Hazards of Reentry Disposal of Satellites from Large Constellations

William Ailor, The Aerospace Corporation

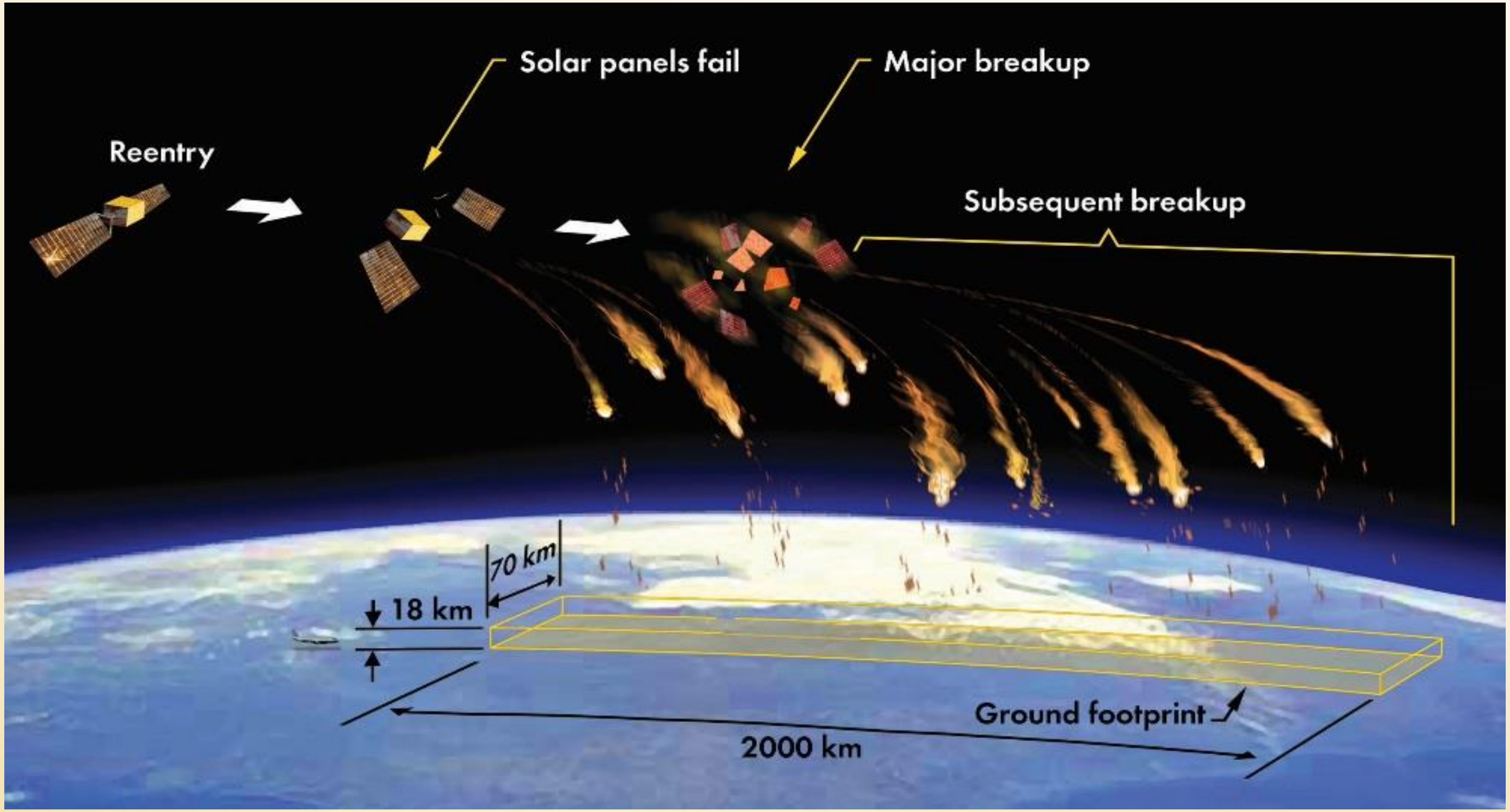
Briefing presented by Michael Kezirian

Acknowledgement

This briefing is based on material in

Ailor, W.H., “Hazards of Reentry Disposal of Satellites from Large Constellations,” *Journal of Space Safety Engineering*, Volume 6, Number 2, pages 113-121, June 2019.

Reentry Breakup Overview



- Cloud of surviving objects spread over long, narrow ground footprint
- Total mass of surviving objects between 10 and 40% of dry mass of original vehicle
- Objects fall through airspace at velocities set by ballistic coefficient of each
- Some objects can be hazardous to people on the ground and in aircraft

Fragments Survive Reentry

Delta II State 2 debris: Left: Lottie Williams holding reentered debris fragment (photo courtesy Brandi Stafford, Tulsa World); Right, Propellant tank in Texas field (photo courtesy NASA).

Composite Overwrapped Pressure Vessels (left: from Centaur stage of Atlas V booster, right: from SpaceX Falcon 9 Stage 2)

Debris from reentry of Iridium satellite on October 11, 2018. (Photo courtesy Fox News).

Casualty Expectation (E_C)

- Number of human injuries or deaths that might occur given a specific event
- E_C depends on
  - Number and size of hazardous objects that impact the surface
  - Impact energy: objects with impact energy of 15 J or higher are considered hazardous
  - Size of unprotected*, standing human (0.3-m radius circle)
  - Human population within geographic impact area at time of reentry event
- If object reentering via orbit decay
  - Location of debris impact not known before reentry
  - Debris can impact anywhere along ground track; Assume population affected is spread along ground track
  - Population under orbit is function of orbit inclination
  - Population is function of time--must use Earth's population on year of reentry

*Note: Estimates for sheltered humans also possible

Background

- Reentry into the atmosphere is preferred option for disposal of objects in Low Earth Orbit (LEO)
  - Random reentry within 25 years acceptable for object whose casualty expectation (E_C) less than **1 in 10,000 (1E-4)**
  - Directed reentry into a safe area required for object whose E_C exceeds that value
- In 2000, possible bankruptcy of first major commercial LEO constellation (Iridium) led to plans to deorbit entire constellation in relatively short time
  - 74 satellites (66 in constellation, 8 spares), circular orbits at 780 km
  - Each satellite had dry mass of ~560 kg
  - NASA predictions that ~30% of dry mass of each satellite would survive reentry
  - E_C for single Iridium satellite reentry: 1/18,405—below reentry hazard limit for single satellite
  - E_C for reentry of all 74 satellites: 1/249
  - Issue posed a liability concern for U.S.
  - DoD action prevent bankruptcy
- Event raised possibility of new issue: cumulative hazard for reentry of satellites from a constellation

Recent Proposals for large LEO Constellations

Constellation	Total Satellites	Orbit Altitude (km)	Orbit Inclination (deg)	Satellite Lifetime (years)	Satellite Mass (kg)
1a	1600	1150	53.0	6	390
1b	1600	1110	53.8	6	390
1c	400	1130	74.0	6	390
1d	450	1325	70.0	6	390
1e	375	1275	81.0	6	390
1	4425		Multiple	6	390
2	720	1200	88.0	6	150
3	120	1400	89.0	12	700
4	112	800	98.6	5	3000
5a	72	1000	99.5	5	700
5b	45	1248	37.4	5	700
5	117		Multiple	5	700
6a	1120	1030	45.0	12	1500
6b	828	1082	55.0	12	1500
6c	1008	970	88.0	12	1500
6	2956		Multiple	12	1500
7a	2547	340	53.0	6	386
7b	2478	341	48.0	6	386
7c	2493	336	42.0	6	386
7	7518		Multiple	6	386
SUM	15968				
Iridium	74	780	86.4	1	560

- Notional constellations representative of recent proposals*
- All values in table are notional, but believed representative of possible concepts
- Analysis enables <u>first-order</u> assessment of possible hazards of disposal

Key:

1 = SpaceX K-band (high altitude)
2 = OneWeb
3 = LeoSat
4 = Theia
5 = Telestar
6 = Boeing
7 = SpaceX V-band (low altitude)

* Peterson, G., et al, “Tracking Requirements for Space Traffic Management in the Presence of Proposed Small Satellite Constellations,” 69th International Astronautical Conference, Bremen, Germany, 2018

Risk to People on the Ground in 2030

Satellite Reentries for Ground Casualties

- Want 1st-order estimate of hazard when all constellations are fully configured, in steady-state operations
  - Year is 2030
  - Satellites replenished & disposed according to their lifetime
  - Number of satellites reentering per year depends on lifetime of satellites in constellation (e.g., when each satellite has a lifetime of 5 years, 1/5 of satellites in constellation of 1000 satellites reenters each year)
- Satellite designs assumed to be similar to that used for first Iridium satellites
  - Similar mix of components such as propellant tanks, thrusters, electronics, batteries, reaction wheels, etc.
  - Satellite of same mass as Iridium satellite (560 kg) in orbit of same inclination is assumed to have same casualty area as Iridium satellite reentered that year
- All reentries from notional constellations are via orbit decay
  - Debris can fall anywhere along ground track of object’s orbit
  - People are un-sheltered

Risk to People on the Ground

Constellation	Total Satellites	Orbit Altitude (km)	Orbit Inclination (deg)	Satellite Lifetime (years)	Satellite Mass (kg)	Ec Each Satellite Reentry (2030)	Ec/year (2030)
1a	1600	1150	53.0	6	390	8.2E-05	2.2E-02
1b	1600	1110	53.8	6	390	8.2E-05	2.2E-02
1c	400	1130	74.0	6	390	5.5E-05	3.7E-03
1d	450	1325	70.0	6	390	5.9E-05	4.4E-03
1e	375	1275	81.0	6	390	5.4E-05	3.4E-03
1	4425		Multiple	6	390	Multiple	5.5E-02
2	720	1200	88.0	6	150	2.0E-05	2.4E-03
3	120	1400	89.0	12	700	9.4E-05	9.4E-04
4	112	800	98.6	5	3000	4.1E-04	9.3E-03
5a	72	1000	99.5	5	700	9.7E-05	1.4E-03
5b	45	1248	37.4	5	700	1.8E-04	1.6E-03
5	117		Multiple	5	700	Multiple	3.0E-03
6a	1120	1030	45.0	12	1500	3.9E-04	3.6E-02
6b	828	1082	55.0	12	1500	3.0E-04	2.1E-02
6c	1008	970	88.0	12	1500	2.0E-04	1.7E-02
6	2956		Multiple	12	1500	Multiple	7.4E-02
7a	2547	340	53.0	6	386	8.6E-05	3.7E-02
7b	2478	341	48.0	6	386	8.2E-05	3.4E-02
7c	2493	336	42.0	6	386	9.5E-05	3.9E-02
7	7518		Multiple	6	386	Multiple	1.1E-01
SUM	15968						2.5E-01

Total satellites reentering/year: 2413

- Guidelines set max E_C for single satellite reentry: 1E-4
- Max cumulative E_C for single large constellation: 1E-1
- If all constellations in place, risk that 1 person on the ground injured or killed every 4 years

Risk to Aircraft in 2030

Damage to Aircraft

- Debris potentially lethal to aircraft if it is capable of producing sufficient damage to cause loss of life or necessitate emergency response by the crew to avoid a catastrophic consequence.
  - Fragment penetration of a critical aircraft structure or the windshield
  - Fragment ingestion by an engine
- Commercial aircraft vulnerable to 9-gm cubes of stainless steel as a threshold for fatal damage[+]
- "One of the worst objects an engine can ingest is a piece of cloth, e.g. a shop rag,"*
- "Thin plastic sheets and quilted pads sometimes used on missile and space vehicles for thermal protection could become part of the falling debris and act somewhat like a rag if ingested."*

[+]Wilde, P., "Impact Testing and Improvements in Aircraft Vulnerability Modeling for Range Safety," 7th IAASS Conference, Friedfrichsafen, Germany, October 2014.

*Cole, J.K., Young, L.W., Jordan-Culler, T, "Hazards of Falling Debris to People, Aircraft, and Watercraft," Sandia Report SAND-97-0805, April 1997.

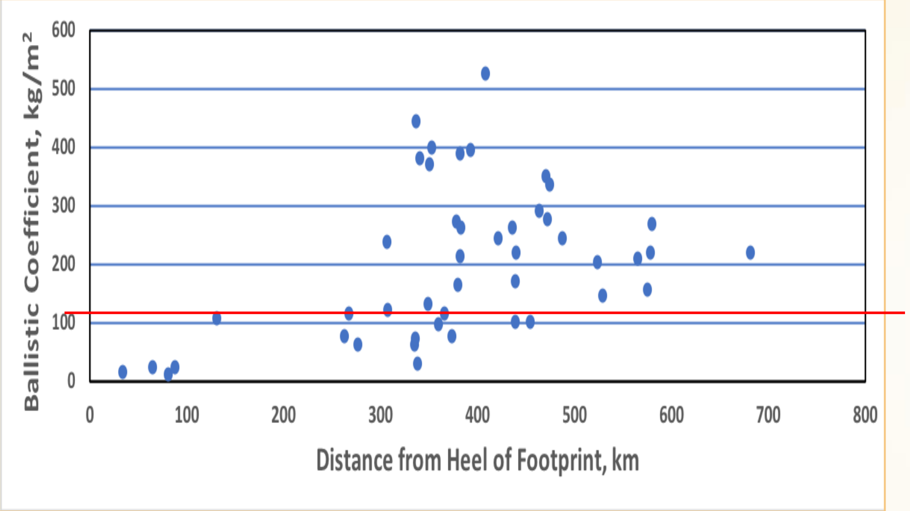
Commercial Aircraft Considered

Aircraft Type	Passengers	Wingspan (ft)	Length (ft)	Height (ft)	Aircraft Airborne
737	177-189	117.4	138.2	41.2	459.17
767	245-375	170.3	1.3	55.3	123
757	243-280	124.8	178.6	44.5	208.4
747	416-524	211.4	231.8	63.7	20.61
777	368-550	199.9	242.3	60.7	61.08
A320	150-164	111.8	123.2	39.6	142.95
A330	253-293	197.8	193.04	57.1	14.22
717	106-117	93.3	124	29.1	42
MD80	142-172	107.8	147.9	29.6	154.4
DC9	80-115	89.4	104.4	27.5	2.6
MD90	141-187	107.8	152.58	30.6	4.4
A300	266	147.1	177.4	54.5	8.7
A318	107	111.8	10.2	41.2	3.1
A321	186-220	111.8	146	38.6	14.6
A319	124-142	111.25	111	38.7	104.2
727	146	108	153.2	34	2.2
DC10	270	165.4	182.1	58.1	3.3

- Commercial aircraft flying domestic flights within the US, flights leaving the US for international destinations, and flights arriving in the US from an international point of origin* (not worldwide flights airborne)
- Dimensions of each aircraft, velocity of aircraft, velocity of fragment, number of passengers, number of aircraft airborne used to estimate the cumulative hazard, casualty expectation for that aircraft type
- Same distribution of aircraft types and airborne aircraft used for 2030 estimates
- Number of aircraft airborne inflated based on population increase expected for 2030
- Results underestimate risks if worldwide flights included

*Patera, R.P., “Risk to Commercial Aircraft from Reentering Space Debris,” AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 18-21, 2006, Honolulu, Hawaii.

Debris Hazardous to Aircraft



Vehicle Atmospheric Survivability Test (VAST) results: radar observed debris falling after reentry and breakup of 5330 kg spacecraft (not launch stage+)

- *Number observed "only a fraction of those observed due to sensor limitations"*
- *Ballistic coefficients estimated for falling debris*

+Launch stages have fewer, but larger, surviving fragments

- Space Shuttle *Columbia* accident: over 80,000 objects recovered; 0.3 expected casualties on commercial aircraft
- Threshold for damage to aircraft >50 kg/m^2
- Satellites larger than 800 kg can yield as many as 300 fragments potentially lethal to aircraft*

Ratio of 300 hazardous objects per 800 kg of satellite mass used for current study

*Ailor, W., Wilde, P., "Requirements for Warning Aircraft of Reentering Debris," 3rd International Association for the Advancement of Space Safety Conference, Rome, Italy, October 21-23, 2008.

Risk to Aircraft

Constellation	Total Satellites	Orbit Altitude (km)	Orbit Inclination (deg)	Satellite Lifetime (years)	Satellite Mass (kg)	No. Haz Frag per Reentry	No. Reentries per year	No. Haz Frag/Year	Probability of Striking Aircraft per Year (2030)	Cumulative Casualty Expectation per year (2030)
1a	1600	1150	53.0	6	390	146	267	39000	1.9E-04	5.0E-02
1b	1600	1110	53.8	6	390	146	267	39000	1.9E-04	4.9E-02
1c	400	1130	74.0	6	390	146	67	9750	3.6E-05	8.9E-03
1d	450	1325	70.0	6	390	146	75	10969	4.2E-05	1.0E-02
1e	375	1275	81.0	6	390	146	63	9141	3.2E-05	7.8E-03
1	4425		Multiple	6	390	146	738	107859	5.0E-04	1.3E-01
2	720	1200	88.0	6	150	56	120	6750	2.3E-05	5.5E-03
3	120	1400	89.0	12	700	263	10	2625	8.8E-06	2.1E-03
4	112	800	98.6	5	3000	1125	22	25200	8.9E-05	2.1E-02
5a	72	1000	99.5	5	700	263	14	3780	1.3E-05	3.1E-03
5b	45	1248	37.4	5	700	263	9	2363	1.6E-05	4.2E-03
5	117		Multiple	5	700	263	23	6143	2.9E-05	7.2E-03
6a	1120	1030	45.0	12	1500	563	93	52500	3.1E-04	7.5E-02
6b	828	1082	55.0	12	1500	563	69	38813	2.0E-04	4.8E-02
6c	1008	970	88.0	12	1500	563	84	47250	1.6E-04	3.9E-02
6	2956		Multiple	12	1500	375	246	138563	6.7E-04	1.6E-01
7a	2547	340	53.0	6	386	145	425	61446	3.1E-04	7.9E-02
7b	2478	341	48.0	6	386	145	413	59782	3.3E-04	8.0E-02
7c	2493	336	42.0	6	386	145	416	60144	3.8E-04	9.1E-02
7	7518		Multiple	6	386	145	1253	181372	1.0E-03	2.5E-01
SUM	15968						2413	468511	2.3E-03	5.7E-01

- Total satellites reentering/year: 2413
- Average number of surviving fragments each reentry: 194
- Probability of striking aircraft: 0.002/year
- Casualty expectation for aircraft: 0.6/year

Summary

- Yearly reentry of large numbers of satellites can pose a significant hazard to people both on the ground and in aircraft
  - Casualty expectation per year for ground impacts could vary from 9E-4 (Constellation 3) to as high as 1E-1 (Constellation 7), both above acceptable limits for a single reentry
  - Probability of striking an aircraft 9E-5 (Constellation 1) to 1E-3 (Constellation 7) (estimates would be higher if including all commercial aircraft worldwide)
- Casualty expectation for uncontrolled reentries of large numbers of satellites from one constellation may exceed 1E-4 limit for single satellite reentry from that constellation
- Satellites in 30 to 50 degree inclined orbits have higher casualty expectations than same satellites in higher inclinations
- Satellite mass, lifetime, and disposal strategy all affect cumulative reentry hazards

Mitigation Options

- Deorbit satellites into a safe area for disposal
  - Minimizes hazards to people on ground and in aircraft
  - Removes satellites from orbit quickly, minimizing growth of space debris
- Design space hardware to reduce number, size and mass of surviving fragments
  - Designs should be verified by direct observation of reentry breakup (similar to VAST tests)
  - Design satellites for longer lifetimes to reduce number disposed per year
- Reenter satellites into the Southern Hemisphere (reduces E_C by an order of magnitude)
- Develop a warning system to alert aircraft away from falling debris
- Include servicing and removal spacecraft as part of constellation design

Conclusions

Based on limited hard data on actual debris survival, this first look at hazards of reentries of large numbers of satellites from large constellation shows

- Cumulative casualty expectations for people on the ground may well exceed single-satellite limits, possibly by orders of magnitude
- Risks to aircraft posed by small debris surviving reentry might be a major problem facing owners of large constellations

Mitigation options include

- Command spacecraft to reentry into safe area to minimize hazards to people on ground and in aircraft
- Use satellite designs and materials that reduce survival of hazardous large and small fragments (satellite design concepts should be verified via observations of actual reentries similar to those conducted for the VAST tests)

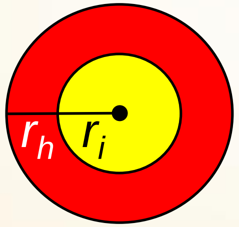
Backup

Casualty Expectation

Method for determining casualty expectation:

1. Find area of debris that survives reentry
   - Depends on component characteristics and flight trajectory
   - “Risky” objects: shielded from heating and/or high melt-point
2. Calculate casualty area – area of interaction with an average human:

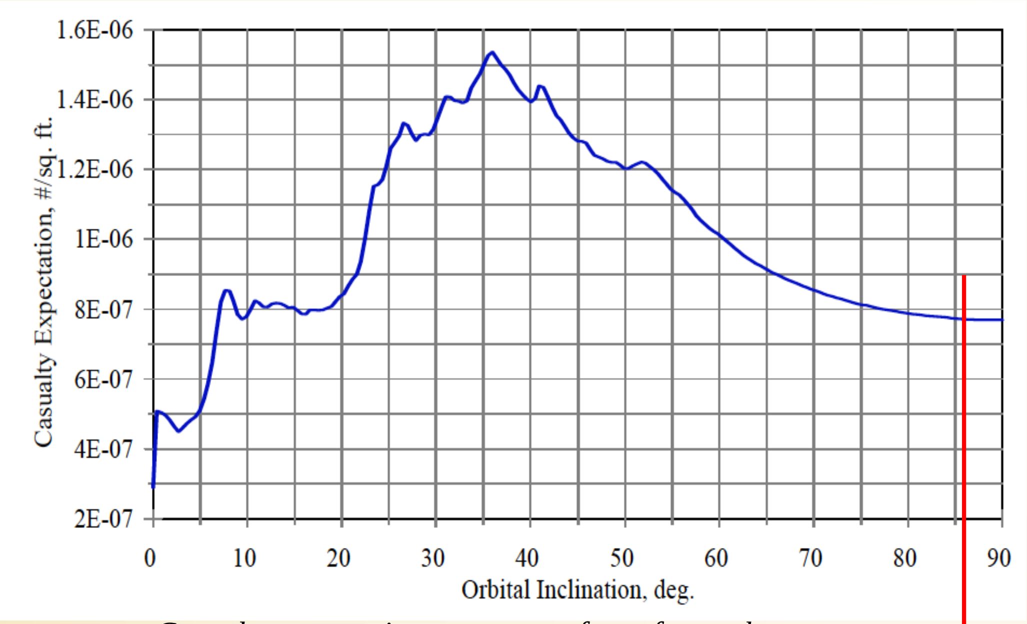
$$A_c = \sum_{i=1}^{N} \left(\sqrt{\pi r_h^2} + \sqrt{\pi r_i^2} \right)^2$$



r_h = human radius = 1 ft (0.3 m)
r_i = radius for i th debris object of N total

3. Find population density for impact area (for random reentry, population density is latitude-weighted based on orbital inclination)
4. Calculate total casualty expectation as product of population density and total casualty area

Correcting Casualty Expectation for Inclination & Date



*Casualty expectation per square foot of casualty area as a function of orbit inclination for 1995 **

Iridium Orbit Inclination 86.4 deg

Correct for Inclination:

If Iridium satellite reentered in 1995 (86.4^o):

E_C = 7.7E-07 x Casualty Area

If Iridium satellite in orbit at 40^o Inclination:

E_C = 1.4E-6 x Casualty Area

Correct for Year of Reentry:

$E_C(t) = E_C(1995) \times (1+0.01099)^{(t-1995)}$

t = 2030

Correct for Satellite Mass:

$E_C = E_C(2030) \times M_{SAT}/M_{IRIDIUM}$

* Patera, R.P., "Hazard Analysis for Uncontrolled Space Vehicle Reentry," AIAA Atmospheric Flight Mechanics Conference and Exhibit, Keystone, Colorado, 21-24 August 2006.