IMPROVING SATELLITE PROTECTION WITH NANOTECHNOLOGY

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Abstract

While the United States has enjoyed an historic advantage in space and the USAF has enjoyed the luxury of operating relatively unimpeded in this medium, the nation has become vulnerable to threats that could damage or disable its vital satellite constellations. This paper examines the threat to satellites posed by ground-based directed energy weapons and the state of satellite-related nanotechnology research and development to demonstrate the applicability for mitigating this type of threat. The paper argues that USAF leaders need to make continued research and development into nanotechnology for satellite applications an investment priority. This will require a long and expensive commitment, only some of which will pay off, but it is necessary if the USAF and the nation are to maintain space supremacy.

Chapter 1
Introduction

"The United States relies on space operations for its security, and this reliance may make us vulnerable in some areas. Identifying vulnerabilities will allow us to apply our full range of capabilities to ensure space superiority and continued support to joint military operations across the spectrum of conflict. Space superiority is as much about protecting our space assets as it is about preparing to counter an enemy's space or anti-space assets....We must protect our space assets."

Chief of Staff--General John P. Jumper, August 2004[1]
AFDD 2-2.1, 2 August 2004

The United States is very reliant on satellites and will likely continue to be for many years to come. Americans have come to depend on satellites and satellite services in order to conduct their daily activities. Space-based technology "enters homes, businesses, schools, hospitals and government offices through its applications for transportation, health, the environment, telecommunications, education, commerce, agriculture and energy. Space-based technologies and services permit people to communicate, companies to do business, civic groups to serve the public and scientists to conduct research."[2]

The United States Air Force (USAF) has become equally dependent, relying on satellites for the planning and conduct of almost every military mission, in peacetime and during war, not only for itself, but to support its sister services and coalition partners. Although space supported the preparation and conduct of operations during Operations Desert Shield and Desert Storm in 1990 and 1991, its significance has increased dramatically over the past several years. Combat operations in Afghanistan and Iraq demonstrate as never before, the operational importance of space to the joint warfighter. Space products and services are now significantly more capable, more abundant, and more integrated into all phases of combat operations.[3]

While the United States has enjoyed an historic advantage in space and has enjoyed the luxury of operating relatively unimpeded, the nation has become vulnerable to threats that could damage or disable its vital satellite constellations. This vulnerability of United States satellites became very real on January 11, 2007, when China successfully demonstrated its capability to destroy an on-orbit satellite. China launched a missile which intercepted and destroyed its FY-1C weather satellite. On January 19, 2007, in an attempt assure the international community, Chinese Foreign Affairs spokesman Liu Jianchao said "there's no need to feel threatened about this….we are not going to get into any arms race in space."[4] The reality is there are many ways to deny, disrupt, or physically destroy satellite systems. These include attacking the ground stations via physical or computer network attack, employing denial and deception measures, jamming satellite communications equipment, physical attack of the satellites, or detonating a low-yield nuclear device in the atmosphere.[5]

Space operations and the ability to deny another country's freedom of access to space are no longer confined to global military powers. Today, small nations, groups, and individuals can acquire ground target data from commercial imagery sources; navigation and weather data from government-owned satellites; and state of the art command and control capabilities through commercial communications satellites.[6]

This paper will discuss how nanotechnology can be used to improve the design of United States satellites to mitigate those threats. The paper will look at potential improvements to generic satellite systems but its scope will not extend to investigating possible benefits to mission payloads. It will also analyze the ability of these nanotechnology-derived improvements to mitigate the threat posed to United States satellites by ground-based directed energy weapons.

The paper will begin by describing the threat to United States satellites posed by directed energy weapons. The paper will specifically examine both lasers and high-powered microwaves, describing what they are and how they may threaten satellites. It will then discuss what countries currently possess these capabilities and what capability adversaries might possess in the 2025 timeframe. From these discussions, the paper draws upon common satellite orbits to show the role orbits play in satellite vulnerability. It also looks at common satellite sub-systems and explores how ground-based directed energy weapons could these systems.

Several definitions for nanotechnology are explored. The paper explains how nanomaterials are different from materials at the micro- or macro-scale, and details the different properties nanomaterials possess.

The paper then explains how the work from nanotechnology research and development projects can be applied to satellite sub-systems, both today, and in the 2025 timeframe. Specifically, the paper discusses surface coatings that could be used to improve satellite thermal control and electrical conductivity, nanomaterials to improve the radiation hardness of commercial-grade microprocessors for use in satellites, and nanomaterials for hardening satellite structures.

The paper concludes with an assessment of the ability for these nanotechnology improvements to mitigate the threat posed by ground-based directed energy weapons. It makes recommendations for continued research and development in nanotechnology as one means for the USAF to maintain its dominance of space through and beyond 2025.

Chapter 2
Directed Energy Weapon Threats to US Satellites

> "We simply cannot afford to defend against all possible threats. We must know accurately where the threat is coming from and concentrate our resources in that direction."[7]
> Edwin Land, founder of the Polaroid Corporation

United States space systems provide a host of critical capabilities to the nation and "the US military is dependent on the use of space capabilities in all types of warfare to maintain a combat advantage over our adversaries."[8] However, today's space infrastructure is largely unprotected and is vulnerable to attack by potential adversaries employing a variety of means which could damage or disrupt satellite operations, from simple jamming to physical destruction. To achieve space superiority and ensure uninterrupted use of United States space assets, the USAF conducts Defensive Counterspace Operations. Air Force Doctrine Document 2-2.1 defines Defensive Counterspace (DCS) Operations as operations to "preserve US/friendly ability to exploit space to its advantage via active and passive actions to protect friendly space-related capabilities from enemy attack or interference."[9] DCS operations include hardening space systems, either by physically hardening the structures to protect from attack or by using filters and shielding to protect the satellite from radiation effects.

Adversaries can use offensive counterspace techniques to degrade United States space capabilities. These can range from passive means, such as denial and deception, to more active means, such as attacking ground or space components. Continued technological advances and proliferation of anti-satellite weapons will enable more adversaries to possess the means to attack or interfere with United States satellites.[10] Among these, directed energy weapons will provide adversaries means way to counter United States satellite operations, specifically using ground-based lasers and high-powered microwaves.[11]

Directed energy weapons offer the advantage of producing operational effects at the speed of light as well as the ability to engage multiple targets. Several nations, such as Russia and China, have either built or are developing the technology to construct ground-based directed energy weapons, either lasers or high-powered microwaves

Ground-based lasers could damage thermal control, structural and power system components and may affect electro-optical sensors on low earth orbiting satellites. Lasers generate and focus intense beams of light that can engage a target from a long distance. Low-power lasers are usually intended to spoof or jam satellite electro-optical sensors, resulting in temporary blindness of the satellite. High-power lasers cause damage or destruction by overheating parts of the satellite. Most susceptible are the satellite's structure, thermal control system, and solar panels.[12]

Long-range, ground-based high-power microwave systems are feasible and, in some cases, have application as potential anti-satellite weapons. The intense radiofrequency radiation from high-powered microwaves could disable or destroy sensitive electronic components.[13] High-power microwaves are likely to damage satellites using soft kill mechanisms, exploiting the satellite's inherent design vulnerabilities, rather than hard kill such as melting or blowing up the satellite. Soft kill damage can occur in one of two ways: in-band damage or out-of-band damage. Microwaves at the same frequency as the satellite's antennas enter the antennas and damage the internal circuitry by overloading them beyond their design limits with electromagnetic energy. Out-of-band damage occurs when microwaves enter through back-doors, or apertures not specifically designed as conduits for electromagnetic energy transmission. The resulting circuitry damage is from electromagnetically induced current resulting in thermal damage.[14] Thus, ground-based directed energy weapons present serious threats to United States satellites.

The question the United States military should ask is, what is the directed energy weapons threat today and how will it expand by 2025? In the near-term the principal threat is from two potential nations: Russia and China.

In a 1997 letter to President Clinton, Russian President Yeltsin acknowledged that at one time, Russia possessed an anti-satellite (ASAT) capability but that they renounced it when they realized the futility of a first-strike notion.[15] The renunciation aside, Russia still possesses ground-based laser systems capable of threatening United States satellites. The ground-based lasers at Sary Shagan in the south-central Soviet Union are capable of killing United States satellites at altitudes below 400 km and damaging satellites at altitudes up to 1,200 km.[16]

According to the DoD's 2005 report on "Military Power of the People's Republic of China," China is working on, and plans to field, ASAT systems. Chinese government officials have publicly indicated their intent to acquire radio-frequency weapons as a means of defeating technologically advanced military forces. China is also involved in advanced, state-of-the-art research and development of laser technologies and has fielded low energy laser weapons in its own forces. Non-weapon military lasers are already widespread in the PLA. Chinese writings suggest that radio-frequency and laser weapons could be used against satellites in orbit.[17]

China is conducting research to develop ground-based laser ASAT weapons and could eventually develop a laser weapon capable of damaging or destroying satellites. Whether China has tested such a capability is unclear.[18] However, in September 2006, the Pentagon released a statement saying "China could blind American satellites with a ground-based laser firing a beam of light to prevent spy photography as they pass over China."[19]

According to Jane's Intelligence Service, China is also believed to be developing high-powered microwave sources for RF weapons and is conducting research on electronics susceptibility to high-powered microwave pulses and atmospheric propagation.[20] This research activity should raise concern within the USAF space community.

Given the current state of technology, the constant rate of improvement and discovery, and globalization, ground-based directed energy weapons with the capability of damaging or destroying United States satellites will be more widely available by 2025. In addition to the threats posed by these countries' directed energy weapons, there is some evidence of increased danger due to technology sharing. Part of the former Soviet Union's significant investment in directed energy weapons may have found its way to China through personnel and business transactions. There is also evidence showing a significant level of Chinese-Russian co-operation on weapons development, making it possible that Russia may have transferred the knowledge to develop a nuclear-reactor powered, ground-based laser with ASAT capabilities to China.[21]

Chapter 3
Satellite Vulnerabilities to Directed Energy Weapons

> "There is a tendency in our planning to confuse the unfamiliar with the improbable. The contingency we have not considered looks strange; what looks strange is thought to be improbable; what is improbable need not be considered seriously."[22]
>
> Thomas Schelling, Political Economist

Satellites are vulnerable to attack. However, the signs of vulnerability are not always clear and therefore not always recognized. Hostile actions against space systems can reasonably be confused with natural phenomena and can be explained as computer hardware or software failure, even though it might actually result from a malicious act.[23] The question with regard to directed energy weapons then is, what about a satellite contributes to its vulnerability? Three things make a satellite vulnerable--its orbit, its design, and its electronics.

Satellites orbit the earth in a predictable fashion, due largely to their speed and altitude above the earth's surface. Depending on the mission, a satellite will generally be placed in one of three types of orbits--Low Earth Orbit (LEO), Medium Earth Orbit (MEO), or Geosynchronous Earth Orbit (GEO).

Satellites in LEO orbit at altitudes between 200-500 miles. This orbit is closest to the earth's surface, but satellites in LEO travel faster than in other orbits, relative to a point on the earth's surface, with speeds in excess of 17,000 miles per hour. A majority of earth sensing satellites (i.e., environmental sensing, intelligence, and imagery) are in this orbit because it allows them to be closer to the things they are sensing, making them more efficient. Compared to other orbits, satellites in LEO are more vulnerable due to altitude and less vulnerable due to speed. This makes them more difficult to find and track, but more susceptible to damage or destruction from directed energy weapons.

Satellites in MEO orbit at altitudes between 1,000-12,000 miles. This orbit is farther from the earth's surface, providing satellites with a larger field of view of the earth than a LEO satellite. In MEO at 12,000 miles above the earth, satellites travel at approximately 8,000 miles per hour relative to a point on the earth's surface. Currently, the United States uses this type of orbit for navigation systems (i.e., Global Positioning System).

Satellites in GEO orbit at 22,300 miles above the earth's surface. In this orbit, a satellite appears to remain positioned over a single point on the earth's surface. For this reason, GEO is widely used for communications and weather satellites. Relative to other orbits, satellites in GEO are less vulnerable due to altitude and more vulnerable due to speed. Their slow speed relative to a point on the earth's surface makes them easier to find and track, but their distance from the earth makes them more difficult for directed energy weapons to damage or destroy.

Given relatively predictable orbits, satellites are vulnerable to physical destruction by directed energy weapons. However, physically destroying the satellite itself, as the Chinese did in their January 2007 ASAT demonstration, isn't necessary. Damaging or destroying any of satellite's major systems would render it ineffective. Areas of vulnerability include solar panels, which provide a large surface area that is easily targetable; optical sensors, which are susceptible to "blinding;" and thermal control of the satellite and its components.

"The power system is the most critical system on any spacecraft because nearly every other subsystem requires power."[24] Solar panels, which usually consist of solar photovoltaic cells, convert solar energy into electrical energy. As a matter of design and physics, they present a large area relative to the rest of the satellite in order to collect as much solar energy as possible. As a result, their large surface area provides an equally large target for a directed energy weapon. It is possible that a laser could heat a satellite's solar cells so much that they lose their ability to conduct sunlight into electricity."[25] As a result, the satellite's power budget might be strained to the point that the batteries could not continue to support the satellite systems. It is also possible that the effect could be less dramatic, the result being a temporary power interruption during the attack but no permanent impact to the power system.[26] Such a capability, in effect, could allow an adversary to turn a satellite "off" without destroying it or causing permanent damage.

Sensing equipment (i.e., imagery) is susceptible to damage from directed energy weapons, usually by being overwhelmed by the incident energy. Lasers can damage or destroy optical instruments, such as charged coupled devices used to record imagery, which has the immediate effect of rendering the satellite incapable of accomplishing its mission.[27] Losing space-based imagery or weather data could have a serious effect on military campaigns.

Because satellites operate in the austere environment of space, thermal control is critical. There are several different sources of thermal energy acting on a satellite--solar radiation, earth-emitted infrared radiation, and heat generated by onboard equipment. In general, there are two types of thermal control systems, passive and active. A passive system relies on conductive and radiative heat paths and has no moving parts or electrical power input. An active system is used in addition to the passive system when passive system is not adequate, for example, on manned missions. Active systems rely on pumps, thermostats, and heaters, use moving parts, and require electrical power.[28] The thermal control systems are designed to keep sensitive components within very tight temperature tolerances, even as the space environment inflicts significant temperature fluctuations. A directed energy weapon used to illuminate a satellite could impede or destroy the thermal control system, making it difficult or impossible for the satellite to protect its critical components.

Satellite electronics are vital for satellite operation and mission accomplishment, but are susceptible to damage due to radiation effects of the space environment. This damage can present itself in one of two ways--soft errors or hard errors. Soft errors occur when a transient pulse or "latchup" in the device memory that causes a detectable error.[29] Latchup occurs when an ionizing trail generates a temporary electrical short circuit by creating a path between a current source and a current sink. The effects are usually reversible and temporary and can be cleared by removing and reapplying power to the affected circuit.[30] Hard errors may be physically destructive to the memory device and the effects tend to be permanent.[31] An example of a hard error would be a permanently destroyed microprocessor or memory device. It can be difficult, however, to determine whether the cause of these problems is due to something man-made or the result of continuous exposure to the space environment.

This vulnerability to space radiation makes satellite electronics equally vulnerable to man-made radiation sources, such as high-powered microwaves. The symptoms would be similar, making it difficult to immediately discern whether the satellite had been attacked. In effect, an adversary could damage the system while maintaining plausible deniability. As the USAF looks for ways to protect its satellites from ground-based directed energy weapons, it should know that possible solutions could also enhance day-to-day protection from the harsh environment of space.

Chapter 4
What Is Nanotechnology?

"The pace of technological change is accelerating, and nanotechnology will be central to that change over the coming decades."[32]
K. Eric Drexler

While ground-based directed energy weapons pose a serious threat to United States satellites, there are emerging technologies whose methods could be used to improve existing technologies to enhance satellite protection. One problem with new technologies is that they are sometimes difficult to understand and often indistinguishable from magic.[33] In an attempt to lift the magic veil, this paper will discuss definitions of nanotechnology as well as information about the building blocks of the technology. The prefix "nano" corresponds to a basic multiplicand of 10^{-9}. In distance, a nanometer is hundreds or thousands of times smaller than a bacterium. Devices and systems at this size reach the limit of tens to hundreds of atoms.

Agreeing on a definition for nanotechnology isn't as easy as it may seem to be. Some subscribe to the view that nanotechnology involves anything that takes place at the sub-micron level. Sub-micron materials, such as hollow silica particles with diameters of 300 nm, have been used for more than 50 years and are now being relabeled as nanomaterials.[34]

Purists approach the definition differently. In 1987, K. Eric Drexler, writing in his book *Engines of Creation: The Coming Era of Nanotechnology*, coined the term nanotechnology as an analogy to microtechnology, which at the time was broadly applied to technology that manipulated matter at the micron scale. This seemed to work since nanotechnology would manipulate matter at the nanometer (nm) scale. To put the size of "nano" into perspective, a strand of human hair is approximately 75,000 nm wide. Ten hydrogen atoms placed in a row would measure approximately one nanometer in length. Generally, nanotechnology encompasses "materials that have one-dimensional properties or have properties that suddenly do not scale linearly with size reduction at the one-to-ten nanometer level."[35] A different definition characterizes nanotechnology as "a technology concerned with the production, study and utilization of lateral structures, layers, molecular units, inner boundary layers and surfaces with critical dimensions or production tolerances that extend from 100 nanometers down to atomic orders of magnitude."[36] Not to be outdone, the National Nanotechnology Initiative developed the following defining features of nanotechnology:[37]

1. Nanotechnology involves research and technology development at the 1 nm to 100 nm range.
2. Nanotechnology creates and uses structures that have novel properties because of their small size.
3. Nanotechnology builds on the ability to control or manipulate at the atomic level.

While there may not be total agreement about the definitions, there is wide agreement that nanoscale materials behave differently than they do at the macro- or microscales. An important reason for this difference is the significant change of material properties and physical phenomena. The first factor is that nanoscale dimensions approach characteristic, or quantum, waveform excitations in the material. The solid-state physics community has been exploring the properties of quantum wells in which one dimension, the growth dimension, is on the nanoscale.

The second factor is that nanostructures have a very high surface to volume ratio, which means no atom is very far from an atomic interface. Because of their chemical, electronic, and reactive properties, nanoparticles can be exploited to produce improved electronic, magnetic, optic, and biomaterials.

Definitions aside, there are two different schools or approaches for “creating” nanotechnology material. These are the “top down” and the “bottom up” approaches. The top down approach involves reducing the structure sizes of microscopic objects to the nanometer scale using machining or etching techniques, the motivation for which is determined by microelectronics where sub-micrometer processes are being developed to move toward nanoelectronics for the next generation of electrical components. The bottom-up approach uses the controlled assembly of atomic and molecular elements to create larger systems. The bottom-up method has led to the development of several self-assembly techniques which can be used to form nanostructured layers or clusters.[38]

Carbon-base materials are ideal as molecular building blocks for nanoscale systems because carbon exists in a variety of forms and provides the basic shapes needed to build complex molecular-scale architectures (i.e., planar sheet, rolled-up tubular, helical spring, rectangular hollow box, conical, etc.). One of the structures most commonly identified with nanotechnology is the carbon nanotube. First discovered in 1991, carbon nanotubes have spawned science and engineering research devoted entirely to carbon nanostructures and their applications due in large part to the combination of their structural perfection, small size, high stiffness, high strength, and excellent electronic properties. Carbon nanotubes are tubular structures of carbon, in which each carbon atom is positioned in a lattice that wraps into a hollow pipe with a diameter from a few to tens of nanometers and can be either single-wall or multi-wall. Single-wall carbon nanotubes are best described as a rolled-up tubular graphene sheet composed of benzene-type hexagonal rings of carbon atoms. Multi-wall carbon nanotubes are multiple concentric single-wall carbon nanotubes. These two structures offer several interesting properties.

First, single-wall carbon nanotubes can be either metallic or semi-conducting, depending on the chiral vector, or amount of twist, of the lattice structure.[39] A carbon nanotube is metallic if electrons can freely move to the conduction band. A semi-conducting carbon nanotube requires additional energy before electrons can move to the conduction band. This has made them a candidate material for potential applications such as nanoscale devices and quantum wires. Researchers have demonstrated working carbon nanotube transistors which are a hundred times smaller than the 130-nanometer transistor gates currently found in computer chips and collections of nanotube transistors working together as simple logic gates.[40]

Single- and multi-wall carbon nanotubes display good elastomechanical properties because the carbon atom arrangement allows for large out of plane distortions while maintaining its strength when subjected to in-plane forces. This means nanotubes will bend under an extreme amount of force, but will return to their original shape when released. The Young’s modulus for carbon nanotubes, a measurement of how much force it takes to bend a material, is about 5 times higher than for steel.[41] These characteristics point toward possibly using nanotubes in extremely lightweight, highly elastic and strong composite materials. However, while they display extraordinary resilience and flexibility at the nanoscale, it’s not clear that these properties translate to the macroscopic scale.[42]

Carbon nanotubes conduct electricity better than metals because electrons traveling through carbon nanotubes follow quantum mechanical rules. Electrons exhibit ballistic transport, essentially behaving like a wave traveling through a smooth channel with no atoms to interfere with their motion. Ballistic electron transport, supported by many studies, is considered one of the reasons that nanotubes exhibit high current density when compared with other materials at similar nanoscale. This has resulted in considerable enthusiasm over the possibility of using carbon instead of silicon in the field of nanoelectronics. Multi-wall carbon nanotubes can pass a very high current density, from 10^6 to 10^8 amperes/cm^2, without suffering adverse effects. However, long-term stability while operating at these current densities remains a question.[43] As conventional CMOS electronics will soon reach economical and physical limits, nanoelectronic technologies may provide the basis for continued scaling of electronics into the next decade, following Moore's Law, and may provide the potential for hybrid architectures combined with traditional electronics.[44]

Carbon nanotubes also have high thermal conductivity, which means they conduct heat well. Unlike metals that depend on moving electrons to conduct heat, carbon nanotubes use the vibration of the covalent bonds that hold the carbon atoms together to conduct heat. Movement of the atoms themselves transmits heat throughout the material. Research has shown the thermal conductivity of single-wall carbon nanotubes to be only second to diamond, which has the highest thermal conductivity of any material.[45]

Public research and development programs for nanotechnology are a worldwide effort and quickly building momentum. A 2005 article in the *Journal of Nanoparticle Research* indicated that at least 60 countries have initiated nanotechnology initiatives and that "worldwide investment in nanotechnology research and development reported by government organizations has increased approximately nine-fold in the last eight years, from $432 million in 1997 to about $4.1 billion in 2005."[46] In the USAF, approximately 70 percent of the Air Force Office of Scientific Research's basic research funds are put toward this work, with the remaining 30 percent going toward Air Force Research Laboratory (AFRL) research programs.[47] The corporate world is also investing in nanotechnology. According to a report by Innovest Strategic Value Advisors, an investment group that closely monitors nanotechnology, advanced materials and nanotechnology investments increased from $68.2 million in the first quarter of 2004 to $83.5 million in the first quarter of 2005, a 22.4 percent increase."[48]

While much of the research has focused on the technology's physical properties and potential applications, some experiments have produced results that have raised concerns, especially since many products using nanomaterials are already on the market and more are on the way. Potential hazards to human health from the uncontrolled release and inhaling of nanoparticles or nanomaterials has thus far been based on analogies and the results of studies on the effects of ultrafine particles. In a DuPont study, fifteen percent of a rat population died due to lesions caused by nanotube clumps in their lungs. In a separate study conducted by Southern Methodist University, researchers found that buckyballs can disrupt fish brain cell membranes.[49] Though by no means conclusive, these studies and others highlight the fact that there's still much to learn. To that end, the Environmental Protection Agency has plans to lead a continued, comprehensive research effort to determine the risks manufactured nanomaterials pose to humans and the environment due to their composition, reactivity, and unique size.[50]

Chapter 5
Applying Nanotechnology to Satellites

Given that the United States is highly dependent on satellites for daily life and military operations and that directed energy weapons pose serious threats to those satellites, the United States must harness emerging technologies to mitigate the threat. Nanotechnology may provide solutions that will enable the United States to mitigate the threat from directed energy weapons.

Hard, durable surfaces with coatings that can withstand extreme temperatures, abrasion, and wear are especially important for space vehicles. The satellite's surface would be one of the first parts to feel the impact of directed energy weapon's thermal or electromagnetic effects. Depending on its construction and design, the surface coating would either reflect, absorb, or transmit the incident energy or would perform some combination of the three. One-hundred percent reflection would be the ultimate protection because all the energy would be rejected; less than complete reflection would result in some absorption which would show as heat build-up, material degradation, or burn through.

Scientists can grow carbon nanotubes that exhibit reflective properties. These structures, called purified metal single-wall nanotubes, are grown as a mix of two isomers, metallic and semi-conducting.[51] The metallic nanotubes in the mixture have much better electrical conductivity and reflectance, but one of the biggest problems is the difficulty of separating the metallic nanotubes from the semi-conducting ones.[52] The resulting mixture isn't pure and must be further processed to remove the semi-conducting nanotubes and the other unwanted carbon particulates. When grown, the nanotubes are contaminated with a residual catalyst which must be removed in order to isolate the metal nanotubes. This is often accomplished using a strong acid which can also negatively alter defects on the nanotube surfaces and their reflectivity. This purification process induces major material and time costs to fabrication.[53]

While completely reflecting thermal and electrical energy would be preferred, dispersing it across the surface would also provide protection. The AFRL is managing a research program that uses carbon nanotube membranes, or Buckypaper, for electromagnetic shielding and to enhance lateral thermal conductivity. Buckypaper is a thin membrane, approximately 10-15 µm thick, of roped carbon nanotubes which are incorporated with composite structure.[54] The carbon nanotube ropes in Buckypaper are either randomly oriented or aligned in the same direction. The alignment determines the electrical and thermal properties. Randomly oriented Buckypaper has shown electrical conductivity in the range 450-670 Siemens per centimeter (S/cm) and thermal conductivity of 56 Watts per meter Kelvin (W/mK).[55] The electrical and thermal conductivities displayed by directionally aligned Buckypaper are 769-1,040 S/cm and 117 W/mK, respectively. A single layer of randomly oriented Buckypaper has an effective electromagnetic attenuation of 21dB/mil in the 4 to 12 GHz frequency range.[56] Buckypaper membranes are being investigated for aircraft lightning strike protection, but could have application to help satellites from electromagnetic events.[57]

Researchers have learned that vertically arranging carbon nanotubes in a sub-surface volume allows it to remove heat from the surface material. Using a process called Chemical Vapor Deposition, scientists can produce several square inches of vertically aligned carbon nanotube forests. In this form, carbon nanotube forests could be applied beneath a reflective coating on the satellite's surface for improved thermal dissipation. The commercial industry is pushing research teams to increase the size of the carbon nanotube forests they can grow because of the potential benefits as field emitters for the plasma screen television market. As such it is believed this process will be fully mature for commercial use by 2025.[58]

Carbon nanotube forests also offer a futuristic use that, though not tested, seems possible in theory. When energized with a small voltage at low pressure, carbon nanotube forests will emit electrons, which is the basis for their use as field emitters for plasma screen televisions. The emitted electrons ionize the atmosphere, generating a plasma shield around the structure. If the incident electromagnetic energy is short duration, the plasma should dampen most of the energy.[59]

In conjunction with the AFRL, the University of Dayton of Dayton Research Institute has developed a method to tailor the electrical conductivity of polymer materials used to build commercial and military aerospace components. This project transforms almost any polymer into a multifunctional material capable of carrying or dissipating significant electrical charge. Specifically designed carbon nanotubes with the current carrying capability of copper but at a much lower density, on the order of 50 to 150 nm in diameter, were carefully dispersed into a polymer matrix resulting in an electrically conductive polymer composite effective over the range 10^{-6} S/cm to 10^{2} S/cm. Researchers believe this technology is ready for commercialization and easily scalable to large batch production[60]

Slightly outside the pure definition of nano, the AFRL has been working with hollow silica particles, approximately 300 nm in diameter, as a pigment for satellite thermal control coatings. This technique uses the low refractive index of a void (i.e., an empty space) to promote energy scattering. The surrounding silica shell is transparent to ultraviolet light and is space-stable. The result is a broader spectrum of reflectance that extends into the ultraviolet frequency range and increased space durability because the particles don't absorb ultraviolet energy.[61]

Space presents an extremely harsh environment for satellites and the effects are especially severe for electronic components. Electronic components aboard a satellite in orbit around the earth encounter high-energy particle radiation many orders of magnitude higher than do similar components on Earth. The future of space nanoelectronics lies with a combination of commercial and radiation-hardened Complimentary Metal-Oxide Semiconductor (CMOS) circuits.[62] "Researchers are adapting commercial designs for space use with minor loss of performance, and modifying commercial processes to improve the radiation tolerance of components."[63]

The Defense Advanced Research Projects Agency (DARPA) and the National Reconnaissance Office (NRO) are working on similar efforts to improve the radiation hardening of CMOS circuits for use in space. Under a two-phase program called Radhard by Design, DARPA; partnering with the DoD Trusted Foundary Program which enables access to leading-edge semiconductor technologies, design libraries and design circuit cores; plans to develop and demonstrate techniques for fabricating strategically radiation hardened integrated circuits. Phase One seeks to demonstrate the efficacy from a technology standpoint and has the goal of getting circuits to withstand radiation total doses of 2 Mrad and dosage rates of 10^{10} rad(Si)/sec; with less than 10^{-10} errors/bitday. Phase Two will refine the data and techniques learned during Phase One to design and construct test structures and integrated circuit devices.[64]

In a similar effort, the NRO's Advanced Science and Technology Space Program Office is conducting a research and development effort that uses carbon nanotubes to enable a one gigahertz microprocessor capable of surviving the highest anticipated radiation levels. Circuit fabrication is compatible with existing CMOS processes and takes advantage of the electrical properties and strength of carbon nanotubes to create an electromechanical switch, a technique called Complementary Carbon Nanotube Logic (CCNL).[65]

CCNL enables switching by applying an electric field between the read/write electrode and the carbon nanotube fabric causes deforms the fabric until it contacts the read/write electrode, which turns the device "on." At this point the electric field can be turned off--van der Waals forces hold the carbon nanotube fabric in place. Reapplying an electric field is required to release the contact with the electrode. CCNL provides three key results. First, the switched bits are nonvolatile. Second, because van der Waals forces hold the carbon nanotube fabric in contact with the electrode, there is no leakage current and no standby current is needed. Lastly, CCNL makes it possible for one electromechanical switch to replace six to twelve memory transistors.[66] Based on the current program timeline, radiation-hardened microprocessors that use CCNL will be ready for space flight qualification in the Fiscal Year 2011 timeframe, as long as the project continues on its current path, with continued funding and no major setbacks.[67]

In addition radiation hardening, nanomaterials are also being investigated for their potential to protect satellites from electromagnetic interference. Through research, Northrop Grumman has demonstrated the feasibility of using nickel nanostrands as an electromagnetic shield for satellites.[68] Nickel nanostrands are made from strands of sub-micron diameter nickel particles that are linked in chains from microns to millimeters in length. They are very similar to multi-wall carbon nanotubes, but have the electromagnetic, chemical, and metallurgical properties of nickel.[69] Electromagnetic shielding that uses nickel nanostrands performs almost as well as current carbon fiber and aluminum shielding and nickel is proving to be an easy material to work with. There are, however, some drawbacks. Because it's a new material for this type of application, it could potentially require new processes. Also, nickel is a heavy metal which is leading to concerns about possible toxicity from particles released during the milling process.[70]

Chapter 6
Conclusion

"New anti-access threats and threats to our military, civil, and commercial space systems are creating new challenges to overcome. In order to continue providing our forces, and those of our allies, the level of support on which they depend, we must modernize our space forces and pursue truly transformational capabilities."[71]
General Lance Lord

The United States has long been dominant in space. Controlling the "high ground" has provided information superiority and significant force enhancement capabilities to the military.[72] This dominance has overshadowed the vulnerability of United States satellites. By studying United States capabilities, other countries have become increasingly aware of the tremendous military advantages that space-based assets provide the United States and are beginning to challenge the long-held peaceful use of space.[73] The January 2007 Chinese ASAT demonstration is the latest example of how easily US space dominance can be threatened. Other examples were highlighted in a National Air and Space Intelligence Center report which stated that China and Russia have either built or are developing the technology to build ground-based directed energy weapons.[74] By 2025, continued technological discovery and improvement, globalization, and technology sharing will contribute to increasing the threat, making these weapons equally available to state and non-state actors.

Ground-based directed energy weapons provide adversaries with the means to attack United States satellites. Though an adversary may have many reasons or objectives for taking such action, two objectives are plausible. First, an adversary could use ground-based directed energy weapons to destroy United States satellites in order to degrade or deny United States capabilities, military, economic, or informational. Successfully destroying a satellite in this manner might accomplish an adversary's objectives, but it would also leave evidence that would allow the United States to trace the attack to the adversary. This would almost certainly result in some sort of retaliatory action. Second, an adversary could choose to degrade a United States satellite or satellite capability over time. This might be accomplished by employing ground-based directed energy weapons over some period of time at lower output power levels than necessary for complete destruction. Because many of the effects experienced by the satellite would be similar to the effects encountered as a result of operating in space, it would be difficult for the United States to pinpoint the cause. Not only would the adversary achieve the desired effect, he would also be able to maintain plausible deniability.

Does nanotechnology help protect satellites against these attacks? According to some researchers and available literature, nanotechnology and nanomaterials can technically be used to protect satellites against the effects of directed energy weapons. However, this has yet to be sufficiently demonstrated. The research and testing of this specific nanotechnology application is in its early stages. Much more work needs to be done to understand how the unique properties of nanomaterials can be harnessed to protect satellites against directed energy weapons threats. This will require the USAF to make this research thrust a priority and maintain it as such, which translates into a long-term financial commitment. Recent comments by Congressional members in the aftermath of the Chinese ASAT demonstration may help raise the priority of this research.[75]

Though nanotechnology isn't yet mature enough to be considered a solution for protecting satellites from ground-based directed energy weapons, the USAF shouldn't ignore it. On the contrary, the USAF should continue investing in nanotechnology research and development to understand and harness its capabilities for protecting critical satellite systems because nanotechnology will have a significant impact on future satellite design.

Though most nanotechnology work is still in basic research (i.e., 6.1), it clearly is a high-risk/high-payoff and transformational space capability critical to continued space supremacy. By 2025 it will have a significant impact on United States satellites, touching on the structure and functions of all satellites in the form of radiation-hardened microprocessers, enhanced surface coatings, and reduced satellite size and weight.

In the near-tem, radiation-hardened electronics and surface coatings are likely to provide the greatest benefits toward protecting satellite systems from directed energy weapons. Structural enhancements derived from macro-scale nano-structures are likely at least 10-15 years away.

Nanotechnology research will likely be more relevant for the United States government than for the commercial sector. As with all research, some of the efforts will pay off and some won't, but it's too early to know which areas will have success. Therefore, USAF must make continued research and development into nanotechnology for satellite applications an investment priority and must pay equal attention to all of these areas. The USAF will need to guide the research effort to ensure work is done to meet its stated needs and requirements. Undoubtedly, breakthroughs will happen, but not necessarily in areas where the USAF is invested or currently knows much about. This will require the USAF to stay current with nanotechnology research and development efforts around the world, in the academic, commercial, and governmental arenas, and be prepared to adapt the results to pursue applications critical for the nation's space systems. This means a long and expensive commitment, but one that's necessary if the USAF and the nation are to maintain space supremacy. Failure to do so will leave the nation in a position from which it will be difficult, if not impossible, to recover.

Notes

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[54] Dr Jennifer Fielding, program manager with the AFRL Structural Materials Branch, Wright-Patterson AFB, OH, email correspondence with author, January 19, 2007.
[55] Editor's note: The unit Siemens per centimeter (S/cm) is considered by many to be obsolete. However, this unit of measure was used by the author and is retained here. The more common unit, Siemens per meter, can be calculated by dividing the S/cm value by a coefficient of 100. Some texts refer to Watts per meter Celsius, instead of Watts per meter Kelvin. As one Celsius degree is equal in magnitude to a Kelvin degree, the reader should note that these units are equivalent. .
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