High Altitude Nuclear Detonations (HAND) Against Low Earth Orbit Satellites ("HALEOS")

DTRA
Advanced Systems and Concepts Office
April 2001

1

3/23/01 DTRA

SPONSOR: Defense Threat Reduction Agency - Dr. Jay Davis, Director
Advanced Systems and Concepts Office - Dr. Randall S. Murch, Director

BACKGROUND: The Defense Threat Reduction Agency (DTRA) was founded in 1998 to integrate and focus the capabilities of the Department of Defense (DoD) that address the weapons of mass destruction (WMD) threat. To assist the Agency in its primary mission, the Advanced Systems and Concepts Office (ASCO) develops and maintains and evolving analytical vision of necessary and sufficient capabilities to protect United States and Allied forces and citizens from WMD attack. ASCO is also charged by DoD and by the U.S. Government generally to identify gaps in these capabilities and initiate programs to fill them. It also provides support to the Threat Reduction Advisory Committee (TRAC), and its Panels, with timely, high quality research.

SUPERVISING PROJECT OFFICER: Dr. John Parmentola, Chief, Advanced Operations and Systems Division, ASCO, DTRA, (703)-767-5705.

The publication of this document does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official position of the sponsoring agency.

Study Participants

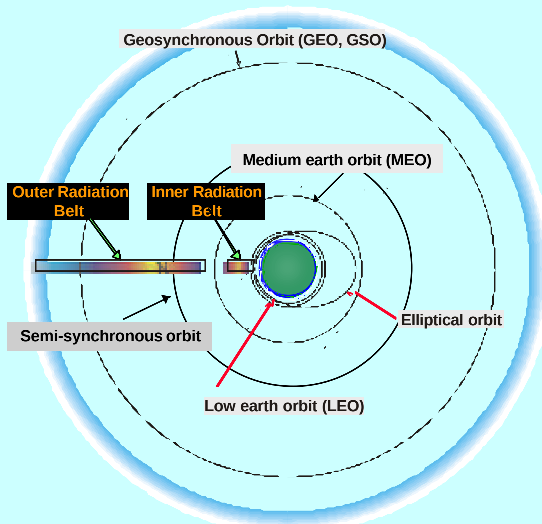
- DTRA/AS
  - John Parmentola
  - Thomas Killion
  - William Durch
  - Terry Heuring
- DTRA/TD
  - Lewis Cohn
  - Les Palkuti
  - Thomas Kennedy
  - Kenneth Schwartz
  - Balram Prasad
- RAND
  - Peter Wilson
  - Roger Molander
  - David Mussington
  - Richard Mesic
  - James Bonomo
- Logicon RDA
  - Glenn Kweder
  - Rob Mahoney
  - Al Costantine
- Mission Research Corp.
  - William White

Focus of This Briefing

- *Vulnerability of commercial and government-owned, unclassified satellite constellations in low earth orbit (LEO) to the effects of a high-altitude nuclear explosion.*
- *Hypothetical scenarios that could lead to such use of a nuclear weapon within a decade.*
- *Costs and consequences of such use.*
- *Recommendations for avoiding those costs.*

What is the Problem?

- LEO satellite constellations will be of growing importance to govt., commercial, and military users in coming years.
- Proliferation of nuclear weapons and longer-range ballistic missile capabilities is likely to continue.
- One low-yield (10-20 kt), high-altitude (125-300 km) nuclear explosion could disable -- in weeks to months -- ***all*** LEO satellites not specifically hardened to withstand radiation generated by that explosion.



Highly idealized depiction of natural radiation belts.
Inclination of each satellite orbit set to zero for display purposes.

4

3/23/01

The Van Allen belts are concentric rings of naturally occurring high-energy particles that surround the Earth . The intensity and size of the natural radiation belts vary constantly due to changing solar wind conditions.

During periods of high solar activity, the "slot" between the belts can be filled with energetic particles that remain for weeks to months.

Inner belt = LEO(150-1500 km) satellite hazard.

Outer belt = MEO(1500-35800 km) & GEO(35800 km) hazard.

A high-altitude nuclear explosion may <u>greatly intensify</u> trapped radiation.

How Could It Happen?

- **Collateral damage from regional nuclear war or TMD/NMD intercept:**
  - Nuclear warning shot in a regional conflict;
  - Effort to damage adversary forces/infrastructure with electromagnetic pulse;
  - Detonation of salvage-fused warhead upon exoatmospheric intercept attempt.

- **Deliberate effort to cause economic damage with lower likelihood of nuclear retaliation:**
  - By rogue state facing economic strangulation or imminent military defeat;
  - Pose economic threat to the industrial world without causing human casualties or visible damage to economic infrastructure.

Scenario 1: Collateral Damage from a Warning Shot (India-Pakistan, 2010)

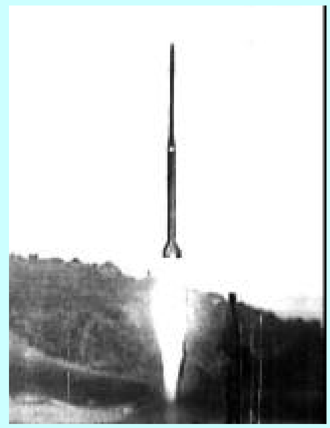
- *Truck bomb kills most of India's command echelon in Kashmir.*
- *India announces large military exercises near the India-Pakistan border.*
- *Pakistan mobilizes its reserves, including special weapons; missile regiments disperse into the field.*
- *Indian armor crosses the Pakistan border.*
- *Pakistan fires a medium-range missile that detonates a nuclear warning shot over New Delhi at night, high enough (~300 km) to reduce ground effects, yet clear enough to "bring India to its senses."*
- *Altitude of detonation enhances damage to LEO constellations.*

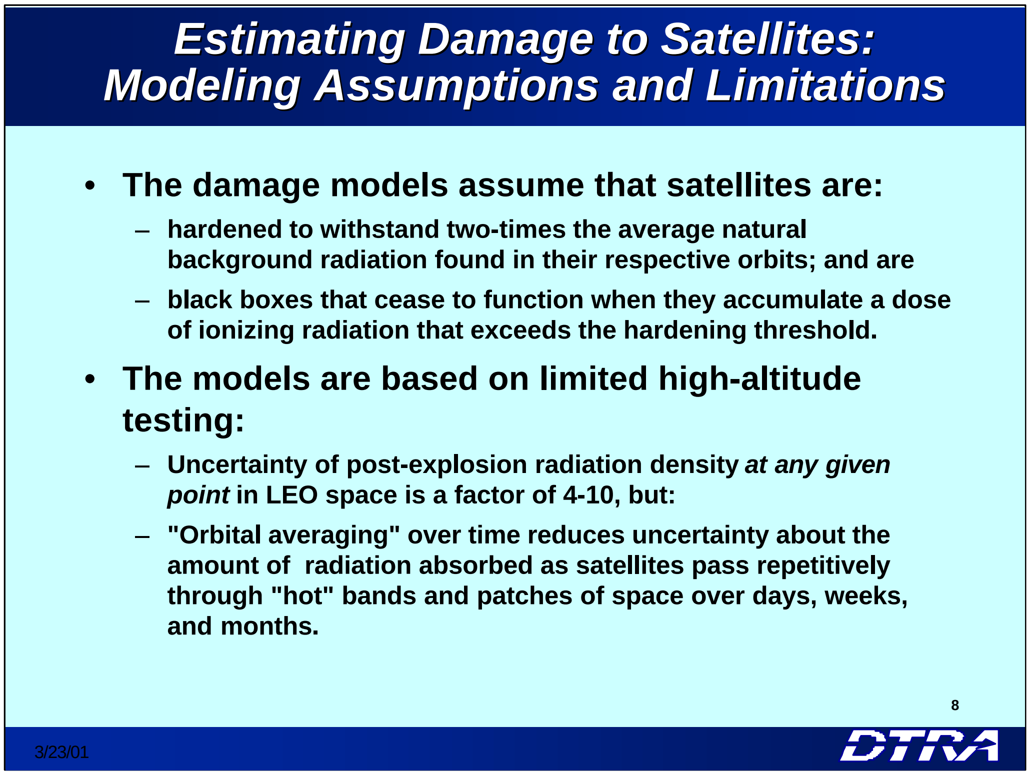
Senior Pakistani officials have said that Pakistan's nuclear warheads have undergone shock and vibration tests and are ready to be mounted on the country's Ghauri, or Hatf V, intermediate-range ballistic missile.

JANE'S DEFENCE WEEKLY
- 3rd JUNE 1998

Scenario 2: Deliberate Use or Salvage Fused Intercept (Korea, 2010)

- North Korean army coup/revolt, civil war ensues.
- Units loyal to Kim Jong-Il control missile/nuclear forces.
- ROK forces launch air strikes against northern missile sites; U.S. forces deploy for an aerial campaign against North Korean NBC assets.
- As ROK, US, and/or coup forces threaten to close down launch sites, nuclear-tipped Taepodong missile(s) launch, in Kim Jong-Il's final gesture of defiance toward the West.
- Warhead detonates on the ascent -- or is intercepted and detonates -- at 120 to 150 km altitude.





Radiation density or flux = electrons/cm2/sec, while fluence = calories/cm2/sec, and absorbed dose = fluence **x** exposed area **x** time.

Radiation Damage Modeling

Nuclear weapon effects

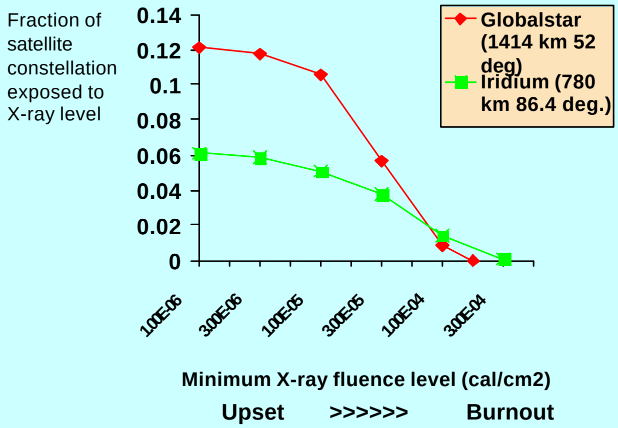
- Prompt X-rays damage satellites within line of sight, decreasing with distance ($1/R^2$);
- Unstable nuclear fission fragments decay, emitting electrons that are trapped in earth's magnetic field, greatly increasing ambient radiation in LEO.

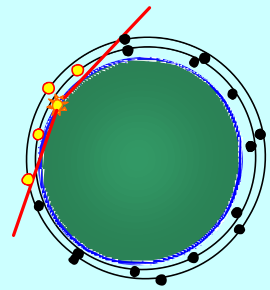
Duration

- **Lower Van Allen Belt region remains "excited" for 6 months to two years.**

Prompt Effects of High-altitude Nuclear Explosion

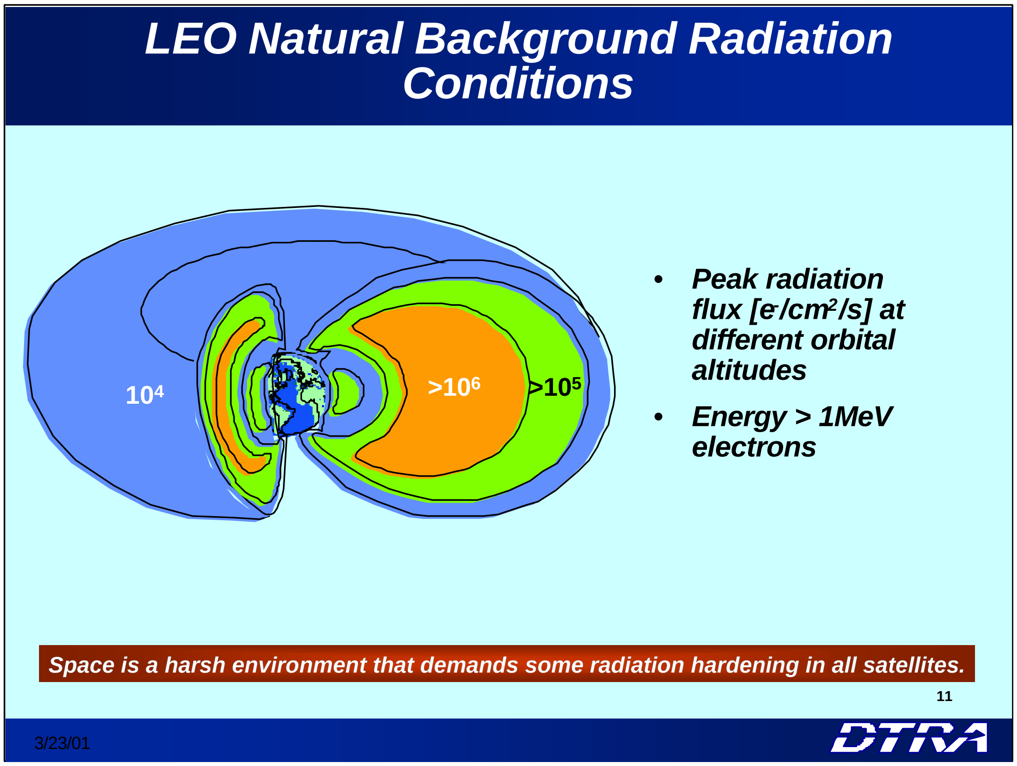
50 KT Burst over North Korea at 120 km altitude





(Simplified, single-plane, polar orbit illustration.)

Prompt X-radiation impacts 5-10% of each LEO constellation.



Trapped Radiation Effects on Space Systems

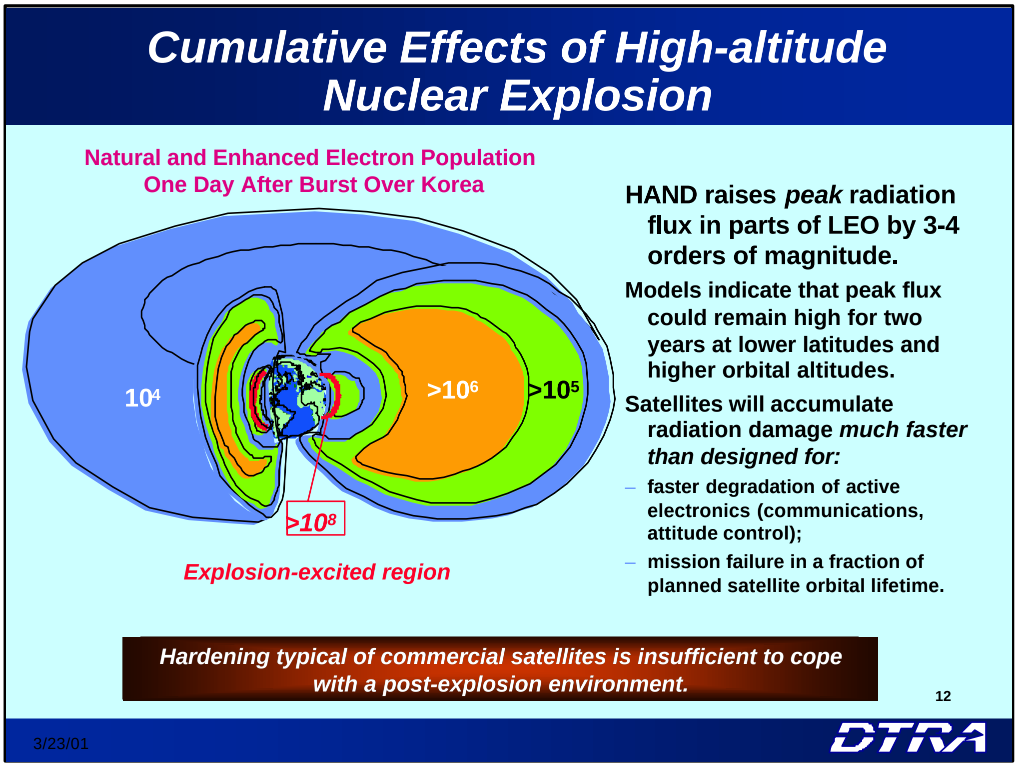
This chart illustrates the trapped radiation effects encountered by satellites at various altitudes.

• Total dose degradation and failure occurs in electronic systems exposed to both natural and nuclear ionizing environments. The primary source of natural total dose is from the protons and electrons trapped in the Earth's radiation belts.

• Semi-synchronous orbit presents the most severe environment because of an intense electron belt at that altitude (~20,000 km). The Global Positioning Satellites in this orbit have about a 10-year lifetime and must be able to survive a megarad of total ionizing dose.

• Most communications satellites, historically, have resided at GEO. Over their 10 to 15 year lifetimes they must survive about 100 krads total dose.

• The lowest-altitude LEO satellites (~ 800 km) encounter a relatively benign environment. A typical lifetime of 3-5 years means that these satellites only need to tolerate about 3-5 krads. LEO satellites in higher orbits (~1,400 km) need to tolerate considerably more (~30-50 krads).

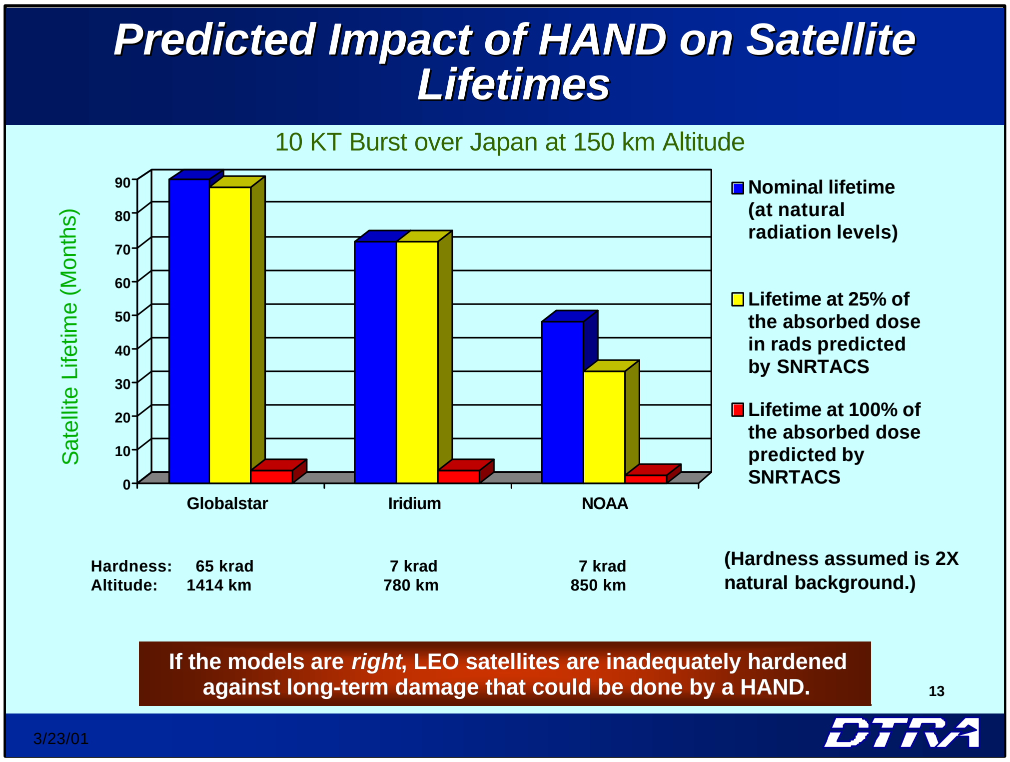


Space Asset Degradation/Failure fromNuclear-Weapon-Pumped Total Radiation Dose

Weapon-produced total dose accumulation comes from gammas, x-rays, neutrons, and debris gamma interactions, plus the contribution from beta decay electrons trapped in the Earth's magnetic field. These nuclear debris electrons form into a belt that varies with the altitude, latitude and yield of the weapon. This enhanced electron belt will surround the earth and cause increased total dose levels in spacecraft that are not in the direct line of sight of the detonation.

The total dose environment slows switching speed and increases the power requirements of a satellite's active electronics. The first sub-systems that fail may include the attitude control electronics or the communications link. Eventually the active electronics fail and the system becomes incapable of performing its mission.

LEO satellites designed to survive only the natural radiation environment would be highly vulnerable to low-yield (10-50 KT) nuclear detonations at high-altitude (120-300 km).



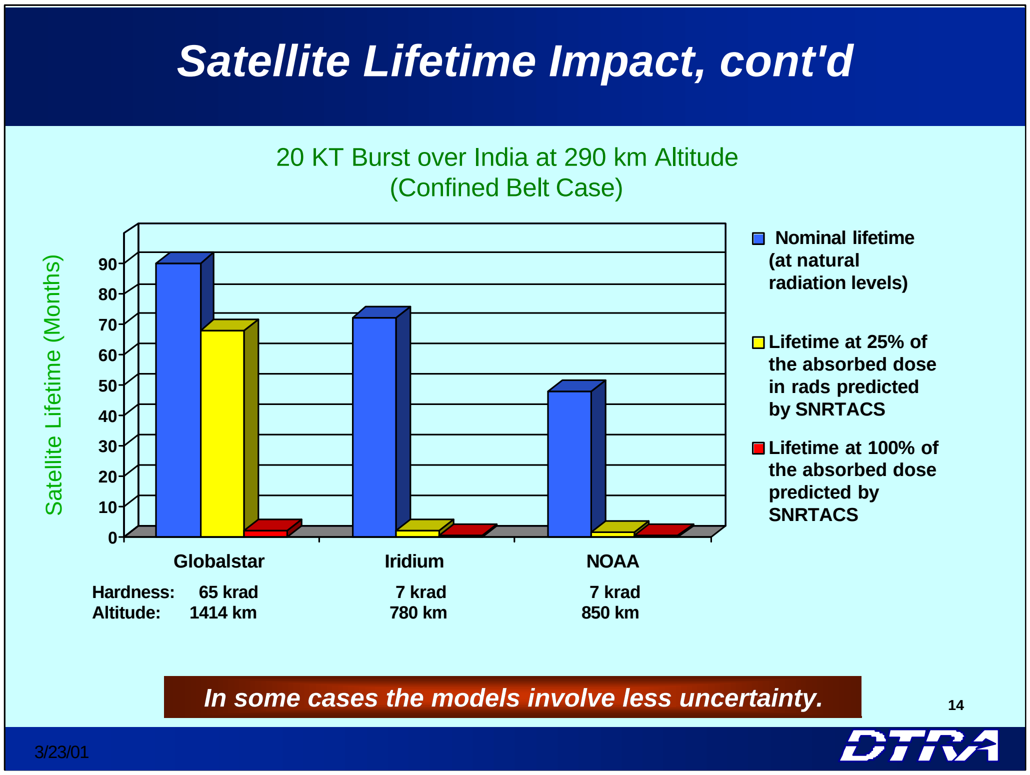
Impact of Total Dose on Satellite Lifetime

This chart depicts the dramatic reduction in satellite lifetime due to long term total dose effects which result from exploding a 10 KT low-yield weapon at a height of 150 km over Japan. This total dose accumulates as satellites transit through the weapon-enhanced (“pumped”) electron belts.

The modeling assumed that satellite systems were hardened to twice the natural background radiation expected for their designed orbital lifetime and that these satellites were not damaged by the initial prompt radiation.

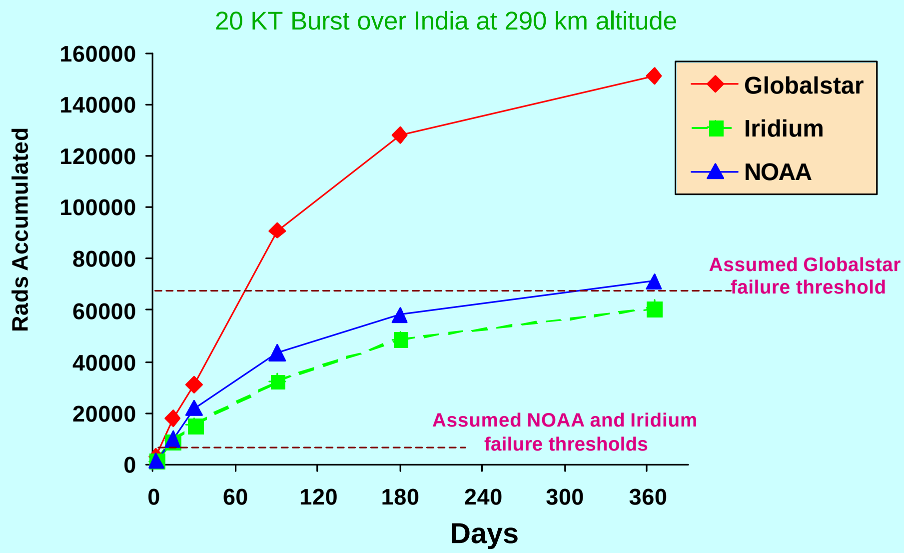
The model cumulates absorbed dose and declares a satellite "dead" when the total absorbed dose exceeds the hardening assumption. For satellites assumed to be hardened to 7 krad, death occurs in 2-4 months. The chart does *not* reflect possible performance degradation due to cumulative radiation damage that would occur before the mortality threshold is reached.

Because there is roughly a factor of 4 uncertainty in the model's predictions of total dose, taking into account "orbital averaging," we included an "error bar" reflecting accumulation at one-fourth the rate that the model predicts. If the model is off by that much, HAND may not have much impact on LEO satellite lifetimes. But it could just as well *underpredict* dose rates by a factor of 4, in which case satellite lifetimes after a high-altitude nuclear burst would be even shorter than depicted in red.



If a nuclear weapon detonates at higher altitude, the belt-pumping effects can be more dramatic, and the damage uncertainties less, at least for those satellites in the normally most benign, lower reaches of LEO.

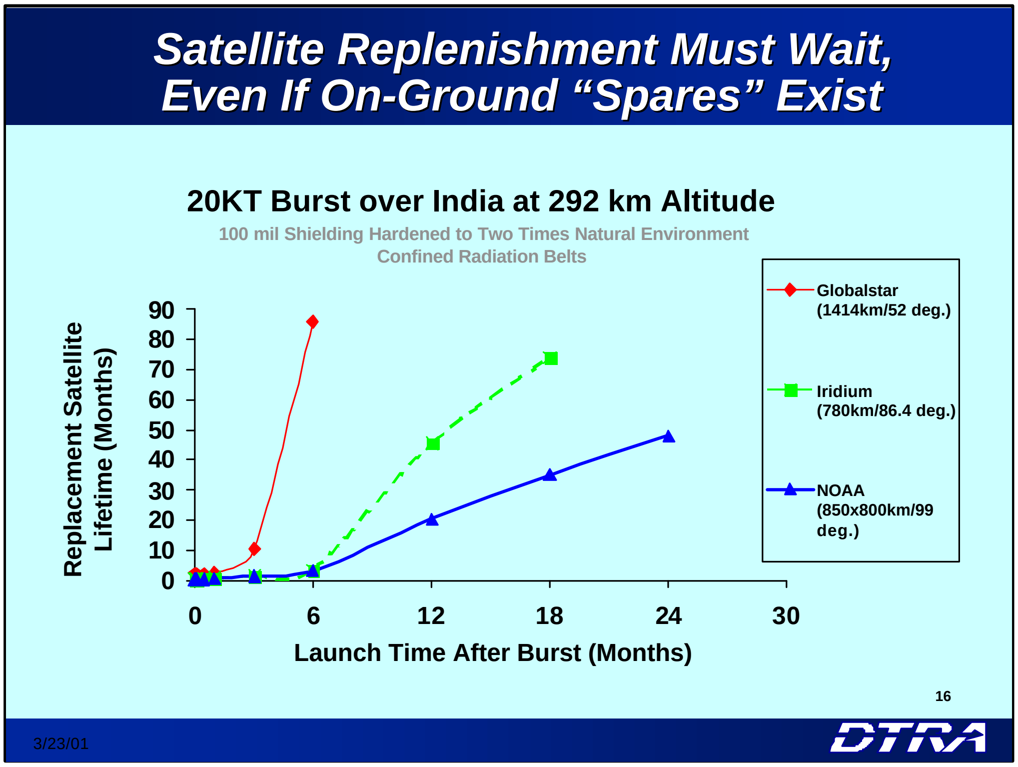
Dose Accumulation Rates, Baseline Model



15

3/23/01

DTRA



Globalstar (assumed here to have been hardened to 2x natural background for a 1,400 km orbit, or 65 krad total dose), could be reconstituted 6 months after a nuclear event and enjoy a near-normal lifespan.

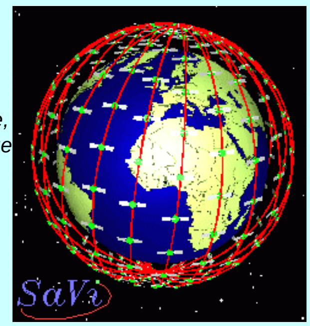
Replacement satellites hardened to just 7 krad and destined for lower (800 km) orbits would fail rapidly if launched less than a year after the same nuclear event. Replacements launched 18-24 months after the fact would enjoy near-normal lifespans.

Once again, this model is just estimating total absorbed dose and watching for that dosage to cross a specified tolerance threshold. Replacement satellites launched into the slowly cooling post-explosion LEO environment may still suffer some radiation-induced performance degradation.

LEO Comsat Functions

Telecommunications Systems:

- ***Provide local/global comms with limited ground-based infrastructure.***
  - *Low latency access where terrestrial infrastructure (fiber optic, twisted pair, cable and cellular) is limited, in competition with regional GEO systems.*
- ***Representative systems and functions:***
  - *Narrowband (voice, paging, messaging): Globalstar (48 satellites plus spares), OrbComm (26+), Iridium (66+); replacement cost >$6 billion.*
  - *Broadband (interactive data, teleconferencing, telemedicine, e-commerce):* [1] *Teledesic (288 currently planned), Skybridge (80); replacement cost >$16 billion.*
- ***Primary applications:***
  - *Corporate communications (intra/extranets),*[2] *mobile users.*
  - *Regions with limited ground infrastructure.*



Teledesic Constellation, from the Geometry Center at the Univ.. of Minnesota, at www.geom.umn.edu/~worfolk/SaVi/

1 J. Montgomery (November 1997). "The Orbiting Internet: Fiber in the Sky." *BYTE.*
2 Cyber-tech 2 Conference, Johns Hopkins Univ., June 1998

17

3/23/01

DTRA

To estimate on-orbit communications satellite bandwidth in 2010, we used launch projections for GEO (replacement and new satellites), using published industry data. Drawing on open sources, there were about 190 satellites in geosynchronous orbit in early 1999. Roughly 45% of the launches between 1996 and 2006 are to replace aging GEO satellites; the other 54% will be new birds. By 2010, there are likely to be about 375 commercial communications satellites in GEO. Assuming that transponder capacity will be somewhat greater, on average, in newer satellites, we estimate roughly 270 Gbps total capacity in GEO in 2010.

Of the LEO constellations projected to be operational in 2010, the narrowband constellations will contribute less than 1 Gbps in toto, while the broadband constellations (Skybridge, Teledesic) may contribute another 200-250 Gbps if they become operational; thus there is a wide error bar on this number.

How important this bandwidth is depends on your assumptions about ground-based alternatives, and the needs of particular users.

(Calculations by Glenn Kweder, Logicon/RDA, drawing on "Satellite Industry Trends and Statistics," C. Boeke and R. Fernandez, *Via Satellite*, July 1996; T. Foley, editorial, *Via Satellite*, December 1999; *Launchspace Magazine*, May/June 1999; "The Satellite Market," L. Journez, http://www.euroconsult-ec.com.)

Defense Consequences of Losing LEO Comsats

- ***Immediate military consequences of HAND would derive from prompt/direct nuclear effects (e.g., HEMP against ground/air assets).***
- ***Longer-term consequences would vary with relative dependence of the services or their support contractors on LEO bandwidth***
  – Heavy dependence on vulnerable classes of LEOs would begin to hurt two weeks to two months after a high-altitude detonation.
  – Degree of hurt would depend on redundancy of DoD bandwidth sources (GEO satellites, aircraft, land systems) and whether an adversary sought to exploit the transition period.
  – Period of greatest risk likely to be 1-2 months following HAND, as LEO systems fail and replacements are sought or brought on line.

Meteorological Systems

- ***Primary functions:***
  - High resolution, global environmental data (temperature, wind speed, humidity) that feed into weather prediction models and help monitor significant weather patterns.
- ***Representative systems:*** DMSP, NOAA systems merging into NPOESS c. 2010
- ***Number of satellites:*** 4, dropping to 3 more-capable units
- ***Replacement Cost:*** ~$700 million
- ***Consequences of Loss:***
  - Severe degradation in 3-5 day forecasting capability.
  - Significant degradation in 0-12 hour marine forecasts.[1] (Thirty-thirty five ships are lost annually due to weather, even with satellite forecasts available.[2)]
  - Degraded performance of Tactical Decision Aids that depend on LEO satellites for mesoscale data over enemy terrain to facilitate dynamic targeting, hazardous weather avoidance, reduced collateral damage and reduced target re-strike.

1 R. Atlas, Goddard Space Flight Center, Personal Communication.
2 International Maritime Organization, "World Maritime Day Report," 1997, 1999. *www.imo.org/imo/wmd*.

19

3/23/01

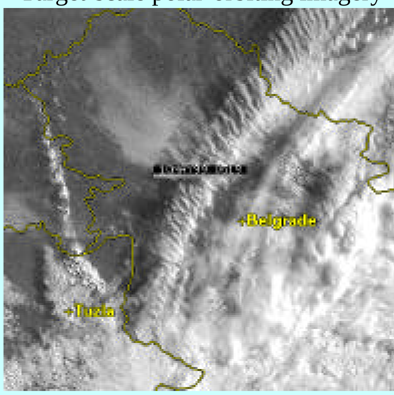
DTRA

Estimated satellite replacement costs $425 million, launch costs $250 million.

LEO vs. GEO Metsat Imagery

Metsats in low earth orbit provide details unavailable from geosynchronous orbit in visible, infrared, and microwave spectra; atmospheric sounding; sea surface temperature.

Target-scale polar-orbiting imagery



Regional-scale geostationary imagery (maplines superimposed)

Source: "NPOESS: A Look into the New Millennium," John Cunningham, NPOESS System Program Director, October 21, 1999. http://npoesslib.ipo.noaa.gov/Program/presentation.htm

20

DTRA

Imaging/Mapping Systems

- ***Primary functions:*** Global imagery for government and commercial applications, including forecasts for the USAID Famine Early Warning System (FEWS) for Sub-Saharan Africa, environmental impact assessment, land management, resource exploitation, peacekeeping support. National Imagery and Mapping Agency (NIMA) strategy is to maximize use of commercial systems in its US Imagery and Geospatial Service (USIGS) and Partnership for Peace Information Management System (PIMS).
- ***Representative systems:***
  - Landsat, Ikonos, Quickbird, Earlybird, Orbview (U.S.)
  - ALOS, ADEOS (Japan); SPOT, Helios (France);
  - Almaz, IMSAT (Russia); Eros/Ofeq (Israel);
  - IRS (India); CBERS (Brazil/China)
  - Radarsat (Canada)
- ***Number of satellites:*** 25+ ***Cost:*** $4-5 billion
- ***Consequences of Loss:***
  - FEWS, other crop/commodity forecasts degraded
  - Loss of supplementary arms control verification
  - Loss of commercial input to NIMA's USIGS, PIMS systems

IKONOS, 1 meter

21

3/23/01

DTRA

Replacement satellite costs about $4 billion, launch costs about $760 million.

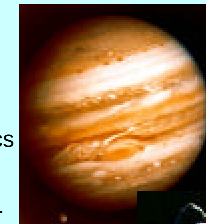
Sources: NIMA \website http://164.214.2.59/pims

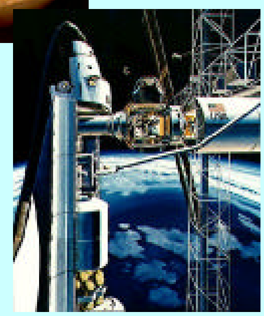
USGS website: http://edcintl.cr.usgs.gov/fews/fews.html

USAID website: http://www.info.usaid.gov/fews

Research, Astronomy, Manned Spaceflight

- ***Primary functions:*** Provide space-based assets to obtain fundamental data on the universe and on space environs.
- ***Representative systems:***
  - Space Shuttle, International Space Station (ISS)
  - Hubble Space Telescope
  - Advanced Satellite for Cosmology & Astrophysics
  - Compton Gamma Ray Observatory
- ***Number of systems:*** 10+ ***Cost:*** $25 billion+
- ***Key applications:***
  - Astronomical research
  - Space-based manufacturing and life processes research
- ***Consequences of HAND:***
  - Damage to electronic components of unique systems.
  - A year or more delay to accomplish ISS repairs: ambient radiation too high for extra-vehicular activities.
  - Shuttle operations similarly curtailed.





Risk Mitigation Options

Risk Mitigation Strategies and Evaluation

- *Replacement Measures*
  - *DIRECT REPLACEMENT*
  - *SUBSTITUTE TECHNOLOGIES*
- *Preventive Measures*
  - *Deter attack through THREAT OF SANCTIONS or THREAT OF RETALIATION*
  - *Maintain capabilities by HARDENING LEO SATELLITES*
- *Economic & Political Costs vs. Effectiveness of Mitigation Strategy*
  - *Which is the most cost effective approach?*
  - *Which has the least political cost?*
  - *Which provides the least uncertainty?*

Which strategy maintains capabilities with least uncertainty at low cost?

Direct Replacement of Satellites

- ***Insurance coverage usually exempts "acts of war," but can be purchased (25-30% of program costs).***
- ***Venture capital unlikely to underwrite equally-vulnerable replacement constellations after a nuclear event.***
- ***Replacement would have to wait until the radiation belts cooled.***
  - Would take several years to repopulate large constellations, competing for scarce launch capacity.
  - Communications market share would be lost *ad interim* in the developed world and emerging markets may not suffice to energize reconstitution.
  - Insurers/financiers may insist on radiation-hardened components as condition of re-investment in LEO.

LEO satellite operators may have just one shot at building commercially viable constellations.

24

3/23/01 DTRA

Expensive, one-of-a-kind scientific instruments like Hubble are unlikely to be replaced. NOAA weather satellites, as noted earlier, could require up to a two year cooling off period before normal satellite survival rates were attainable, without additional hardening.

Substitute Technologies

- ***For civil LEO Comsat customers:***
  - Users in developed countries will have terrestrial alternatives, at some additional cost of service.
  - Users may have near-term space alternatives at MEO or GEO altitudes, depending on:
    - "slack" bandwidth or availability of spare satellites in higher constellations;
    - uncommitted launch capacity, spare satellites available to launch, uncommitted frequency slots, and funds available to reinvest in ground segment.
  - Users in developing countries, which are likely to have an increasing impact on world commerce, will have fewer immediate options.

Substitute Technologies, *cont'd*

- ***For potential military LEO Comsat customers:***
  - MEO and GEO constellations may be attractive alternatives to LEO, out of range of the threats detailed here, but planned constellations will not meet growing service demand, 2010+.*
  - Theater capabilities (High Altitude, Long Endurance UAVs, manned aircraft, wireless ground nets) may be feasible, if costly, operational alternatives.
  - To ensure reliable reach-back communications capability in a transient nuclear environment in theater will require relatively simple EHF mitigation techniques.
  - Communicating with frequencies other than EHF during transient nuclear environment in theater will be a very short-term problem for HALEOS in the kiloton range.
- ***For manned spaceflight and high resolution weather data:***
  - No direct substitutes for LEO systems.
- ***For ground imaging:***
  - Aircraft-based systems substitute for tactical and small-area applications.
  - No direct substitute for large-area, long-term monitoring applications.

* Peter M. Stauffer, "Army After Next: SATCOM Support," USARSPACE briefing. Unclassified, February 11, 1999.

In the event of a HAND, the manned space program would have to stand down for a year or more as radiation levels subsided.

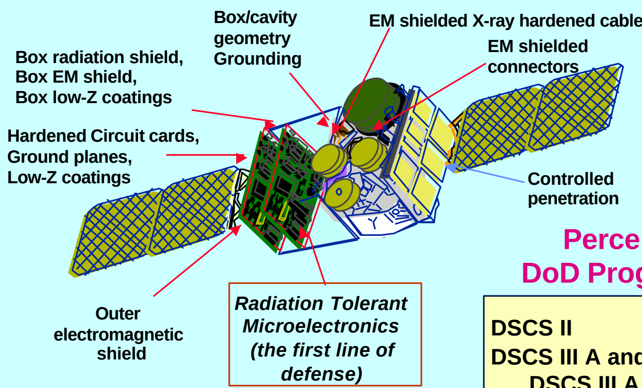
Deterrence and Retaliation

- ***Are there credible deterrent strategies to HALEOS?***
  - Uncertainty undermines the credibility of threat to retaliate
    - *Perpetrator must believe that US has the will & capability to carry out threat.*
    - *domestic and international political support for such threats maybe difficult to generate.*
- ***Threat of economic sanctions:***
  - Pace of sanctions impact is on same order as pace of satellite failure; but
  - Not much leverage on an insular/rogue state's behavior.
  - Threat to impose sanctions may be lost in the noise of an ongoing conflict.
  - Might encourage perpetrator to use HALEOS as a response to economic sanctions.

Deterrence and Retaliation, cont'd

- ***Threat of nuclear retaliation:***
  - US/friendly territory/forces would not be directly harmed
    - *lack of in-kind or commensurate targets (moral difficulty in crossing nuclear threshold)*
    - *loss of LEOS through collateral effects of third parties' conflicts especially problematic for retaliation*
  - Difficult to generate allied/public support for threat of retaliatory action
    - *Hard to establish danger in public's mind in advance, and damage would be slow to occur*
    - *The event, even if deliberate, could be dubbed accidental by the perpetrator*
- ***Threat of conventional retaliation:***
  - Willingness to use smart conventional weapons has been demonstrated; but
  - credibility requires capacity to strike difficult targets, e.g., mobile, buried, or hardened targets
  - In practice, limited to compact target sets

Satellite Hardening: Components and Costs



Percentage of DoD Program Costs[a]

DSCS II	5%
DSCS III A and B	5%
DSCS III A	8%
DSCS III B	2%
FLTSATCOM I and II	6%
FLTSATCOM I	7%
FLTSATCOM II	3%
GPS II	1%

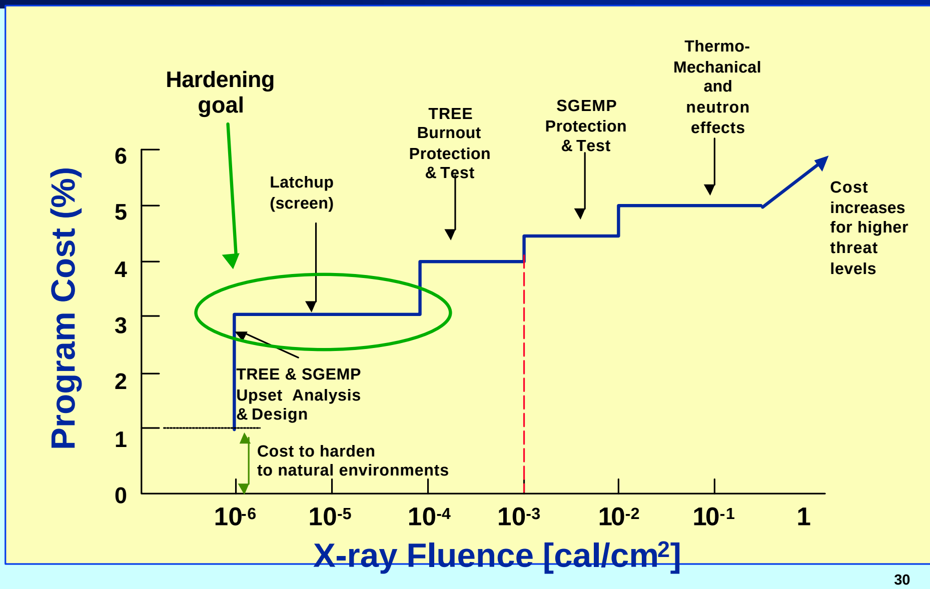
a/ Institute for Defense Analysis Paper P-2857, "Estimating the Costs of Nuclear-Radiation-Hardened Military Satellites," Nov. 1994. Unclassified.

DoD programs hardened these constellations against prompt, high-dose effects of nuclear explosions.

Illustration depicts generically the sorts of satellite components that require radiation hardening to survive exposure to a nuclear-pumped environment.

Low-Z - refers to atomic number (e.g. Aluminum is a low Z metal)

Cost Increase for Hardening Depends on the Objective



30

DTRA

Satellite Hardening: Issues and Obstacles

- ***DoD experience with costs of hardening cuts two ways:***
  - Current systems in GEO hardened to natural background & nuclear effects and costs were spread over relatively few production satellites.
  - Redesign or retrofit is more costly than building radiation hardness into a new design
  - Sufficient hardening to survive HAND-induced total radiation dose could ***add 2-3 percent to satellite costs*** beyond that required to harden against the natural environment.
- ***Industry and DOD are working elements of hardening:[1]***
  - 32-bit onboard computers hardened to 1 mega-rad total dose;
  - Application-specific integrated circuits hardened to 100 krads total dose; radiation-hardened SRAM and gate arrays.
- ***But operators may need prompting by public policy to design for survival in a nuclear-pumped environment.***

[1] C. Mahle, et al., "Key Technology Trends -- Satellite Systems," *Global Satellite Communications Technology and Systems*, a report from the World Technology Division, International Technology Research Center, Loyola College of Maryland, for the National Science Foundation and NASA, December 1998.
C. Burroughs, "Tests ensure satellite electronics endure long-term radiation exposure," *Sandia Lab News*, 50:16, August 14, 1998.

Conclusions:

- ***Vulnerable LEO constellations may present tempting targets to future nuclear-missile-armed rogues, lowering the nuclear threshold.***
- ***Or they may be destroyed as a by-product of nuclear detonations with other objectives (e.g., EMP generation, salvage-fusing at intercept).***
- ***HAND against LEO constellations may:***
  - Knock out important military communications, imaging, and weather forecasting support with peak impact 1-2 months after the event.
  - Cause socio-economic and political damage, varying with levels of dependence on LEO constellations:
    - › *Potential shock to the global financial and economic system.*
    - › *Capacity lost with LEO satellite destruction may spike the global price of bandwidth.*
    - › *Emerging markets that rely on LEO connectivity could face substantial costs in switching architectures or lengthy broadband disconnect/brownout.*
- ***Impacts could be mitigated by advance planning and redesign to increase radiation hardening in new LEO systems or by block upgrades to existing systems.***
  - USG could subsidize hardening, make it a condition of government use of US-based LEO comsats, or use only higher-altitude comsats.
  - Hardening of international satellite consortia (e.g., Skybridge) likely to require intergovernmental action.