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Space Debris and Other Threats from Outer Space

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Joseph N. Pelton

Space Debris and Other Threats from Outer Space

Guest Editor: William H. Ailor

Joseph N. Pelton
Executive Board, International Association for the Advancement of Space Safety, Arlington, USA

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ISU (Society) Page

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1. Serious Threats from Outer Space

Joseph N. Pelton[1]

(1) 40th Street. North 4025, Arlington, 22207, USA

Joseph N. Pelton
Email: joepelton@verizon.net

Abstract
Have you ever wondered if you might be hit by a piece of space junk falling out of the sky? Well not to worry. The chances of being hit by a piece of orbital debris or a meteorite are fewer than your getting the world's rarest disease or being killed by a falling coconut if you only visited a tropical paradise for only 1 h in your entire lifetime. In over a half century of space activities there is perhaps one instance of a cow being killed in Africa and that was many decades ago. More recently in 1997 a woman was reportedly brushed on the shoulder by a lightweight fragment of space debris falling from the skies.

This must be the context of our thinking…the vast new dimensions of our science and our discovery… and of the awful majesty of outer spac

—Adlai Stevenson at Harvard University (196

What Space Threats Should Concern Us Most?

Have you ever wondered if you might be hit by a piece of space junk falling out of the sky? Well not to worry. The chances of being hit by a piece of orbital debris or a meteorite are fewer than your getting the world's rarest disease or being killed by a falling coconut if you only visited a tropical paradise for only 1 h in your entire lifetime. In over a half century of space activities there is perhaps one instance of a cow being killed in Africa and that was many decades ago. More recently in 1997 a woman was reportedly brushed on the shoulder by a lightweight fragment of space debris falling from the skies.

But there is still a very good reason for you to read this book. In fact, there are serious threats fro space that are actually of mounting concern that you should know about and what actions could be taken to forestall these threats. The growing amount of space debris in the skies could make it difficu in the future to access space for many crucial applications, such as communications, navigation, remote sensing, weather forecasting, military surveillance, nuclear monitoring, or even space exploration. A surprising amount of the world scientific, economic and military activities are now based on spacecraft operations. Solar radiation that penetrates the ozone layer can and indeed does cause skin cancer, and currently occurring changes to the ozone layer are elevating this concern. The most intensive cosmic radiation from gamma rays if unchecked and sustained can also trigger harmf and even bizarre mutations of our genes so as to prevent healthy and normal reproduction.

~~Solar flares or coronal mass ejections could kill astronauts or wipe out our electrical grids in~~ a powerful and instantaneous way, as happened as recently as March 1989. Although very unlikely, a massive and potentially harmful near-Earth asteroid could destroy much of life on Earth, as was the case with the so-called K-T event (i.e., the Cretaceous Tertiary Mass Extinction Event) that fortunately occurred some 65 million years ago. This single calamitous cosmic occurrence caused between 65 and 70 % of all species on Earth to be killed—including the dinosaurs—in what is known simply as a mass extinction event [1]. On the scale of bad things to happen, this would be very, very bad indeed.

However, let's start at the beginning to recap what has happened since the Space Age began. Let' quickly review why today we know much more about cosmic threats than we ever did before, and wh in learning about space through sending probes aloft we have managed to create some serious new problems of our own making.

At the Beginning of the Space Age

The age of spaceflight began well over five decades ago on October 4, 1957, with the launch of *Sputnik*. When this first spacecraft was launched into Earth orbit, it was hailed as a major advance in human scientific and engineering achievement [2]. The stark realities of the Cold War between the Soviet Union and the United States, however, also painted this first space launch in a vivid military context as well. This Soviet coup in space jolted a vibrant American space program into action. In jus a few years there were a number of spacecraft and missile launches occurring in both the United Stat and the U.S.S.R. [3].

Back in 1957 little thought was given to what might be the risks associated with *too* many spacecraft launches. Over a half century later, however, the accumulation of human-built space debri in orbit is now a quite real problem. "Space junk" is now increasingly seen as a creditable threat to humanity's longer term ability to access and utilize space. In literally dozens of ways humanity is dependent on satellites to communicate, to navigate, to track killer storms, and to provide an effectiv military defense capability. "Space junk" every day and in every way is becoming a true threat.

If we could effectively stop the creation of all new space debris, we would still not have solved th problem. In fact, the accumulation of debris, just due to collisions from existing space junk, 50 years hence would still be significantly worse. But in fact we are still launching more and more satellites, and space debris continues to mount.

Visionary Ideas are Easy to Often Easy to Dismiss

About a quarter of century ago the possibility that space debris might constitute a tangible threat to our longer term space programs was raised by space scientists and especially by Donald Kessler. Unfortunately at the time this was largely treated as simply a laughable idea. No one is laughing now Figure 2.1, later in the book, shows rather graphically how this problem seemed to sneak up on us ov the past few decades. Human skepticism often serves us well, but sometimes it smothers the most important new ideas. In the area of space this has often been the case.

Robert Goddard, the father of modern rocketry, and other innovators have taught us that there is often a thin line between longer-term vision and what are generally considered as outlandish or quixotic ideas.

In 1919 the Smithsonian Institute published a report by Robert Goddard outlining his plans to launch liquid-fueled rockets. In this treatise he indicated how such rockets could eventually reach the

Moon. In 1920 the *New York Times,* with more arrogance than scientific knowledge, responded by running a derisive editorial to call Robert Goddard “The Moon Man” for his audacious claim that one day rockets would carry human adventurers to the lunar surface. Goddard persevered and successfull launched his first liquid-fueled rocked on March 26, 1921. Goddard famously said: “Every vision is a joke until the first man accomplishes it. Once realized, it becomes commonplace.” But it was not unt a day after the Apollo Moon landing in 1969 that the *New York Times* ran a correction and an apolog for its errors in the 1920 editorial—albeit some 49 years late [4].

Today space debris is no longer a “laughable idea” More and more people will have the opportunity to fly into space on governmental and commercial spacecraft in the twenty-first century. Up until the end of 2012 only about 500 people have flown into space. As twenty-first century commercial space industries mature, we will actually see more and more “citizen astronauts” flying on sub-orbital flights or even going into orbit. Unfortunately, for all future astronauts, whether government or private spacefarers, the risks to them from space debris will mount as they ride on rockets or live aboard space stations. For most people who will never venture into space, there are sti areas of concern. The space debris actually does come down and sometimes at unfortunate times and places.

The Mounting Problems of Space Debris

Right now the biggest risk is that vital communications satellites or other key spacecraft can be destroyed by space debris traveling at speeds in excess of Mach 20. The ability of space debris to knock out spacecraft or injure or kill astronauts in space must now be taken seriously. There is also a concern that falling debris could cause property damage or even kill, but this probability fortunately very, very small. The point is that now is the time to address all of these concerns.

How was this problem created? Over a period of time more and more space launches occurred. With these launches various types of debris began to accumulate. There are now explosive bolts, exploded fuel tanks, paint chips, upper stage rockets, rocket fairings that covered satellites that were being deployed in higher orbits, defunct satellites, and finally—in the last few years—debris from colliding satellites and even debris from a defunct satellite deliberately being hit by a ground-based missile.

At first there was only a minor amount of debris. But over the decades the debris accumulated. In time scientists began to understand that all this debris was beginning to pose a serious risk and a spreading “pile of space rubble” was accumulating—particularly in certain orbits. This now huge amount of space junk has now begun to threaten human longer-term access to space. Just as we now worry about the “sustainability” of life on Earth due to greenhouse gases and over population, we are worried about the “sustainability” of access to space due to space debris.

An enormous quantity of human-made debris is swirling around Earth, particularly in low Earth orbit (LEO). Scientists have determined that there are literally millions of debris elements in Earth various orbits—primarily LEO, but also Medium Earth Orbit (MEO) and geosynchronous earth orbit (GEO)—all of which have begun to fill up with space junk.

Many of these elements—literally millions of them—are of microscopic size and involve things such as chips of paint. It is currently estimated, however, that there are between 500,000 to 750,000 objects in orbit that are on the order of 1 cm in size. The first reaction of most people is something like, whew, those are really little guys that surely cannot do much harm.

Figure 1.1 shows a 1-cm puncture in the high gain antenna on the Hubble Space Telescope. A chi of paint traveling at 17,000 mph or over 28,000 kmph can put a serious crack in the window of a spac shuttle or rupture an astronaut’s spacesuit. An element as large as 1 cm can do substantial harm, and something as large as 10 cm (4 inches in size) could potentially destroy a communications or remote sensing satellite or some other valuable space resource. Shielding or armor on satellites against debri is really effective only up to about 1 cm.

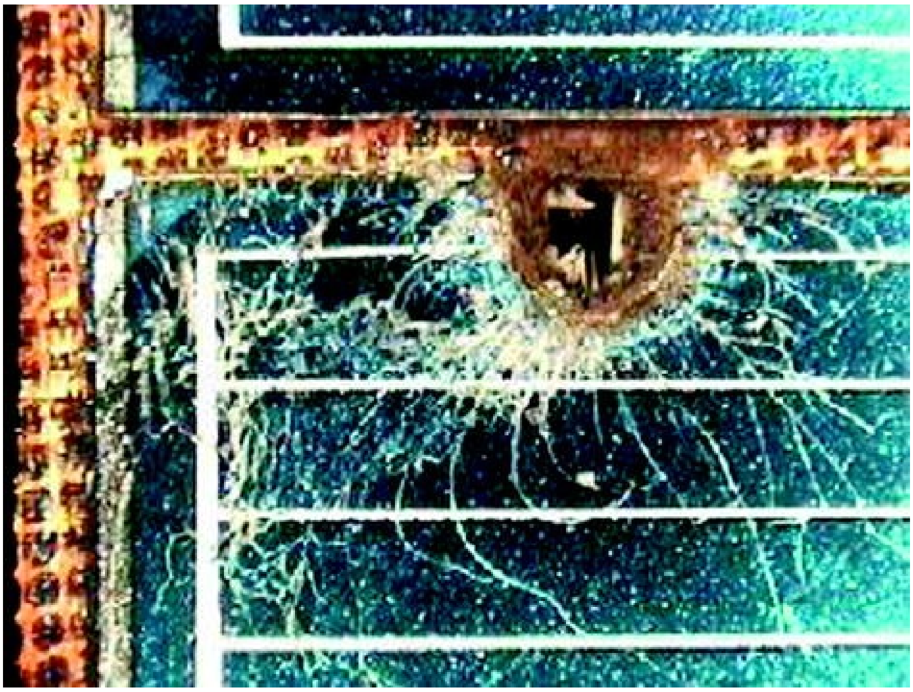

Fig. 1.1 Puncture in Hubble Space Telescope array cause by space debris (Image courtesy of NASA)

The Challenge of Tracking Space Debris

In 1980 there were just fewer than 5,400 sizeable objects (i.e., greater than 10 cm in size spinning around in low-Earth orbit) that were being actively tracked. By 2010 the number of large space debri objects had increased to 15,639. Today there are some 22,000 objects that are 10 cm or larger being tracked by the U. S. Air Force Space Surveillance Systems (AFSSS). This is a combination of ground based plus several satellite-based tracking systems.

The current Very High Frequency (VHF) radar is being upgraded by a new “space fence” radar system operating in the S-band that will provide much greater resolution. (See Fig. 1.2) The Air Forc Space Surveillance System which was first implemented in 1961, in part as a missile tracking system that is now aging. Thus the Air Force has now contracted for a debris tracking system that is to be fully implemented by 2017. Tests carried out in March 2012 confirmed the new tracking capabilities and the effectiveness of the overall design of this so-called Space Fence by accurately tracking space debris elements. The details of this system will be discussed in greater detail in Chap. 2 [5].

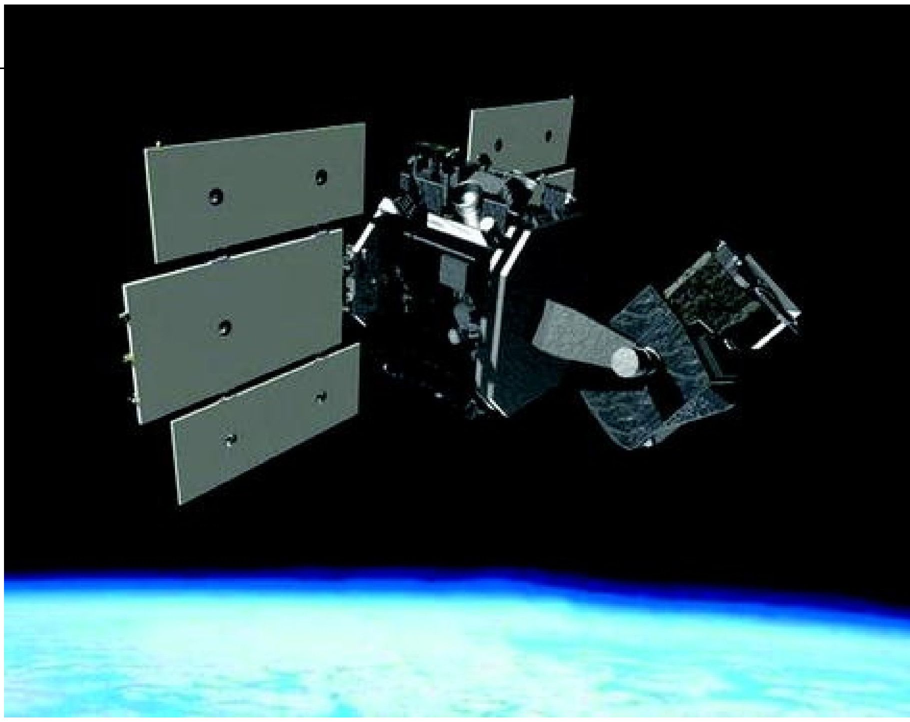

Fig. 1.2 U. S. Air Force satellite used for space debris tracking (Graphic courtesy of the U. S. Air Force)

Of the 22,000 objects being tracked by the current AFSSS about 1,000 objects represent functional satellites, but the rest are "defunct" satellites or other forms of space junk.

The largest pieces of debris are most important to track for at least two reasons. First, these bigger objects can literally destroy the International Space Station (ISS) or other billion-dollar space facilities because of their huge kinetic energy, equivalent to large bombs. Secondly the collision of large space objects—regardless of their operational status—can create perhaps many thousands of major new debris elements. Big space objects colliding with each other is the number one problem we must seek to avoid, although it is imperative to find ways to reduce the formation of any type of new debris as well as a way to remove orbital debris from orbit in a systematic way regardless of size.

Over 6,300 Tons of Debris in Earth Orbit

The build-up various sized debris elements over the past two decades has now become alarming. The following chart from NASA explains the size of the various types of debris and their relative distribution. Fortunately most of the hundreds of millions of debris elements now in Earth orbit represent microscopic elements such as chips of paint. These microscopic elements are just the size of a grain of salt, but when traveling at speeds of perhaps 28,000 kmph (or about 17,500 mph), still pack quite a wallop, a wallop sufficient to penetrate the spacesuit of an astronaut or perhaps pit or even penetrate a window on a space vehicle (See Fig. 1.3).

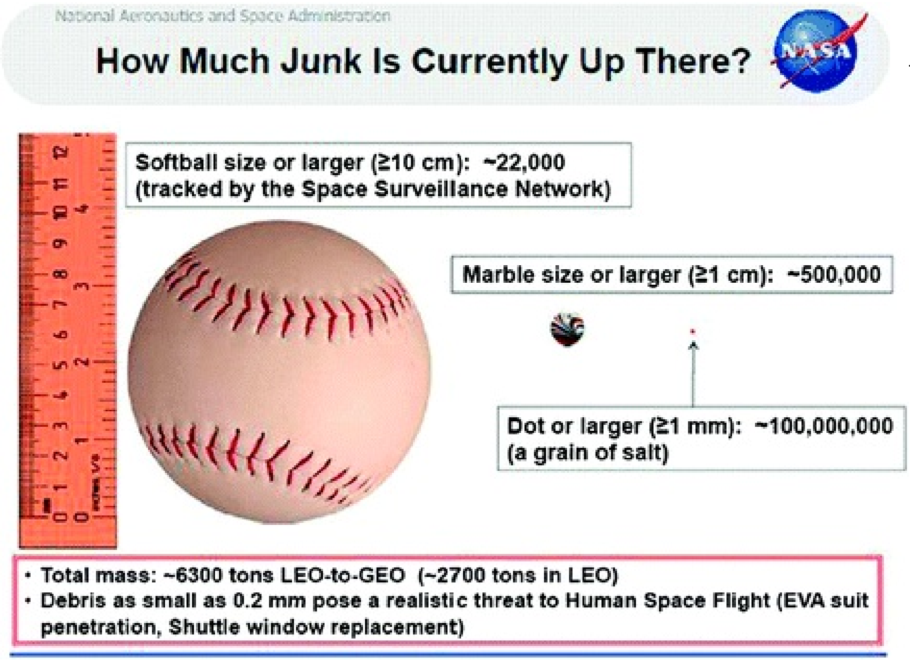

Fig. 1.3 Breakdown of the 6,300 tons of mass in Earth orbit (Graphic courtesy of NASA.)

The nature of this problem, i.e., big objects colliding, has been vividly demonstrated within the past decade. First there was the collision of the operational Iridium 33 mobile communications satellite and the defunct Russian Cosmos 2251 weather satellite. Then there was the occasion when a Chinese anti-missile deliberately hit a defunct Chinese weather satellite. In both events on the order o 3,000 new tracked debris elements were created and resulted in a new level of threat to the International Space Station. In short these two events led to an impulse increase in “trackable” space debris objects by some 6,000. The Fig. 1.4 creates a representation of the debris created by the missil hit on the Feng-yun weather satellite and how this new swarm of debris relates to the orbit of the International Space Station as represented by the “white orbit” in the illustration.

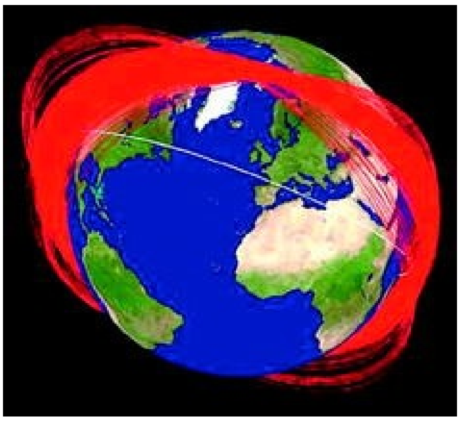

Fig. 1.4 Artist representation of orbital debris created by the destruction by missile of the Feng-yun weather satellite (Graphic courtesy of NASA Space Debris Program Office)

The greatest concern with regard to space debris is the so-called “Kessler Syndrome”. This is a condition whereby colliding space junk creates a deadly ongoing avalanche of more and more debris elements. Space scientist Donald Kessler in 1978 wrote a paper that warned that this type of problem could actually occur [6].

His paper explained how an ongoing series of collisions of space debris could lead to a cascade effect whereby the problem would become worse and worse once a “tipping-point” had been reached Kessler’s warning—now known as the Kessler Syndrome—explained that once this tipping point was

reached the problem would grow out of control. His early predictions of this effect, however, were no
taken too seriously.

The truth is that important forecasts about space, from those of Sir Arthur Clarke concerning global satellite communications to those of Robert Goddard about lunar vehicles with human crews, were ridiculed or ignored when first made. Now, as the space debris problem has grown just as Kessl forecast, this problem is widely acknowledged around the world [7]. In fact, a report by the U. S. National Research Council in September 2011 concluded that the problem was “worse than had been early thought” [8].

Currently, the only mechanism for removal of debris is orbital decay through atmospheric drag and Earth’s gravitational attraction, which ultimately leads to re-entry. Unfortunately, such gravitational removal of debris only works effectively for low-Earth orbits. For satellites in medium Earth orbit above the Van Allen Belts, it takes hundreds to thousands of years for objects to re-enter Earth’s atmosphere. For geosynchronous orbits, that are essentially one-tenth of the way to the Moon and where the pull of gravity is only 1/50th of that at Earth’s surface, the gravitational decay process for debris elements is essentially negligible. For a geo satellite to come down would literally take many millions of years. Consequently, there is currently no effective removal mechanism for MEO o GEO debris elements unless there were to be active rockets designed for controlled de-orbit.

As noted in Fig. 1.3 the build-up of debris elements in Leo orbit particularly in the polar area has now reached the incredibly high number of 2,700 tons, which far exceeds the gravitation degradation of a few tens of tons a years. Figure 1.5 shows that Leo polar orbits in particular are now extremely congested. This figure shows in some detail the debris that is being tracked in LEO by the U. S. tracking system.

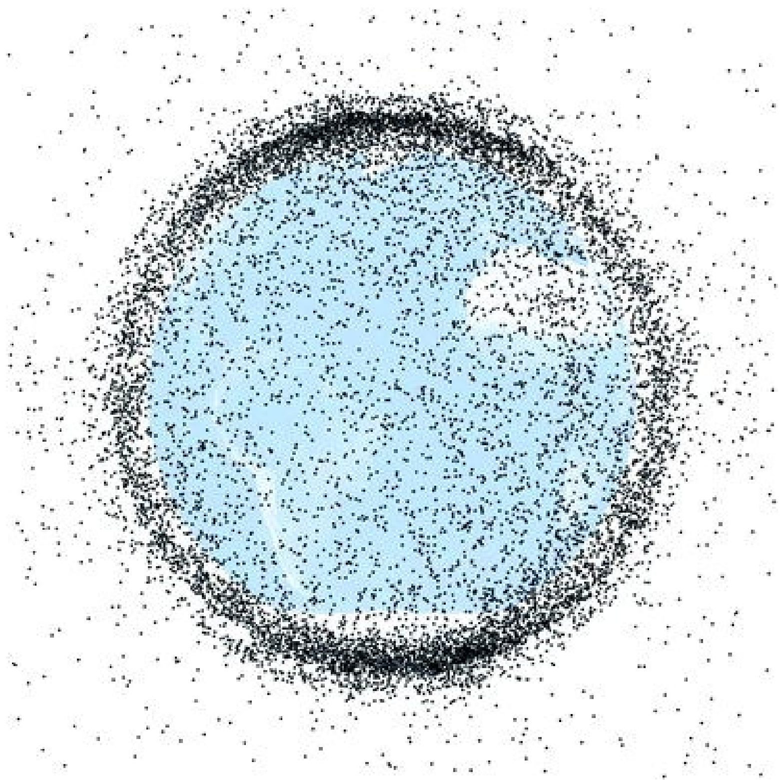

Fig. 1.5 Debris elements in LEO pictured over South America and Africa (Image courtesy of NASA Space Debris Projects Office)

Debris is Increasing Faster than its Decay

Historically, the creation rate of debris has outpaced the removal rate by a fairly wide margin. This is leading to a net growth in the debris population in LEO at an average rate of approximately 5 % per year. Although this may not sound like much, it means the amount of debris in orbit is now very substantial and based on past experience will likely continue to grow.

Although the low-Earth debris orbits in effect “spread out” as they orbit Earth they come much closer together over the North and South Polar Regions and thus serve to increase their chances of collision by a considerable degree.

To put the problem into a more accurate “visual perspective”, it important to note that because th scale used in Fig. 1.4 is actually something like 10 million to one, the risk of collision is indeed muc less than it would appear. It’s like when one looks in a rear view mirror and it says that “vehicles ma be closer than they appear”. Recognize that the same is true here. The debris elements shown above, fact, are 10 million times further apart and that the volumetric space of Earth and space within whic the orbiting debris is depicted here is 10^{21} times (or 1,000,000,000,000,000,000,000 larger).

A major contributor to the current debris population has been fragment generation via explosions of fuel tanks and more recently by collisions. It is hoped that future explosions can be minimized by venting of fuel prior to the operational end of life of satellites—as recommended by the current mitigation procedures. It may take a few decades for the practice to become implemented widely enough to reduce the explosion rate, which currently stands at about four per year.

Several environment projection studies conducted in recent years indicate that, with various assumed future launch rates, the debris populations at some altitudes in LEO will become perhaps completely compromised. In these projections collisions could take over as the dominant debris generation mechanism, and the debris generated will feed back into the space environment and induc more collisions—in short, an in-orbit cascade that creates more and more debris.

According to studies conducted by J-C Liou and N. L. Johnson, the most active and endangered LEO region is between the altitudes of 900 and 1,000 km, and, even without any new launches, this region is highly unstable. It is projected that the debris population (i.e., objects 10 cm and larger) in this “red zone” will approximately triple in the next 200 years, leading to an increase in collision probability among objects in this region by a factor of ten [9]. In reality, the future debris environme is likely to be worse than as suggested by Liou and Johnson, as satellites continue to be launched into space. In late June 2012 this author was at the Kennedy Space Center where the Delta IV Heavy vehicle launched a surveillance satellite into orbit and this satellite with on-board positioning fuel alone weighed some 30 tons.

The Liou and Johnson paper concludes that to better limit the growth of future debris populations active debris removal (ADR) from space needs to be considered. The various technical and operation options that are being considered for such removal are discussed later in this book.

The problem of tracking debris, of course, becomes more difficult as one moves further away fro Earth in higher orbits. In the geosynchronous geostationary orbit, for instance, the minimum size tha can be tracked is 30 cm in contrast to about 10 cm in LEO. Among the tracked pieces of debris, there are about 200 satellites abandoned in geostationary geosynchronous orbits occupying or drifting through valuable orbital positions and posing a collision hazard for functional spacecraft. Fortunately accurate tracking systems, charting of possible conjunctions that could result in high velocity collisions, and active collision avoidance maneuvers minimize these risks. The Satellite Data Association (SDA) that will be discussed later now plays a key role in this activity.

As noted earlier the survival time of the debris in orbit continues to changes with the higher orbit Objects in 1,000-km orbits can exist for hundreds of years. At 1,500 km, the lifetime can go up to thousands of years. Objects in geosynchronous or super synchronous orbits can survive for millions o years.

And there are other realistic space threats that also need to be taken seriously. Although space debris has now become a top issue that must be dealt with in order to sustain useful access to space, this is just one of the “threats” that must be addressed. The harsh environment of space puts satellites space stations, and even rocket launchers at risk. These risks include, micro-meteorites, solar flares, coronal mass ejections (CMEs), and cosmic radiation. These natural hazards can disable or totally destroy functioning satellites and spacecraft as proven by past events. These events are less under ou control than space debris, but shielding and other protective actions can help protect against these types of hazards as well. Currently these natural threats pose a higher risk level than space debris, bu over time space junk, unless aggressively attacked by Active Debris Removal (ADR), will become a higher level threat.

Potentially Hazardous Asteroids and Mass Extinctions

What is often not mentioned is that these natural debris and natural phenomena could actually pose threats even to people on the ground. Solar flares, coronal mass ejections, cosmic radiation, meteorites, asteroids and comets, and yes, even space debris can pose risks to people on the ground. These risks to people right here on Earth’s surface will be addressed in later chapters of this book. Most of these risks would involve only a limited number of people.

But there is one type of natural hazard that not only threaten astronauts and spacecraft but could indeed threaten life on Earth in a big way. This threat is known as Potentially Hazardous Asteroids (PHAs), and this is in no way just a “theoretical” risk. Actually this is something to be taken quite seriously. It is believed that an asteroid, rich in the poisonous substance iridium and perhaps 10 kilometers in diameter, plunged into Earth some 65 million years. When it impacted Earth it created huge cloud around Earth that blocked out the Sun for several years. As a result the dinosaurs and well over a third of all life-forms on the planet died off. Another asteroid or large comet could do equal damage to humans and other life forms if it were to hit Earth in future years.

Even a smaller asteroid such as Apophis, which is about 300 m in diameter, if it were to hit in an ocean near a large city could bring death to tens of millions of people, and if it were to hit in, say, the United States it could possibly wipe out an entire state. Fortunately Apophis is scheduled to fly by in 2029 and 2036 and then be on its way [10]. This very real subject of “killer asteroids and comets” an what we are doing to be ready for them, will also be addressed in later chapters.

In short after addressing the problem of growing amounts of space junk the discussion will turn to various types of natural threats in and from space and even potential threats to people here on the planet’s surface. In all cases the discussion will go beyond identifying risks to explore protective actions. It is not enough to just explain that there are threats. There are indeed a number of actions being taken to protect the billions of dollars in space assets from both space debris and natural space hazards. In fact, military satellites deployed in strategic regions are even hardened against nuclear weapon explosions, electronic magnetic pulses (EMPs) and cosmic radiation. As new techniques are developed to protect space assets and extend space situational awareness, these solutions can presumably be applied to help protect people here on Earth as well.

Purpose of the Book

The purpose of this book is to provide a good overall understanding of the nature of the various space threats and what techniques, new technologies and strategies can be developed to cope with these various hazards.

In addition there are programs operated by space agencies and research centers around the world related to protection of humanity against natural threats from space. These include:

- Operation of sophisticated systems to monitor solar activities such as solar events that can ~~generate hazardous “space weather” (i.e., solar energetic particles—SEPs—and coronal mass~~ ejections—CMEs—as well as cosmic radiation from the Sun and beyond).
- Intensive use of space telescopes and sensors and ground observatories to the orbits of asteroids and comets.
- R & D activities to develop systems to cope with potential “killer asteroids”.

Despite all of these activities, there is evidence that what is being done may well not be enough.

Structure and Highlights of the Book

The structure of this book is to first introduce the nature of the problem of space threats and to note that the methodological approach to the subject is completely multi-disciplinary. Thus the technical, operational, economic and financial, and legal aspects of the problems related to space threats will b addressed along with possible solutions in each of these areas. In some cases an interdisciplinary approach is used simply because the solution may require new technology, new international legal regulations and financial incentives or penalties if corrective action is not taken.

Four chapters of the book provide a good deal more information about the various problems associated with space debris. These chapters address the technical, operational, institutional and ever financial and regulatory arrangements associated with attempts to address and mitigate this growing and increasingly very real problem. The remaining chapters of the book address the very real threats that exist in space that come from natural space phenomena, including coronal mass ejections, solar flares, solar and cosmic radiation, and finally potentially hazardous near-Earth objects (NEOs), including comets and asteroids. Here is a quick recap with some key highlights.

Chapter 2 will address in depth why the threat of space debris and the Kessler Syndrome is increasing. This chapter explains that even if there were to be no new space debris created from new launches that the problem would still keep increasing for decades to come just from the space debris that is already out there. Chapter 2 also seeks to provide a general understanding as to how and why the problem of space debris will increase over time. This analysis notes we need to develop not only new technical and operational solutions, but also new regulatory, institutional and financial mechanisms and procedures as well.

Chapter 3 addresses the nature of the space debris problem and possible solutions that actually vary fairly widely in terms of the various orbits. The biggest and most urgent problem involves LEO and Sun-synchronous polar orbiting satellites as the top priority. Despite the fact that there is a critic need to get large space junk out of LEO, we should not lose sight of the need to clean up all the space around Earth in all the orbits. In short, solutions and corrective actions for all types of orbits from LEO out to geosynchronous orbit must be eventually found and implemented.

Chapter 4 addresses the institutional and regulatory issues. In particular, this chapter presents the specific efforts of the Inter Agency Space Debris Coordinating Committee (IADC) and the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS). These international bodies have been seeking for some time to address the problems of space debris and the longer-term sustainabilit of space. So far they have evolved to the point of “voluntary guidelines” to minimize orbital debris. But we need to go much further. In addition to these two key international bodies there are other organizations and activities that are helping to develop improved space situational awareness and to coordinate activities among space system operators to avoid possible collisions. Two examples of such organizations are the Space Data Association and the U.S. Air Force Space Command that provides the prime space tracking capability.

The longer-term sustainability of space currently starts with the development of improved trackin capabilities. ~~But this is only the start of the process. There are a series of legal, regulatory and~~ liabili issues related to orbital debris and space operation concerns that applies to all current and future spac faring nations. The current international liability provisions related to spacecraft and orbital debris, unfortunately, do not help with efforts to remove orbital debris from orbit. In fact, the current international liability convention might well be considered a barrier to this process. Indeed that is the opinion of most space legal experts that have addressed this problem. Most recently the COPUOS in 2011 established a Working Group on the Longer Term Sustainability of Space that examines the various issues related to making sure that all nations have the future ability to use space in a productive and effective way. This working group is addressing all of the technical, operational, and legal matters that are involved.

Chapter 5 addresses space debris remediation processes and the current status of space technolog and related ground systems that might be employed to undertake space debris removal. In general, none of the technologies are really mature. Even if these various methods could be brought to technical and operational maturity they do not currently constitute cost-effective means to accomplis the task. In short a great deal of future research is needed in these areas to develop effective, cost-efficient methods for orbital space debris mitigation and also to avoid anything that might seem to b employing the use of “space weapons”. In fact, finding ways to accomplish space debris removal wit technology that would not be considered as a space weapon is one of the key challenges to overcome.

We next move on from space debris related issues to the very real concerns of natural space hazards and the problems and issues related to the so-called phenomena known as “space weather,” cosmic radiation and potential collision with asteroids or comets. Here we explore the fact that the ‘natural threats’ from space endanger both our spacecraft in orbit and actually can endanger us here o Earth as well.

These natural space phenomena certainly include hazards to spacecraft and space operations. Satellites must be designed to withstand the very real difficulty of long-term operation in the very harsh space environment, where in-orbit repair or refurbishment is generally not an option. But the hazards involve more than just designing satellites to withstand the rigors of space and thus we will explore why and how we need to protect modern electronic infrastructure from space hazards as well Although space debris is a very real threat to the long-term sustainability of space-related activities, is important to understand that there are a number of very real natural space threats as well.

The hazards addressed in the later chapters actually could represent a much larger threat to humanity than space debris—and by several orders of magnitude. But fortunately that is not the whol story. Although the threat levels are high, the chances of many of the most hazardous events actually occurring—as triggered by natural space phenomena—are quite small. One of the great challenges fo space scientists today is how to deal with threats that are very large, but with their chance of occurrin being quite small.

Fortunately the protective shield of the Van Allen Belts, the ozone layer, Earth’s atmosphere and especially Earth’s geo-magnetosphere provide us critical life-saving protection. There are, however, currently two emerging problems in terms of Earth’s protective system against threats from space. One problem is that Earth’s geo-magnetic field seems to be developing “cracks” that could let highly destructive radiation and ionic particles as well as poisonous gases through with deadly effect. This i a problem being studied by space probes with some urgency. The other problem is what to do if Earth’s protective atmosphere begins to rise to unacceptably high temperatures as the result of clima change. If the atmosphere that protects us should grow too hot, it would raise an entirely new danger that may raise new issues about humanity’s longer-term survival. There is real concern that this heating process, if it should go up on a global average by two or three degrees Celsius, might reach a “tipping point” where reversal of this gradual process might become irreversible. This is, of course, unl~~ess some totally new technological solution might be found. Fortunately humans are often clever~~ finding survival technologies.

Unless one is flying in space above the Van Allen Belts the threats from natural space hazards today remain quite small. These various hazards include so-called solar flares and coronal mass ejections that coincide with the 11-year solar cycle that varies from solar minimum to solar maximum. Most of the times we are quite safe here on Earth, but every 11 years there is a risk that o electrical grids and electronic systems could be zapped big time. We know from The Carrington Eve of 1859 and the more recent massive coronal mass ejection of 1989 that these are dangers that canno be ignored and must be taken seriously [11]. We will also consider the hazards that come from cosmi and solar ultraviolet radiation that is a threat to astronauts and cosmonauts as well as an increasing threat to people in the extreme latitudes near the Polar Regions where the ozone holes now exist.

Chapter 6 addresses the threats posed by solar flares and coronal mass ejections (CMEs). So calle “space weather” from the Sun and the cosmos occurs all the time. There are solar eruptions that occu periodically, and during so-called solar max these threatening events are about 15 times more likely occur than at solar minimum. So-called CME events are characterized by the release of massive amounts of super charged ions that are ejected from the Sun’s corona, which is a raging mass of supe heated plasma that reaches one million degrees Celsius. As a result of these periodic solar events a highly destructive mass of ions are released. These ions and charged particles travel at millions of miles an hour and actually pose a major threat to satellites and spacecraft in space. A number of protective measures need to be employed to protect satellites and orbital spacecraft from these occasional blasts, some of which are violent enough to threaten not only not only satellites in orbit bu as noted earlier electrical grids, electronic equipment, and facilities on the ground. In short, CMEs, i the most severe cases, can endanger much of the modern infrastructure on Earth. This means not only power grids but pipeline systems and highly distributed computers and telecommunications network as well. Just think of the consequences if all the microprocessors on all the vehicles and aircraft in th world were to be blown out by a super-massive solar eruption.

Chapter 7 will focus on solar and cosmic radiation and can likewise present hazards to space asse as well as people right here on Planet Earth as well. Widening holes in the ozone layer allow through truly harmful X-ray radiation in the Polar Regions. Solar and cosmic ultraviolet radiation travels essentially at the speed of light or close to 300,000 km/second or 186,000 miles/second. Solar eruptions that contain super charged electron ions as well as alpha and beta particles travel at huge velocities. Despite this great speed these eruptions nevertheless travel on the order of a 100 times slower than the speed of light or energetic gamma rays. This is indeed fortunate. The speed differential allows solar flares and CMEs to be detected via solar observatories and space-based sensors so that satellites and key facilities can be powered down and electrical systems switched off protect against the “big hits” from these solar storms or super space weather events. Without this typ of warning system hundreds of orbiting spacecraft worth hundreds of billions of dollars could be at risk and essential satellite operations lost for communications, navigation, remote sensing, weather forecasting, and military-related services.

Chapter 8 examines how potentially hazardous asteroids (PHAs) and comets pose an ongoing risk to humans, and Chap. 9 addresses what is currently being done to address and forestall these potentially calamitous events. These NEOs are rarely of large enough size to actually pose a major threat, but on average—about every 50–100 million years—these natural orbital debris can truly clobber Earth and its inhabitants. The good news is that we believe that we have identified some 90 % of the potentially hazardous asteroids that are 1,000 m or more in diameter and might come within 9 million miles (or 14.4 million km) of Earth. The bad news is that it is estimated that there are anothe

10 % of these large threats still to be identified and some 80 % of such asteroids some 100–1,000 m i size ~~to be cataloged. An asteroid of this smaller size could still hit us with the force of tens of~~ thousands of atomic bombs. What is perhaps most important of all is to understand that impacts of objects in this size range are much more frequent than every million years. In fact the chance of a Tunguska-size impact this century is in the order of 1 in 10 to 1 in 5. Later in this book we address th so-called Torino Scale, that is sort of like the Richter Scale for potentially hazardous asteroids. This chart indicates both the likelihood of strikes and the type of damage various-sized NEOs might cause if they hit Earth.

And there are also a large number of potentially hazard comets still to be detected as well. Currently the odds seem to be in our favor, but there are a number of specific asteroids we are tracki with particular concern.

In the short term a much more serious threat for spacecraft are the millions of meteorites and micro-meteorites that can strike and disable a spacecraft. There are a series of recurring meteor showers that pose high levels of risk, but damage from a meteor or even a meteorite can occur at any time. Indeed it is estimated that about 15 % of the strikes on satellites today are from micro-meteorites and not miniscule space junk.

Chapter 10 recaps the major points from the book. Thus this chapter seeks to provide a synoptic overview of the various types of space threats to space assets and even to people residing on Earth or flying through Earth's atmosphere. The strategies and technologies that address these various hazard are summarized as the "Top Ten Things to Know about Space Threats".

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2. The Space Debris Threat and the Kessler Syndrome

Joseph N. Pelton[1]

(1) 40th St. North 4025, Arlington, 22207, USA

Joseph N. Pelton
Email: joepelton@verizon.net

Abstract
One might logically ask this question. If we typically have less than a hundred launches into space each year—after discounting suborbital flights and sounding rockets—why can't we quickly bring th problem of space debris under rather quick control now that we have international guidelines in place This is not really a mysterious problem, but it is certainly a complex one. The simple answer is, debr begets debris.

The most beautiful thing we can experience is the mysteriou
It is the source of all true art and scienc
–Albert Einste

Why is the Problem Getting Worse?

One might logically ask this question. If we typically have less than a hundred launches into space each year—after discounting suborbital flights and sounding rockets—why can't we quickly bring th problem of space debris under rather quick control now that we have international guidelines in place This is not really a mysterious problem, but it is certainly a complex one. The simplest answer is tha debris begets debris.

There is a perhaps a somewhat useful metaphor here, which might be helpful to set the problem i context. Although this is certainly not a completely accurate picture it might help to visualize the problem and set the issues of orbital debris clean up in context.

It is not hard to shoot out a large number of street lights, but it can take a long time to clean up th broken glass, repair the sockets and wiring, and restore that which was rapidly destroyed. Further the streetlight, when first installed, consists of a lamp pole, a light bulb and a glass lamp cover. The streetlight that is destroyed may involve hundreds of pieces of debris to be cleaned up and carefully disposed. If just one light were to be shot out in outer space, the pieces would over time spread out over a huge area that would eventually encircle the entire planet. As a thought experiment thin know what if one had allowed this sort of damage to continue in this manner for a half century many thousands of times with no effective repairs. It should be clear that a quick clean up and recovery ma take quite a while to complete.

The other thing to consider is that if two largest items collide in space at about 25,000 km an hou the result is not four or six debris items, but perhaps more like 3,000 tracked objects and many more thousands of smaller, untrackable objects.

The collision in this case is more like an atomic explosion in terms of energy release than a stick of dynamite exploding. This type of incredibly high speed crash not only generates a huge new amou of debris elements, but the debris elements over time tend to widely disperse. Figure 1.4 above indicates the dispersal of the 3,000 debris elements from the missile destruction of the International Space Station which is clearly imperilled by this debris. We sincerely need to hope that no more such large collision events occur before we find a way of removing large debris elements from orbit to illustrate the point. The thin white line represents the orbit.

The very careful and rigorous study by J.-C. Liou and Nicolas Johnson indicated in 2006 that just the current amount of debris could generate a tripling of the space junk over the next 200 years. This is because space debris collides and generates more debris of smaller and smaller size. Since Liou's and Johnson's analysis there have been over 500 additional launches, and many of these had multiple payloads. The main problem is thus not cleaning up after new launches (although this is certainly par of the equation) but rather dealing with the current debris that is slowly grinding out additional debri elements. Even here there is a need for "triage" to address the most crucial problem first and then see solutions to the rest of the problem later. This most urgent part of the debris mitigation process woul be to remove from the low Earth Sun synchronous polar orbits the largest pieces of debris first. This because these derelicts in space could generate the largest amounts of major new debris elements if there would be a major collision. This we know directly from experience.

There have been a number of studies conducted by various space agencies about space debris and its future potential increase. On one hand these studies are reassuring and on the other quite disturbing. At one level, these studies confirm there is a huge amount of open space around Earth relatively free of debris. Even in a so-called "congested area" such as the polar region in low Earth orbit, as depicted in Fig. 2.1, the likelihood of a collision remains extremely small. Figure 2.1 seems so frightening in large part because the scale depicted in this graphic is about 90 million to 1. The worst news of all is that more debris is forming than is returning to Earth due to gravitational effects In fact there are now well over 6,000 tons of debris in orbit.

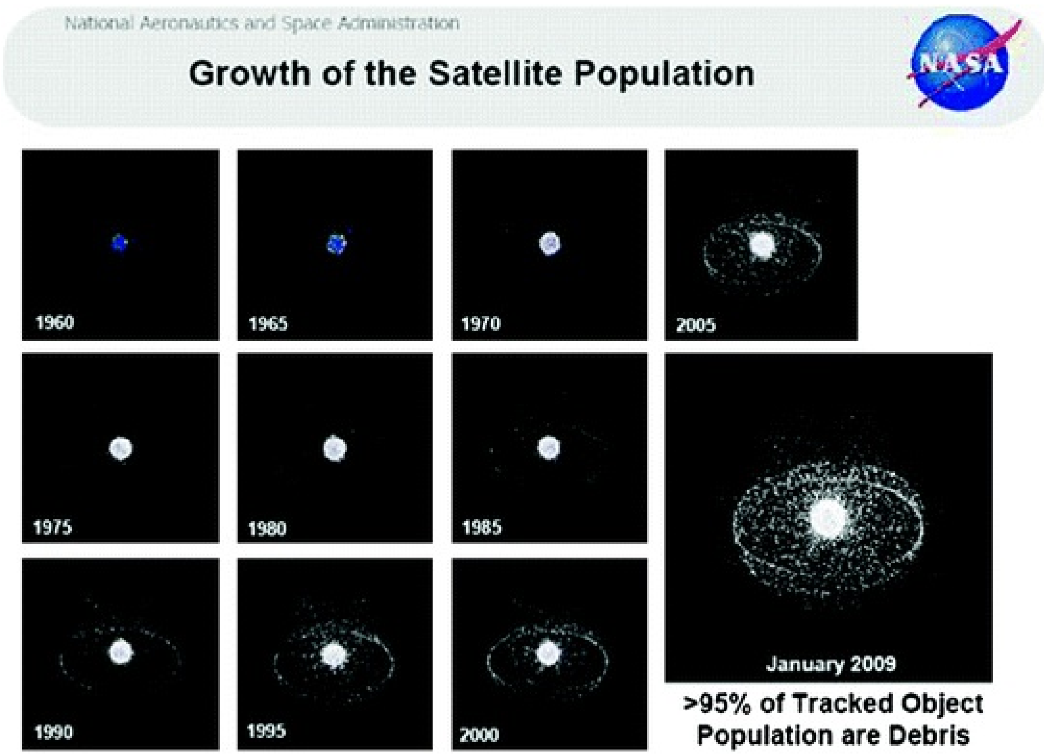

Fig. 2.1 Charting the significant increase in space debris that has occurred since 1960 (Graphic courtesy of NASA)

Space Debris in Orbit

The creation of additional space debris comes from a great variety of sources such as explosions of fuel tanks, launch vehicle upper stages and fairings as well as active and defunct satellites being bombarded by debris, and so on. Further micro-meteorites from space are constantly raining down on the inner parts of the Solar System. These micro-meteorites are responsible for an estimated 12–15 % of the “hits” on spacecraft, based on the latest studies by various research institutes and researchers that monitor this activity.

Twenty-five years ago the cascade effect of debris crashing into other orbital objects produced a modest amount of new debris elements as can be seen in Fig. 2.1. But in time things began to change. Today this cascade effect is the largest source of new debris elements as the number of micro-debris elements that are less than 1 mm in size has climbed into the millions. There are perhaps enough of these various debris elements from the smallest chips of paint to the largest derelict satellites and upper stage rockets to increase the “number” of debris elements by a factor of four to six times over the next two centuries, even if there was to be a total moratorium on all future launches. This projection is based on the findings from the Liou and Johnson study in 2006 and factors in the number of new elements since that time including the Iridium-Kosmos collision and the Chinese anti-satellite missile test.

Orbital debris is not evenly distributed around Earth’s orbit. There are particular bands where these orbital debris are currently concentrated. The worst congestion is in the LEO region and particularly the Sun-synchronous polar orbits. The depiction of the LEO region that is below the Van Allen Radiation Belt is clearly shown in Fig. 2.1 above. The other orbital region such as the MEO region above the Van Allen Belts and the GEO region still contain a number of satellites and debris elements, but relative speaking these are much less congested. This is because that not only are there far fewer debris elements, but also because the debris has a much larger volume in which to spread. Figure 2.1 shows the build up over time of the debris around Earth and how it has escalated in recent years. In 1980 the problem was hardly apparent, and even by 1985 it seemed almost trivial, but today it is clearly a larger and growing issue.

There are a number of other important aspects to note with regard to the orbits that are of importance. One aspect is that there are different disposal concepts that apply to these three different orbits. One logical disposal mode is to fire jets so that a satellite in LEO will simply de-orbit and burn up on its descent or splash down into the ocean. For geosynchronous satellites the disposal method is to push the spacecraft to a graveyard orbit that is higher than the geo orbit. When thus positioned there, these satellites can stay in super synchronous orbit for millions of years.

The greatest challenge is presented by the MEOs in terms of the disposal of satellites at end of life. Only a small amount of increment fuel is required to de-orbit a LEO satellite or to push a GEO satellite into a higher graveyard orbit. The disposal of MEO satellites is a problem in that a 40 % greater amount of fuel—beyond that used for orbital positioning—is needed to de-orbit a spacecraft launched into this orbit. This constitutes a very large economic penalty in terms of launch costs and increasing the size of propellant fuel tanks. Other options might be explored to move MEO satellites at end of life into some type of "graveyard or parking orbit", but this would not be an easy or permanent solution because the Sun, Earth and Moon would impact this type of orbit and thus it would not be stable.

Actually the problem and complexity of this final disposal issue only increases when probed further. Satellites can lose their ability to be commanded and thus be stranded in their orbits. Elemen of the launch such as the upper stage rocket, fairings that served to protect the satellite from the ~~atmosphere during launch and other extraneous parts can be launched and stranded in orbit with~~ no mechanism to de-orbit them except for gravitational pull and atmospheric drag. Some satellite operators have claimed that they were requested not to de-orbit their failed satellites from operators o defense-related satellites because of possible collision with clandestine satellites uses for surveillanc

If the launch of a spacecraft is into LEO, these elements will eventually degrade, but this is not th case with MEO or GEO orbit. And, of course, not all satellites are launched into LEO, MEO or GEO orbit. Some satellites are launched into highly elliptical orbits such as the so-called “Molniya” orbit, named after the Russian satellite with this name. Or satellites can be launched into a somewhat simil highly elliptical “Loopus” orbit. There are also various other orbits such as the Quasi-Zenith or Figure 8 orbit (i.e., a geo orbit inclined 45 degrees), super-synchronous orbits and even unintended orbits. These last can result from a launch failure when the rocket fires too long or not enough, and thus the rocket is put on the wrong path.

Once a satellite or rocket motor becomes stranded in orbit, it can become a source of additional debris. Any of these stranded or even actively controlled space objects can be hit by another piece of debris at high speed and generate other debris. A fuel tank or a battery might explode and create additional elements of debris. The recommended procedure of venting fuel tanks for end of life satellites is considered an important procedure now widely practiced to help minimize space debris.

The uneven distribution of orbital debris creates problems with regard to those who perceive this as a serious issue and those willing to support in an active way the cleaning up of the mounting amounts of space junk. Those who operate satellites in GEO orbit are inclined to respond to concerns about rising debris by saying this is largely a LEO and polar orbit problem and not one that affects m Those who operate MEO orbit systems might say much the same.

The increasing build up over time in orbital debris will, of course, be a problem for everyone who seeks to safety launch into orbit since launchers must travel through LEO on their way to a higher orbit. Further there is increasing debris in all orbits and unless the problem is addressed in the nearer term the longer term costs and difficulty of debris removal will exponential increase over time. Just a the issue of the sustainability of the Earth’s environment is becoming exponentially worse and more difficult and expensive to address over time, the same type of problems exist with “kicking the can down the road” with regard to space debris.

The Urgency of Action and Orbital Priorities

The urgency of addressing the space debris problem is clearly perceived to be at different levels by those whose missions are related to LEO, MEO and GEO orbit systems. Thus if there are financial approaches devised to collect funds to address this problem, it is likely that contribution levels might well be different for those launching to LEO, MEO, GEO or points beyond. The discussion of orbital debris also often focuses on which countries are responsible for the creation of this problem in the first place. Clearly it is only a few spacefaring nations that were the prime cause of today’s space junk. The primary countries in this regard are clearly the United States, China and Russia.

Although these three countries—or enterprises based in these countries—are the clear source of this debris, the source of secondary, tertiary, or even quandary debris that has come from subsequent collisions in space is much harder to assess. Instead of trying to assign specific responsibility to a particular country and thus looking backwards in time for a solution, it might be more appropriate to try to look forward to a more integrated global solution. The number of countries launching rockets and spacecraft into space is still only ten in number. The three primary launching countries plus Europe launch about 90 % of all rockets into space and well over 95 % of the total payload mass to orbit—and this will likely remain the case for some time to come.

Upgrading Debris Tracking Capabilities

A great deal of activity is now devoted to tracking space debris. Since 1961 the U. S. Air Force has been operating the Space Surveillance System that has been using increasingly outmoded Very High Frequency (VHF) radar tracking and in-orbit resources to track the mounting amount of space debris. As the amount and number of debris objects has increased exponentially, this system has become increasingly unable to keep up with the tracking requirements. This system, which was originally conceived as a means to detect a missile launch attack against the United States, is increasingly utilized to help protect key U. S. orbital assets. This includes anticipating possible collisions with the International Space Station (ISS) by a major debris element and indicating how raising the ISS orbit the correct time could eliminate such risks.

The U.S. Air Force has contracted with Lockheed Martin to upgrade the existing radar systems ar implement what is known as the “space fence” to have much more precise tracking capabilities. The first elements of this new capability were tested in February and March 2012 and successfully demonstrated orbital debris tracking capability. Based on these tests, the air force approved the desig and an implementation plan. Steve Bruce, vice president of the Space Fence program for Lockheed Martin, said in a statement after the tests: “Our final system design incorporates scalable, solid-state S-band radar, with a higher wavelength frequency radar capable of detecting much smaller objects than the Air Force’s current system [12].” This new space fence system will thus eventually be able t track object in LEO down 1 cm or 0.4 inches in diameter. This is more or less equivalent to the capability to track some 500,000 space debris elements [13].

The control center for this new Mark II space fence orbital tracking system is now operational, even though it will be several years before the new multi-billion dollar capability is fully installed ar operational. (See Fig. 2.2)

Fig. 2.2 Mark II S-band radar space fence operations center (Graphic courtesy of Lockheed Martin Corporation)

Space Traffic Management

The space launch environment has clearly become more complex, with growing space launching capabilities and different sorts of commercial space activities. One thought that has arisen with the