Features analysis of data from SAIC (2023) and Union of Concerned Scientists (2023) as of January 2023. We have included only satellites that were found in both datasets, which excludes anything launched in 2023 because Union of Concerned Scientists (2023) data were last updated January 1, 2023. Additionally, those satellites that had decayed before 2023, as determined from SAIC (2023), have been removed.

Mitigation Mechanisms

There are three primary mitigation mechanisms:

- First, to some extent, satellites can be designed to withstand nuclear weapon effects.[7] Shielding can protect some systems from X-rays, for example; however, some components, such as solar panels, cannot be effectively shielded. And neutron radiation and gamma rays are so penetrating that satellites cannot be practically shielded against them. Design considerations can mitigate against trapped electrons as well. Commercial satellites are typically designed for the expected normal variations of space environment of their orbits. Nevertheless, some satellites experience anomalies even from the normal variations of the space environment (Baker, 2000; Hands et al., 2018; Iucci et al., 2005). The radiation environment from a HANE can enhance the expected normal radiation environment by orders of magnitude, which will almost certainly exceed the design specifications of most commercial satellites. For example, the Argus effect from a detonation in LEO could expose satellites that cross the populated L-shells to a total

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[7] Because of the natural space environment, satellite designs typically incorporate some of these abilities. However, the level to which they can withstand nuclear weapon or extreme space weather effects is a design consideration, including the costs to harden and risk assessments of whether they will be needed.

ionizing dose several orders of magnitude higher than they are designed to withstand. The average expected lifespan of a satellite in LEO is about five years, with some designed to last a few years longer (Congressional Budget Office, 2023). For a HANE that exposes a satellite in LEO to an order of magnitude (factor of 10) greater electron density, an expected lifespan of five years would be reduced to approximately six months. If the satellite had been in orbit for three years at the time of the HANE, it might fail within a few months.

- Second, another mitigation is to replace satellites by launching new ones. For such a strategy to be effective, satellites and the boosters to get them into orbit would need to be available on standby. But even if satellites and boosters are on standby, this strategy is practical only once the Argus effect has subsided enough that the satellite can withstand the electron environment. Depending on the severity of the Argus effect and location of the needed orbit relative to the L-shells populated by the Argus effect, the space environment might prohibit safe operations for months to years.
- A final potential mitigation is to hasten the reduction of the number of trapped electrons. One of the mechanisms that naturally reduces the population of trapped-electron density is interference with very-low frequency (VLF) electromagnetic radiation. VLF is the frequency range from about 10^3 to 10^4 Hz. Human-generated emission of VLF radiation, either from Earth's surface or from satellites in orbit, could be a partial remediation of the Argus effect and is the subject of study (Naumov and Rudenko, 2014; Ni et al., 2022; Song et al., 2022; Stone, 2020). However, these capabilities remain in the research stage and are not currently available for employment.

Chapter 7. Conclusions

Nuclear detonations at 30 km can place systems on the ground at risk by generating EMP, but detonations at that altitude are expected to have minimal direct effects on satellites from EMP and prompt radiation. Detonations at 30 km could generate some Argus effect if the yield is in the range of hundreds of kilotons or above.

Nuclear detonations at 400 km in the LEO band will place many satellites at risk. Satellites as far out as GEO will not be affected by a HANE in LEO. But prompt radiation from a detonation of 110 kilotons or greater will place at risk up to about 20 percent of the satellites in LEO. A detonation of any considerable yield will place a large fraction of LEO satellites at risk from the trapped electrons from the Argus effect. Exactly how many satellites will be at risk from the Argus effect depends on the details of the L-shells populated, the satellite orbits (including their inclinations), and the degree of hardening of the satellites. Because LEO is the most populated orbital band, a 400-km detonation, or any detonation within LEO, will significantly degrade space-based communications, remote sensing, and weather services.

Abbreviations

EMP	electromagnetic pulse
F	fluence
GEO	geosynchronous orbit
HANE	high-altitude nuclear explosion
HEO	highly elliptical orbit
LEO	low Earth orbit
MEO	medium Earth orbit
SGEMP	system-generated electromagnetic pulse
Si	silicon
VLF	very low frequency

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The report provides two illustrative cases: a hypothetical nuclear detonation at 400 km altitude at low earth orbit and a detonation at 30 km altitude, an altitude suitable for generating electromagnetic pulse. The authors examined the effects from prompt radiation, delayed radiation effects, and effects on the atmosphere.

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