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USSTRATCOM CENTER FOR COMBATING WMD

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TECHNICAL REPORT

Collateral Damage to Satellites from an EMP Attack

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August 2010

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In support of The Commissions to Assess the Threat to the United States from Electromagnetic Pulse Attack, this paper examines the potential damage to satellites from high altitude nuclear detonations not specifically targeting space assets. We provide and overview of representative classes of satellites, their orbits, and their economic and military importance to the U.S. lessons learned from atmospheric nuclear test of the late 1950's and early 1960's are presented. In particular, the STARFISH PRIME test of 1962 injected long-lived trapped energetic electrons into Earth's magnetic fields, causing the early demise of several satellites.

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ABSTRACT

In support of *The Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack,* this paper examines the potential damage to satellites from high altitude nuclear detonations not specifically targeting space assets. We provide an overview of representative classes of satellites, their orbits, and their economic and military importance to the U. S. Lessons learned from atmospheric nuclear tests of the late 1950's and early 1960's are presented. In particular, the STARFISH PRIME test of 1962 injected long-lived trapped energetic electrons into Earth's magnetic field, causing the early demise of several satellites. Physical principles governing natural and nuclear weapon enhanced space environments, including trapped radiation (Van Allen belts), are described. We review effects of various types of natural and nuclear radiation on satellite electronic components, surface materials, and systems. In particular, we note that weapon-induced ultraviolet radiation and its damaging effects on surface materials may have been underestimated in previous studies.

Twenty-one trial nuclear events with varying yields and locations were postulated as credible terrestrial EMP attacks or other nuclear threats. Of these, seventeen were at low L-shells and consequently present a hazard to low-Earth orbit (LEO) satellites. Four were at high magnetic latitude, threatening GPS or geosynchronous (GEO) satellites. We present effects of these events on three representative LEO satellites, on the GPS constellation, and on a generic GEO satellite. The Air Force SNRTACS code was used to characterize the nuclear-weapon-generated trapped electron environment; the Satellite Toolkit (STK) was used to assess prompt radiation exposure. We conclude that LEO satellites are at serious risk of exceeding total-dose limits for trapped radiation if generally accepted natural space hardening criteria are invoked. We believe, however, that the probability of an individual satellite being sufficiently close to a detonation to be threatened by prompt radiation effects is relatively low. GPS and GEO satellites are threatened only by the very high yield (~ 10 Mt) detonations of our trial set.

We review uncertainties in our ability to predict nuclear-detonation-produced satellite damage along with our confidence in the efficacy of these predictions. Uncertainties as large as one to two orders of magnitude are postulated, particularly as relating to the prediction of trapped radiation from nuclear bursts.

We recommend that the Department of Defense initiate policies to:

- Reassess survivability of satellite space- and ground-based systems that support U.S. defenses,
- Increase the level of nuclear hardening and subsidize implementation for commercial satellites that support essential national missions,
- Increase funding for research in high altitude nuclear effects in order to reduce uncertainties and the safety margins they engender, thereby decreasing the costs associated with hardening.
- Pursue studies on the feasibility of electron radiation belt remediation.

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CHAPTER I
INTRODUCTION

Use of a high altitude nuclear detonation as an electromagnetic pulse (EMP) attack on a terrestrial target may generate both immediate and long-term radiation threats to Earth-orbiting satellites. In support of *The Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack,* this paper was written to examine potential collateral damage to satellites from high altitude nuclear detonations. It is an analytical study of enhanced radiation environments produced by high-altitude detonations above various geographical regions, and their effects on representative satellites conducting long-term missions of both military and civilian importance. Threats were chosen to be representative of those we believe appropriate in a time frame ranging from the present to 2015. We believe this is the first paper to examine systematically collateral effects on satellites from an EMP attack executed in virtually any region of the Earth. Effects of both (a) direct radiation from a detonation as well as (b) subsequent effects of an enhanced trapped-electron population, will be addressed.

The salient issues examined in this paper are:

- What categories of satellites are vulnerable to malfunction or damage, immediately and ultimately?
- How long would satellites not immediately damaged by prompt radiation continue to function in the hostile electron belt environment?
- How does damage depend on weapon design and yield, and on the altitude and location of a detonation?
- What are the regrets for loss (temporary and permanent) of satellites in orbit?
- At what point in time would the nuclear-enhanced space environment cease to pose a threat to either a satellite or its mission?
- What satellites should be considered expendable and which should be hardened?
- What are appropriate levels of hardening?

The last two issues are subjective in nature and are addressed only peripherally herein. However, we do seek to provide enough information to raise the level of awareness of evolving threats and to assist decision makers toward realistic appraisals of vulnerabilities and longevities of satellites should they be exposed to a nuclear-enhanced radiation environment.

It is important to recognize that a satellite is part of a larger system that includes ground stations that issue instructions to the satellite, transmit and receive communications traffic from it as a relay, and act as reception facilities for the data that the satellite's sensors collect. Ground stations are at risk from EMP effects, and the medium through which a satellite's radio signals propagate can also be disturbed for as long as several hours due to ionization of the atmosphere by the nuclear burst. In this paper we principally address effects on satellites themselves.

There is little question that unhardened satellites are vulnerable to high-altitude nuclear explosions. It is a recognized fact that any country or organization with sufficient technology, missile lift, and guidance capability can damage or destroy a satellite in orbit using a number of different weapons and kill mechanisms. Some military satellites are hardened against credible radiation threats and all satellites are hardened to withstand the natural space radiation environment for their required lifetime in orbit. However, there is a tendency to judge an EMP threat as unlikely, and to make investments in mitigation of other threats a higher priority.

An extensive scientific and engineering literature deals with the phenomenology and effects of nuclear and space radiation on satellites. The *I.E.E.E Transactions on Nuclear Science* from 1963-2003 contains a comprehensive set of papers that document the growth and depth of the state of the art. Papers from the I.E.E.E. Annual Conference on Nuclear and Space Radiation Effects have traditionally been presented in the December issue. The *Journal of Geophysical Research* publishes scientific research on the theory and observation of space radiation.

Space radiation consists of energetic electrons, protons, and heavy ions originating from many sources, including (a) primary and secondary cosmic rays; (b) direct solar emanations as well as particles energized via the interaction of the solar wind with Earth's magnetic field; and (c) particles trapped by Earth's magnetic field for periods of days to years, forming the "Van Allen belts." Contemporary satellites are hardened against the anticipated exposure to space radiation during their design lifetime.

In the late 1950s and early 1960s there were sixteen high altitude nuclear detonation experiments, some of which contributed substantial additional trapped radiation, changing the morphology of the Van Allen electron belts, increasing their intensity, and hardening their energy spectrum. At least eight satellites that were in orbit during this time were damaged by long-term effects of nuclear-enhanced trapped radiation. Their modes of failure are well documented in the technical literature and are discussed in Chapter IV. There are also papers that treat the ramifications of these "pumped" belts on the current satellite population [Webb 1995, Pierre 1997, Cohn 2001, Keller 2002] and others that examine the effects of direct radiation from high altitude detonations on military satellites [DTRA EM-1, Northrop, 1996].

Owing to the specific charter of the Commission, emphasis of this paper must be confined to collateral damage from an EMP attack. It is acknowledged that a direct attack upon a satellite opens many issues beyond the study reported herein. In cases where there are threats beyond the scope of this paper, we can only acknowledge them and suggest sources for further study.

CHAPTER II
STATEMENT OF THE PROBLEM

Satellite systems today provide cost-effective services that permeate the foundations of contemporary society, economy, and civil infrastructure in many, if not most, developed countries. They provide telecommunications services that are central to today's globally integrated economy; they provide "big picture" data required by modern climate monitoring and weather forecasting. Satellite-borne sensors monitor agricultural conditions worldwide and provide data upon which yield forecasts are based, thereby making the market more efficient and stabilizing agricultural economies.

Today there are approximately 1000 Earth orbiting satellites and of this number approximately 550 are in Low Earth Orbit (LEO).

Table II.1. Examples of Active LEO Assets by Mission (US Assets in Blue) May 2003

Intel	Earth/Ocean/ Atmosphere	Weather	Space Science	Nav Search and Rescue	Comms
NRO	AQUA	NOAA	HST	Nadezhda	Iridium
Ofeq	TERRA	DMSP	Galex	Cosmos	Globalstar
Helios	Envisat	Meteor	ISS		Cosmos
IGS	Ikonos		FUSE		
Quickbird	EO-1		TRACE		
Cosmos	SPOT				
ZY-2	TRMM				
TES	Orbview-2				

The United States has a large investment in satellite systems and enormous societal and economic reliance on telecommunications, broadcast, and sensor services for civil infrastructure. Unlike most nations, the United States heavily utilizes space-based assets for military and intelligence purposes. Early satellites with military and intelligence functions were dedicated systems, but with the evolution of technology and driven by satellite economics, a mix of dual-use satellites (*e.g.*, Global Positioning System, GPS) and leased commercial satellite services (*e.g.*, Ikonos, QuickBird, and Iridium) have become vital.

The overwhelming majority of satellites in orbit are designed, built, launched, and operated by commercial enterprise. Because the pace of technological change grinds relentlessly, there is strong economic incentive to maximize financial returns from expensive satellites within a few years after launch—before a competitor appears in orbit with superior capabilities at lower cost. Hazards of the natural space environment are known with relative certainty, and protection against those hazards is an integral part of spacecraft design. Hardening commercial satellites against even one high-altitude nuclear explosion—admittedly an unlikely event in the world view of most investors—would raise costs, reduce financial benefits and, given limits on booster payloads, quite possibly reduce satellite capabilities and competitive position. In the absence of an incentive, commercial satellite operators are happy to maximize profitability and to discount a small perceived risk of loss due to a nuclear detonation.

Satellite vulnerability to high-altitude nuclear explosions is not a question of whether an adversary *would* detonate a weapon as hypothesized, but instead turns entirely on questions of technical feasibility. *Could* an adversary—either a nation state or a nongovernmental entity—acquire nuclear weapons and mount a credible threat? The answer is unquestionably "Yes." One must assume both nuclear weapons and delivery systems are available to credible adversaries now and will continue to be so for the foreseeable future. For those that elect to purchase rather than develop nuclear weapons and delivery systems, technically capable and willing purveyors are available. North Korea, for example, has nuclear reactors to produce plutonium in quantity, missile technology sufficient to reach well beyond Japan, and a track record as an active trader in the international arms market. With an economy in shambles, a desperate need for hard currency, a repressive government not subject to checks and balances of an informed populace, and a ready market, there is little doubt that further proliferation of nuclear weapons and delivery systems is likely. As geopolitical circumstances change and as alliances evolve, the mix of proliferants will undoubtedly change.

Throughout this investigation there have been continuing questions dealing with economic regrets associated with the loss of civilian satellites and tactical regrets associated with the loss of military space assets. Questions about the latter are much easier to answer than those dealing quantitatively with the Gross Domestic Product.

CHAPTER III
SATELLITE POPULATIONS

There are approximately 1000 active satellites in Earth orbit providing a wide variety of services. Approximately 330 satellites in geosynchronous (GEO) orbit (35,786 km altitude over the Earth's equator) provide critical communications, intelligence surveillance, and large scale weather observation services. Because GEO satellites remain stationary over a particular location, they are always available for service to that region. Nearly all international TV broadcasts and data exchange activities (banking transactions, etc.) go through geosynchronous satellites. Because a geosynchronous satellite "hovers" over a specific region, continuous monitoring of that region for national security purposes or weather forecasting is possible.

Approximately 30 Global Positioning System satellites (GPS), orbiting at 20,200 km altitude and 55 degrees inclination, provide critical navigation services to both the international community (airline and ship navigation) and the U.S. military. Smart bombs used in Operation Iraqi Freedom would have been ineffective without critical guidance information from the GPS satellite constellation.

Although GEO and GPS satellites are critically important to U.S. military and economic security, it is satellites in Low Earth Orbit (LEO) that will dominate most of the discussion in this paper. These satellites are the ones that would be most affected by a high altitude EMP burst. (GEO and GPS satellites are unlikely to be severely damaged by EMP bursts having less than multi-megaton yields.)

LEO satellites perform vital services for the United States. From a National Security standpoint, reconnaissance satellites, both government and commercial, provide global monitoring of trouble spots around the world. These satellites are critical assets to aid the War on Terrorism. LEO weather satellites provide critical data for both civilian and military purposes. These satellites complement the suite of weather satellites in GEO orbit by providing much higher spatial resolution of weather patterns as well as providing weather observations at extreme latitudes inaccessible to GEO satellites. Earth and ocean monitoring satellites, such as TERRA and AQUA, provide multi-spectral observations of land and sea to monitor ocean currents, pollution, fish movement, ice formation, land erosion, soil moisture content, health status of vegetation and spread of disease, as examples. These data have both economic and military value. During the Iraqi Freedom operation, Earth resources satellites were used to monitor dust storms that have a major effect on military air operations. From a national prestige point of view, satellites such as the Hubble Space Telescope, Space Shuttle, and the International Space Station (ISS) are a source of pride and inspiration to Americans. They are a symbol of America's preeminence in the world. LEO mobile communications/data satellite constellations such as Iridium, Globalstar and ORBCOMM provide unique services to both commercial and military users by allowing communications anywhere in the world using small handheld devices.

There are approximately 550 satellites from numerous countries in LEO performing missions like the ones described above. Figure III.1 shows the division of satellites among various mission categories. Communications and messaging satellites dominate the figure because a constellation of several dozen satellites is required to assure complete and constant coverage over the entire globe. Such large constellations are expensive to launch and maintain, which is why organizations backing constellations such as Iridium and Globalstar have passed through bankruptcy. The unique aspects of these satellites, however, have appeared to rescue economically at least one and possibly more of these constellations. In late 2000, the U.S. government issued a contract to Iridium Satellite LLC to procure unlimited mobile phone service for 20,000 government users. If contract options are exercised, the total procurement will be worth $252M and extend out to 2007 [Space News, 2000].

Intelligence, weather and Earth/ocean monitoring satellites make up 22.5% of the LEO population. As mentioned before, many of these 120+ satellites provide critical economic and military information. The 25 or so navigation satellites are used primarily by Russian shipping vessels; many of these satellites are also equipped with search and rescue beacons to pinpoint the locations of all downed light aircraft, ocean vessels in distress, and lost campers having search and rescue transmitters. About 28 satellites are dedicated science missions monitoring the Sun, Earth's magnetosphere and geodesy, and the far reaches of space. Manned space endeavors are included in this category. The last category consists mainly of small amateur radio satellites and demonstrations of new technologies in space. There are about 83 of these satellites.

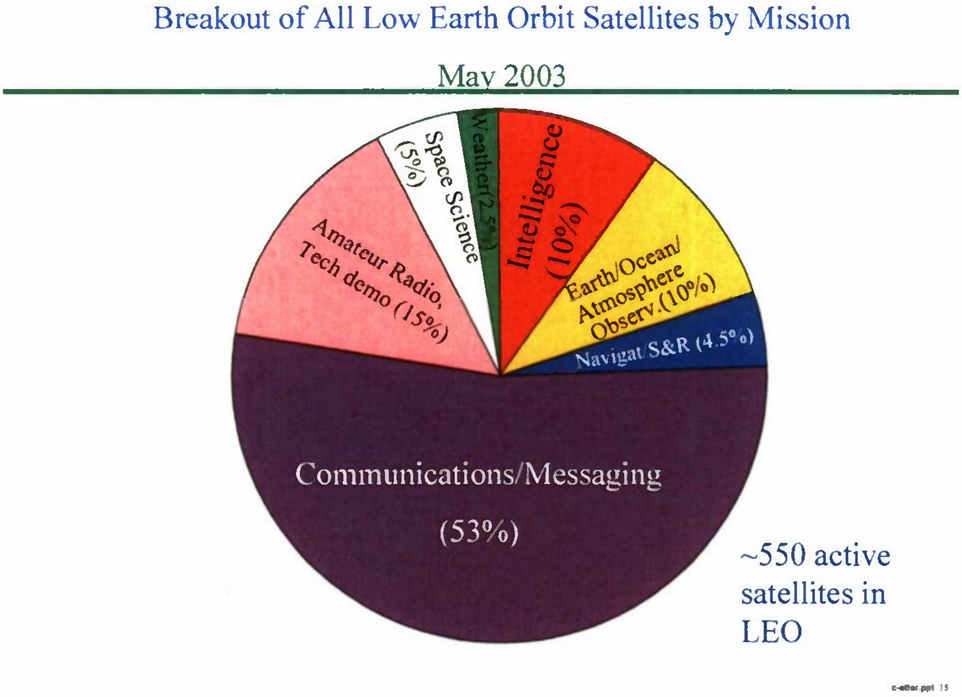

Figure III.1. Distribution of low-Earth orbit satellites by mission.

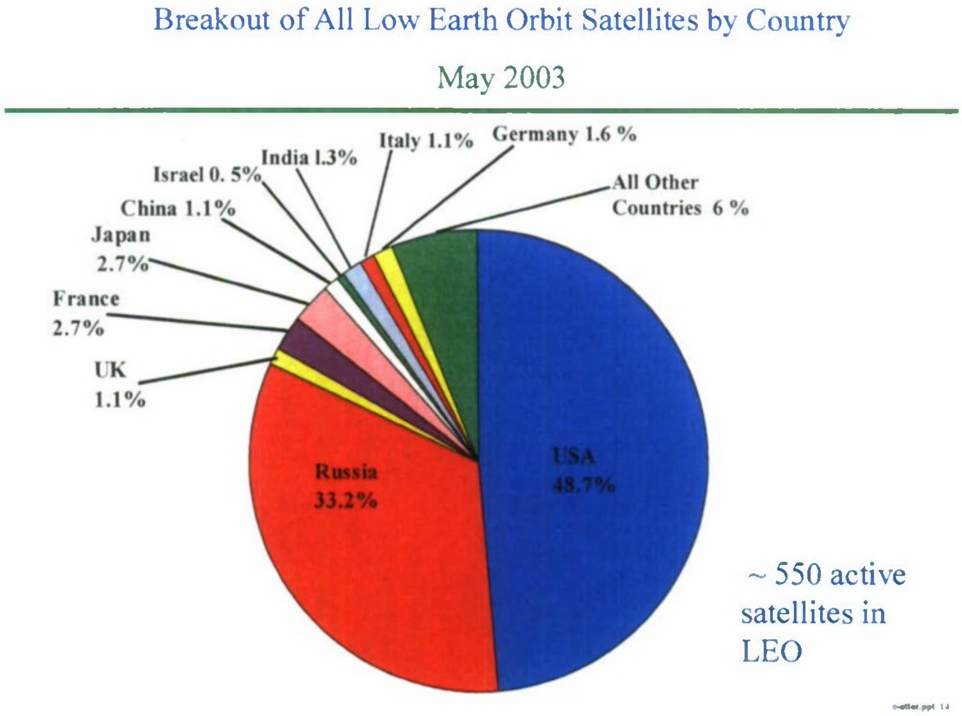

Figure III.2. Distribution of low-Earth satellites by country.

Figure III.2 shows the distribution of low-Earth orbiting satellites by country. Nearly half of all LEO satellites are U.S. owned or are primarily used by the U.S. About one-third belongs to Russia. The remainder is distributed among numerous other nations.

Figure III.3 shows the distribution of U.S. owned/used satellites by mission. Note the large percentage of assets that have a mobile voice/messaging and data transfer mission. The bulk of these assets consist of the Globalstar, Iridium and Orbcomm constellations. These systems have had a difficult time establishing themselves as financially viable over the last several years, but that trend may be reversing. Iridium currently has a contract with the U.S. government. Globalstar's 2003 first quarter revenues were triple what they were a year ago, while losses fell more than 80%. Business at Orbcomm is doubling every 8 months, and the company is processing 60-70 contracts to provide messaging/tracking services for the trucking and shipping industry in addition to providing remote monitoring of gas and water meters. The total investment in these constellations of satellites is about six billion dollars.

Intelligence satellites in LEO provide important monitoring of hot spots around the world via optical, radar and electronic monitoring. Details of the constellation of LEO intelligence satellites are classified.

U.S. weather satellites in LEO include the civilian NOAA program and military Defense Meteorological Satellite Program (DMSP), each of which maintains several spacecraft in orbit at all times. Both of these systems employ visible, IR and microwave sensors to monitor weather patterns, ice conditions and sea state for civilian and military purposes.

Earth/Ocean/atmospheric monitoring satellites include satellites such as Landsat, TERRA, AQUA, Quickscat and SeaWIFs. These assets play an important role in long-term climatology studies as well as in monitoring pollution, crop health status, and the spread of infectious diseases. Many of these satellites played a critical role in recent military conflicts.

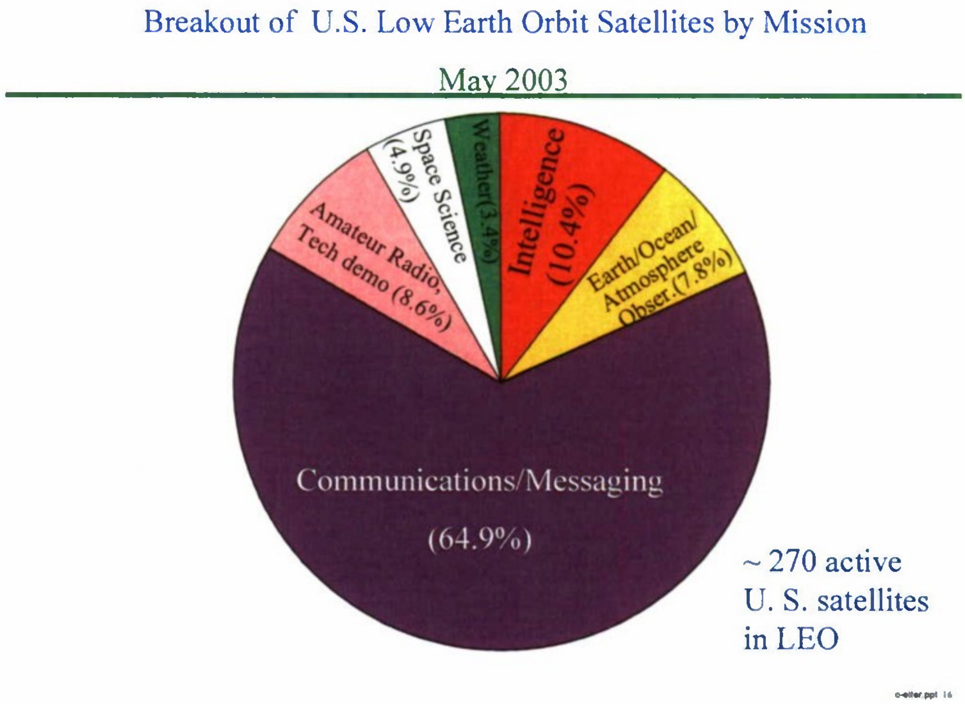

Figure III.3. Distribution of U.S. low-Earth orbit satellites by mission.

Table III.1 lists all U.S. owned/used LEO satellites and the estimated total dollar investment made in U.S. LEO satellites, including launch costs. Some entries, such as the number and value of NRO assets, are estimates based on unclassified information available. One can see from the table that the total U.S. investment in this area is approximately $90B with about half of that amount credited to the International Space Station (ISS). Although the total U.S. investment in LEO satellites is estimated to be on the order of $90B, it is probably unlikely that the U.S. would have to expend that dollar amount to return the LEO constellation to an acceptable level after a nuclear event. The International Space Station, which makes up the bulk of the $90B+ investment, is designed to be serviced by Shuttle crews and barring a direct nuclear attack on the asset, the Station could probably be salvaged for a fraction of the $47.5B listed in the table. In addition, some space assets, such as UARS and Topex-Poseidon, are at the end of their useful lives and would not be replaced or have already been replaced. In spite of these considerations, the U.S. would probably still have to spend about half ($45B) to recover assets considered important to science, national security, and the economy. This would include the NRO assets, expensive new science missions such as TERRA and AQUA, polar weather satellites such as NOAA and DMSP, and repairs to the large number of electronic components on the ISS which may require multiple Shuttle flights and hundreds of astronaut EVA hours.

Table III.1. U.S. LEO Satellite Investment.

Satellite	Number of Satellites	Satellite Cost ($M)	Number of Launch Vehicles	Launch Vehicle Cost ($M)	Total Cost ($M)
ACRIMSAT	1	13	1	14	27
Alexis	1	17	1	14	31
apex-1	1	22	1	6.5	28.5
AQUA	1	952	1	55	1007
ARGOS	1	162	1	55	217
CHIPSAT	1	14.5	1	27.5	42
Coriolis	1	224	1	35	259
DMSP	4	1816	4	140	1956
EO-1	1	193	1	50	243
ERBS	1	200	1	250	450
EYESAT	1	3	1	5.5	8.5
FAISAT-1	1	5	1	5	10
FAISAT-2	1	5	1	5	10
FALCONSAT	1	0.5	1	0.5	1
FORTE	1	35	1	15	50
GALEX	1	16.5	1	14	30.5
FUSE	1	100	1	60	160
GFO	1	85	1	23	108
Globalstar	52	2392	14	564.9	2956.9
GRACE -1	1	70	1	8	78
GRACE-2	1	70	1	8	78
HESSI	1	40	1	14	54
HETE-2	1	9	1	15	24
HST	1	3000	1	500	3500
ICESAT	1	200	1	27.5	227.5
IKONOS-2	1	60	1	22	82
IMAGE	1	39.8	1	55	94.8
IRIDIUM	72	3500	15	1500	5000
ISS	1	40000	15	7500	47,500
JASON-1	1	185	1	27.5	212.5
JAWSAT	1	0.23	1	3	3.23
LANDSAT-4	1	400	1	55	455
LANDSAT-5	1	400	1	55	455
LANDSAT-7	1	666	1	55	721
M-1	1	10	1	4.33	14.33
M-2	1	10	1	4.33	14.33
MICROSAT-1	1	0.5	1	1	1.5
MICROSAT-3	1	0.5	1	1	1.5
MTI	1	150	1	23	173
MUBLCOM	1	7.5	1	7.5	15
NOAA-12	1	454	1	35	489
NOAA-14	1	454	1	35	489
NOAA-15	1	454	1	35	489
NOAA-16	1	454	1	35	489
NOAA-17	1	454	1	35	489
NRO	24	12000	24	6696	18696
OPAL-1	1	0.5	1	0.5	1

Satellite	Number of Satellites	Satellite Cost ($M)	Number of Launch Vehicles	Launch Vehicle Cost ($M)	Total Cost ($M)
OPS-1292	1	500	1	500	1000
OPS-8737	1	500	1	500	1000
ORBCOMM	36	180	11	154	334
ORBVIEW-1	1	5	1	14	19
ORBVIEW-2	1	43	1	14	57
ORBVIEW-3	1	60	1	14	74
OXP-1	1	0.5	1	0.5	1
PCSAT	1	0.5	1	0.5	1
PICOSAT-9	1	0.5	1	0.5	1
QUICKBIRD-2	1	60	1	55	115
QUICKSCAT	1	93	1	35	128
REFLECTOR	1	0.5	1	0.5	1
REX-1	1	6	1	6	12
REX-2	1	6	1	6	12
SAMPEX	1	35	1	9	44
SAPPHIRE	1	0.5	1	0.5	1
SEDSAT-1	1	0.5	1	0.5	1
SNOE	1	5	1	10	15
SORCE	1	85	1	14	99
STENSAT	1	0.5	1	0.5	1
STEP-2	1	100	1	14	114
SURFSAT-1	1	0.5	1	0.5	1
SWAS	1	64	1	14	78
TERRA	1	1300	1	142	1442
TETHER-PICOSATS	1	0.5	1	0.5	1
THELMA	1	0.1	1	1.2	1.3
TIMED	1	207.5	1	27.5	235
TOMS-EP	1	29.3	1	14	43.3
TOPEX-POSEIDEN	1	480	1	85	565
TRACE	1	39	1	14	53
TRAILBLAZER-2	1	10	1	8.5	18.5
TRMM	1	100	1	76	176
TSX-5	1	85	1	14	99
UARS	1	630	1	500	1130
Total		**73971.93**	**158**	**20343.26**	**94315.19**

CHAPTER IV
HISTORY OF DAMAGE TO SATELLITES

Hazards to satellites from both natural and nuclear-produced radiation environments are irrefutably demonstrated by data taken after high altitude nuclear tests in 1958-1962, frequent damage from solar events, and from 65 years of R & D. These experiences will be discussed in this chapter.

IV.A High Altitude Nuclear Tests

From 1958 until the atmospheric nuclear test moratorium in 1963, over a dozen high altitude nuclear tests were conducted (Table IV.1). Some of these tests produced minor, if any, radiation belts due to the low altitude and/or low yield of the detonation. Several, however, including the last three Soviet tests and the U.S. STARFISH PRIME test, produced significant belts that lasted from one month to several years. Table IV.1 lists test parameters for all of the high altitude detonations.

Table IV.1. HANE Events Chronology

SHOT NAME	DATE	LOCATION	ALTITUDE	YIELD
YUCCA	4/28/58	Pacific	Balloon, 26km	1.7kt
TEAK	8/1/58	Johnston Island	77km	3.8Mt
ORANGE	8/12/58	Johnston Island	43km	3.8Mt
ARGUS I	8/27/58	South Atlantic 38.5°S, 11.5°W	~500km	1-2kt
ARGUS II	8/30/58	South Atlantic 49.5°S, 8.2°W	~500km	1-2kt
ARGUS III	9/6/58	South Atlantic 48.5°S, 9.7°W	~500km	1-2kt
Soviet, K1	10/27/61	South Central Asia	150km	1.2kt
Soviet, K2	10/27/61	South Central Asia	300km	1.2kt
STARFISH PRIME	7/9/62	Johnston Island	400km	1.4Mt
CHECKMATE	10/20/62	Johnston Island	Hi. Alt., 10's of km	Low
Soviet, K3	10/22/62	South Central Asia	290km	300kt
BLUEGILL	10/26/62	Johnston Island	Hi. Alt.,, 10's of km	Sub Mt
Soviet, K4	10/28/62	South Central Asia	150km	300kt
Soviet, K5	11/1/62	South Central Asia	59km	300kt
KINGFISH	11/1/62	Johnston Island	Hi. Alt., 10's of km	Sub Mt
TIGHTROPE	11/4/62	Johnston Island	Hi. Alt., 10's of km	Low

IV.B Satellites Damaged by High Altitude Nuclear Tests

When the U.S. detonated the 1.4-megaton STARFISH PRIME device on 9 July 1962 at 400 km altitude, a total of 24 satellites were in orbit or were launched in weeks following (Table IV.2) [Astronautix.com; Weenas 1978; Jakes 1993].

Table IV.2. Satellites On Orbit at the Time of High Altitude Nuclear Tests.

Name	Launch Date (dd/mm/yy)	Operation Ceased	Period (Min.)	Perigee (KM)	Apogee (KM)	Incl (Deg.).
VANGUARD 1	17/03/58	ca/05/64	134.3	652	3965	34.3
TRANSIT 2A	22/06/60	ca/08/62	101.7	626	1070	66.7
SAMOS 2	31/01/61	21/10/73	95.0	483	563	97.0
EXPLORER 9 (Balloon)	16/02/61	09/04/64	118.3	636	2582	38.6
DISCOVERER 20	17/02/61	28/07/62	95.3	285	782	80.4
INJUN/SOLRAD 3	29/06/61	06/03/63	103.8	859	1020	67.0
MIDAS 3	12/07/61	?	160.0	3427	3427	91.1
MIDAS 4DSB	21/10/61	?	166.0	3311	3739	95.9
DISCOVERER 34	05/11/61	07/12/62	97.2	216	1025	82.7
TRANSIT 4B	15/11/61	02/08/62	105.6	950	1110	32.4
TRAAC	15/11/61	12/08/62	105.6	950	1120	32.4
SAMOS 5	22/12/61	?	94.5	233	751	89.6
OSO 1	07/03/62	06/08/63	96.2	550	591	32.8
1962 H1	07/03/62	07/06/63	93.9	237	689	90.9
COSMOS 2	0/6/04/62	19/08/63	102.5	212	1559	49.0
MIDAS 5	09/04/62	?	153.0	2785	3405	86.7
COSMOS 3	24/04/62	?	93.8	298	330	65.0
ARIEL 1	26/04/62	ca/11/62	100.9	390	1210	53.9
1962(SIGMA)1	15/05/62	?	94.0	290	645	82.5
COSMOS 5	28/05/62	?	102.8	203	1599	49.1
1962 OMEGA1	18/06/62	?	92.3	377	393	82.0
TIROS 5	19/06/62	04/05/63	100.5	591	972	58.1
1962 (GAMMA) 1	27/06/62	14/09/62	93.7	211	640	76.0
COSMOS 6	30/06/62	08/08/62	90.6	274	377	49.0
TELSTAR	10/07/62	21/02/63	157.8	955	5656	44.8
EXPLORER 14	02/10/62	08/10/63	2185	278	98850	33
EXPLORER 15	27/10/62	09/02/63	314.7	310	17300	18
INJUN 3	13/12/62	03/11/63	112.1	238	2389	70.3
RELAY-1	13/12/62	00/02/65	185.1	1310	7390	47.5
TRANSIT 5A	18/12/62	19/12/62	91.4	333	344	90.6
ALOUETTE 1	29/09/62	?	107.9	993	1040	80.5
SAMOS 6	7/3/1962	06/08/63	93.9	235	681	90.9
ANNA 1B	31/10/62	?	107	1151	1250	50

Table IV.3 shows that at least eight satellites suffered damage that was definitely related to the STARFISH PRIME event [Weenas, 1978]. This damage was studied and documented in the scientific literature.

Table IV.3. Satellites Damaged by High Altitude Nuclear Tests.

SATELLITE	TIME IN ORBIT	DAMAGE
TRAAC	15 Nov 61- 12 Aug 62	• 1120 km x 950 km/32.4^0 • Solar cell damage due to STARFISH PRIME • Satellite stopped transmitting 36 days after the STARFISH PRIME event due to STARFISH PRIME radiation
Telstar-1	10 July 62 - 21 Feb 63	• 5656 km x 955 km/45^0 • 7 Aug 62 - Intermittent operation of one of two command decoders • 21 Aug 62 - complete failure of the one command decoder • Intermittent recovery made via corrective procedures – power adjustments to affected transistors – continuous commanding – modified commands • 21 Feb 63 - complete failure of command system – end of mission • Lab tests confirm ionization damage to critical transistors
Explorer 14	2 Oct 62-8 Oct 63	• 98,850km x 278 km/33^0 • problems encountered 10-24 Jan 63 • Encoder malfunction-11 Aug 63-ended transmissions • After 8-9 orbits, solar cell damage: – Unshielded p-on-n:70% – Unshielded n-on-p: 40% – 3-mil shielded cells (both types): 10%
Explorer 15	27 Oct 62-9 Feb 63	• 17,300 km x 310 km/18^0 • minor short period encoder malfunctions • Undervoltage turnoff 27 Jan 63 • Second undervoltage turnoff 30 Jan 63 – encoder permanent failure
Transit - 4B	15 Nov 61 - 2 Aug 62	• 1110 km x 950 km/32.4^0 •Solar panels showed 22% decrease in output 25 days after the STARFISH PRIME event – Lead to demise of satellite
Alouette - 1	29 Sept 62 - ?	• 1040 km x 993 km/80^0 •Satellite place on standby status Sept 72 due to battery degradation • Satellite overdesign prevented failure, however degradation still occurred due to STARFISH PRIME.
OSO-1	7 March 62 - 6 Aug 63	• 591 km x 550 km/32.8^0 • Solar Array degradation due to STARFISH PRIME event • Provided real-time data until May 64 when its power cells failed
Ariel-1	26 April 62 - Nov 62	•1210 km x 390 km/53.^{0} •Undervoltage condition occurred 104 hours after STARFISH PRIME event –Solar Cell efficiency reduced by 25% •Intermittent loss of modulation both on real-time telemetry and tape recorders –Speculation that this modulation problem was a result of a STARFISH PRIME - induced electrostatic discharge on the satellite
Anna-1B	31 Oct 62- ?	•1250km X 1151Km/50^0 •Solar Cell deterioration due to STARFISH PRIME

The most celebrated victim of STARFISH PRIME was the world's first communications satellite, Telstar, which relayed voice and television signals across the Atlantic. Telstar was launched on 10 July 1962, one day after the STARFISH PRIME nuclear explosion. About one month after launch, there was an indication that one of two command decoders on board the satellite was failing. By utilizing modified and continuous commands to the satellite, the decoder was temporarily recovered. Complete failure of the command system did finally occur in February of 1963. Radiation tests were subsequently conducted on the ground and the failures were traced to a problem with certain npn transistors enclosed in nitrogen canisters. Furthermore, the failures were clearly determined to be a result of total dose ionization damage from high energy electrons. These transistors were part of the Telstar command decoder circuitry [Mayo, 1963]. Other satellites that failed (Transit 4B, TRAAC, Ariel, OSO-1, Anna-1B) did so as a result of a drastic loss of output power from critical solar arrays caused by high energy electrons from STARFISH PRIME [Fischell, 1963]. Figure IV.1 clearly illustrates the dramatic reduction in solar cell output power as a result of the STARFISH PRIME-induced radiation environment. Note that solar cell short circuit current on both the Transient Research and Attitude Control (TRAAC) and Transit-4B satellites suffered a dramatic drop right at the time of the nuclear event. A 22% drop in TRAAC solar cell current occurred over 28 days following the nuclear event. The same percentage drop in current occurred on the Transit-4B satellite over 20 days following the STARFISH PRIME detonation. Rapid deterioration of solar cells led to the demise of Transit-4B 24 days after the STARFISH PRIME event followed shortly thereafter with the loss of TRAAC 36 days after the nuclear event.

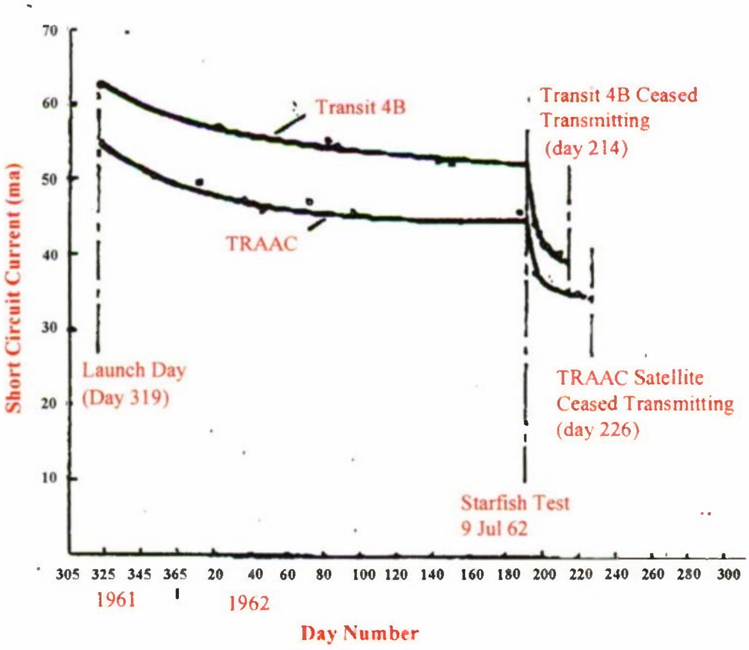

Figure IV.1 TRAAC and Transit 4B Solar Cell Degradation

Another satellite, the Canadian Alouette spacecraft, suffered damage from STARFISH PRIME radiation even though the satellite was over designed [Adamson, Sept 2002]. There was also considerable concern for human space flight since the human body was much more sensitive to radiation than satellite electronics. On September 5, 1962, President John Kennedy met with SECDEF McNamara, NASA officials and other experts to discuss upcoming high altitude nuclear tests and possible health repercussions for Mercury astronaut Walter Schirra who was scheduled to go into orbit a few weeks later. Concerns that Schirra might be exposed to unacceptably high levels of radiation if high-altitude tests were conducted lead the administration to postpone further testing until after the mission [Presidential Recordings Project, Fall 2001]. A few days after Schirra's flight, an Air Force spokesman announced that Schirra would have been killed by residual STARFISH PRIME radiation if he had flown above 640 km altitude [Grimwood].

There were other satellites on orbit at the time of STARFISH PRIME, but there is no documentation that these satellites suffered any problems from radiation. There are several potential explanations for this. It is quite possible that many of these satellites did indeed suffer problems but these facts were not documented or were documented at one time and then the information was lost. For example, very little documentation exists on the TIROS-5 satellite. The failure of the medium-angle weather camera on the satellite, one day before the STARFISH PRIME event, may have significantly lowered the load on the electrical system which could have masked any solar array degradation problems caused by STARFISH PRIME [Weenas, 1978]. Some satellites were U.S. classified space assets and Soviet spacecraft. In both cases, security factors would have limited the amount of public documentation about any satellite anomalies on these satellites. In addition, much of the electronics in a Soviet satellite were enclosed in a relatively thick, pressurized module for convective cooling purposes. This would require a thicker spacecraft structure to maintain pressure integrity [sputnik1.com; russianspaceweb.com]. The extra shielding thickness would have further protected internal electronics from damage by fission electrons and thus Soviet satellites at that time may have been more resistant to nuclear radiation than their U.S. counterparts.

IV.C Failures Resulting from the Natural Radiation Environment

Over the years, scores of satellites have been upset, degraded, or destroyed just due to the natural radiation environment (see Figure IV.2). Many of the satellite failures were caused by electrostatic discharge (ESD) events caused by deposition of low energy electrons on the exterior of the satellite. One (indirect) source of these electrons is Coronal Mass Ejections (CMEs), which are huge quantities of plasma blown off from the sun that sometimes intersect the Earth's magnetosphere where they create magnetic storms. Probably the most famous ESD satellite failures were the two Canadian ANIK E-1 and E-2 satellites. These satellites provided important services for Canada, including news, weather, and entertainment programming. Daily newspaper information from a national news-gathering cooperative was interrupted for hundreds of daily newspapers. The temporary loss of these satellites also interrupted telephone and cable TV service in Canada [Solar-Terrestrial Energy Program, 1994]. Both ANIK satellites suffered a failure in momentum wheel control circuitry needed to maintain attitude control for critical antenna positioning. ANIK E1 was eventually able to switch to its backup control circuitry. However, both the primary and backup control circuitry for ANIK E-2 failed and the satellite was unusable for seven months until a rescue plan could be put in place to allow continuous ground-commanded control using precious attitude control fuel on the satellite.

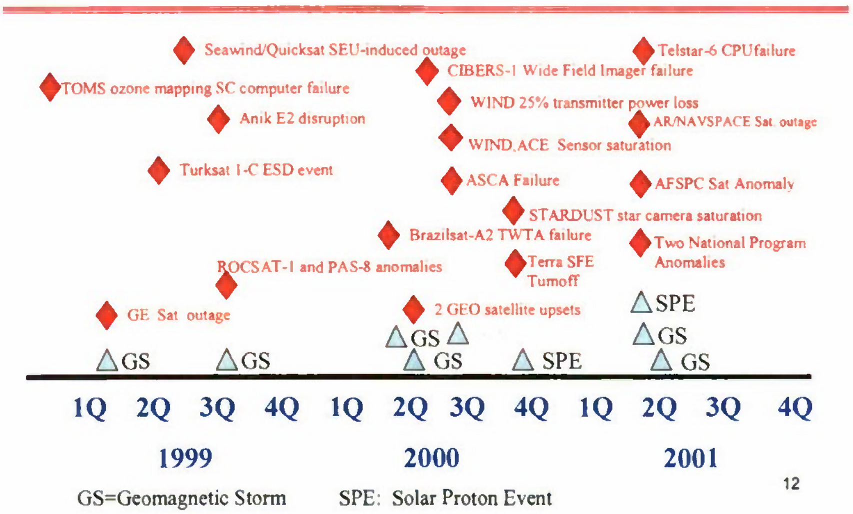

Figure IV.2 Chronology of Satellite Anomalies and Space Weather Events.

IV.D Laboratory and Underground Nuclear Testing

The Atmospheric Test Ban Agreement of 1963 stimulated strong technology programs within the Department of Defense and the National Aeronautics and Space Administration to investigate the nature of radiation effects on space systems and to find design techniques to mitigate them. One only needs to peruse the literature [IEEE Transactions on Nuclear Science and Engineering, 1963-2003] to appreciate the National efforts expended on technology to make our space assets appropriately survivable to a nuclear attack.

One could not perform radiation tests on complete satellites in orbit, but there had been a continuing effort to develop laboratory radiation sources to examine components and subsystems. Tests in these facilities were, and still are, referred to as Above Ground Tests (AGTs). AGTs were complimentary to Under-Ground nuclear Tests (UGTs) that were a closer approximation to above-ground detonation of a tactical nuclear weapon. In fact, all of these tests can, under the best of circumstances, only approximate a real tactical nuclear *environment* and are called *Effects Tests,* as opposed to *Environmental Tests.* The former can only be reliable if one understands the coupling of the radiation to the test objects.

The testing protocol was to use the best possible analytical method to predict the response of a constituent *material* to a test radiation. Then an actual radiation test was done to test the fidelity of the analysis. If the analysis was validated, another analysis was done to predict the response of a *component* made with this material and the component was tested in the radiation source. If this component prediction was validated, the prediction of the response of a more complete *circuit* would be made and that would be tested. This iterative process was conducted at increased complexity each time in the AGT and when the developer was satisfied, a final test was conducted in a UGT, after which the analysis was extrapolated to a tactical environment.

It was well recognized that the UGT was extremely expensive, difficult to instrument, and carried a high risk of failure, so as much as possible was done in AGT to make the risk as low as possible. One important feature of the UGT is that it forced the builder to do the necessary AGT homework in order to maximize the probability of a successful UGT. The testing and hardening process was expensive and restricted to military satellites whose missions were critical.

In the 1970s the Defense Nuclear Agency attempted to design and construct an X-ray test facility in which a full satellite could be tested, but budgetary considerations and Air Force opposition resulted in demise of the program.

In 1980 a test satellite called STARSAT (SGEMP Test and Research Satellite) was exposed to the X-rays from an underground nuclear detonation. The satellite model was constructed in order to study the iterative test and analysis protocols described above. The DSCS satellite Program Office provided much of the satellite structure, including some of the DSCS subsystems.

Figure IV.3. Experimental chamber containing STARSAT in the HURON KING event.

In this test the satellite was placed in a vacuum chamber as illustrated in Figure IV.3. The vertical tubular object on the right was connected to a vertical evacuated line-of-sight (LOS) pipe that extended from the buried nuclear device to the ground surface. The pipe contained a closure system that was automatically actuated immediately after the detonation-produced X-ray pulse arrived and before radioactive effluence could escape. The shed-like enclosure on the left of the structure contained signal conditioning equipment. Behavior of the satellite during exposure was monitored both in a remote trailer and also in the General Electric development laboratories in King of Prussia, Pennsylvania. The tracked wheels were to allow the whole configuration to be pulled away from the LOS pipe before the earth subsided after the detonation.

The experiment was highly successful, except for the misbehavior of an attitude control circuit. This malfunction was traced to an experimental artifact and confirmed in a subsequent UGT.