A11

Orbital Debris and Breaking Cognitive Biases

Darren McKnight (Integrity Applications, Inc.)

Results from the Massive Collision Monitoring Activity (MCMA) are presented highlighting that monthly there are near misses in low Earth orbit (LEO) between massive derelicts with probabilities of collision (PC) that meet or exceed the PC when Iridium-33 and Cosmos 2251 did indeed collide about a decade ago. This situation has been largely unmonitored and uncharacterized since these conjunctions involve two derelict objects (i.e., no operational systems). Worst case, if two of the 18 SL-16 rocket bodies in the cluster centered at 850 km were to collide, the cataloged population would be doubled in an instance. Characterizing two years of interactions culminated in the generation of a "worst offenders" list; if the top five of these 20 objects were removed it would eliminate the potential of 50,000 trackable fragments (and 250,000 lethal, nontrackable debris) from being generated; this is a 10% reduction of debris-generating potential on-orbit. JAXA highlighted this risk in 2010; MCMA merely provides a quantifiable representation of the situation identified previously by Japanese scientists.
While the greatest probability is posed by groupings of objects in near circular orbits in LEO clusters, there is a subset of massive derelicts in elliptical orbits (~185) whose perigees cross through LEO that pose a unique risk of cross-contaminating hazard to 12-hr and 24-hr (i.e., geosynchronous orbit, GEO) orbits due to potential collisions in LEO. Details of these interactions are show the consequence of such events could affect all space operators.

Worst Offenders		
	Object	Cluster
1	27006 / SL-16 R/B	*975
2	27386 / Envisat	*775
3	9044 / SL-8 R/B	975
4	15037 / SL-8 R/B	975
5	15056 / SL-8 R/B	975
6	22308 / SL-8 R/B	975
7	8646 / SL-8 R/B	975
8	18129/COSMOS 1861	975
9	10732 / SL-8 R/B	975
10	22285 / SL-16 R/B	850
11	23405 / SL-16 R/B	850
12	23088 / SL-16 R/B	850
13	4799 / COSMOS 385	975
14	6708 / SL-8 R/B	975
15	32053 / SL-8 R/B	975
16	31793 / SL-16 R/B	850
17	28353 / SL-16 R/B	850
18	5239 / SL-8 R/B	975
19	19531 / NOAA 11	*850
20	22566 / SL-16 R/B	850

Biography

Darren McKnight

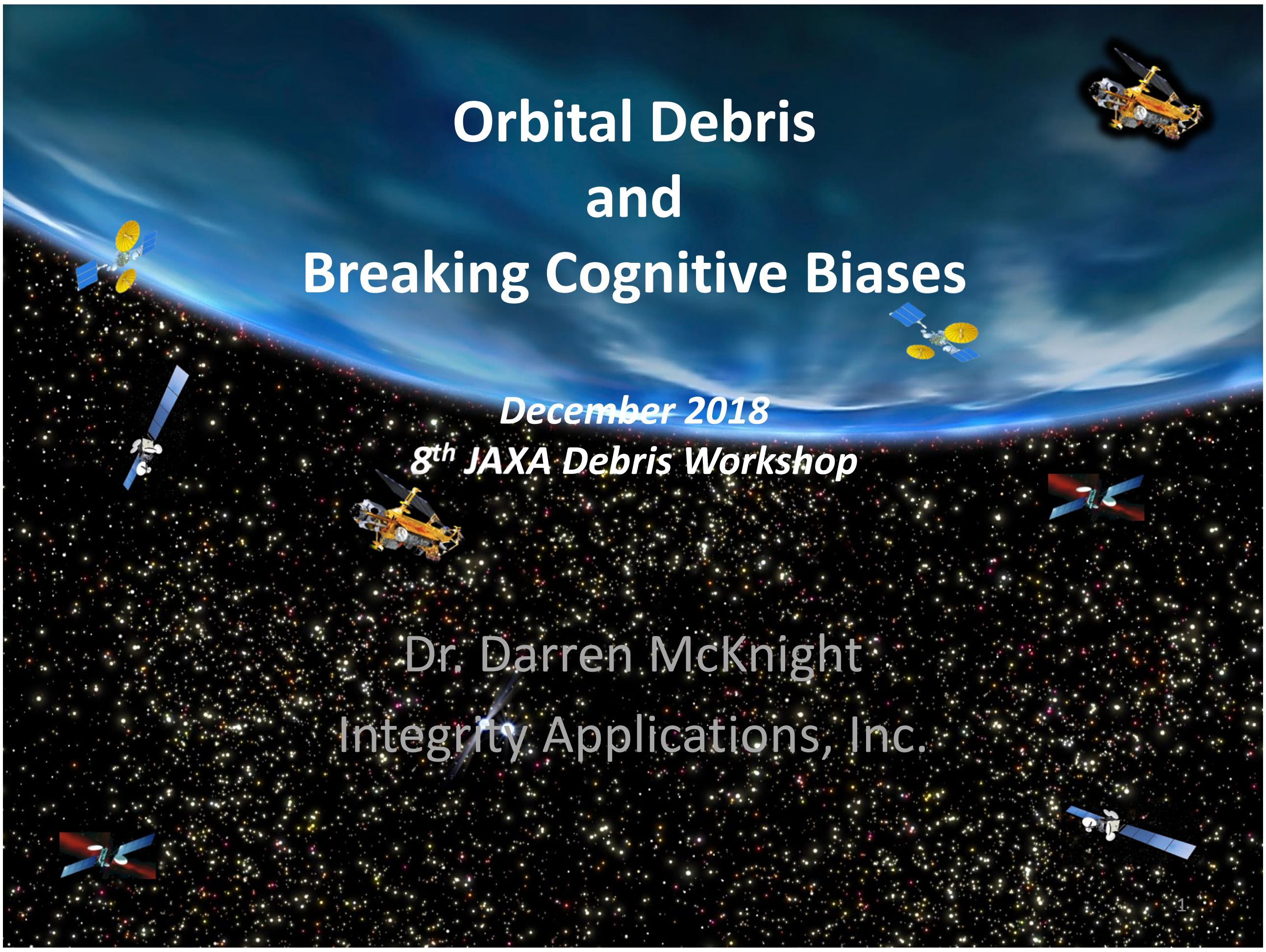
Dr. Darren McKnight is currently Technical Director for Integrity Applications, Inc. (IAI) based in Chantilly, Virginia. He leads teams to develop creative solutions across widely disparate domains: **space systems, renewable energy, predictive awareness for infectious disease outbreaks, bioterrorism, orbital debris, workforce productivity, and youth soccer training.** Dr. McKnight released his latest book, Make Yourself Indispensable, in March 2015. This treatise leverages his years of serving as an innovation catalyst for a variety of government and commercial clients in a wide variety of technical domains.

Before coming to IAI, Darren served as Senior Vice President and Director of Science and Technology Strategy at Science Applications International Corporation (**SAIC**). Dr. McKnight also served as **Assistant Professor of Physics at the Air Force Academy** from 1986-1990.

As a member of the **International Academy of Astronautics' (IAA) Space Debris Committee**, he has been active in position paper development, selection of symposia papers, and execution of the annual International Astronautical Congress. He is active as a member of the **International Association for the Advancement of Space Safety's (IAASS) Space Hazard Committee** merging the analytic world of natural and manmade space hazards.

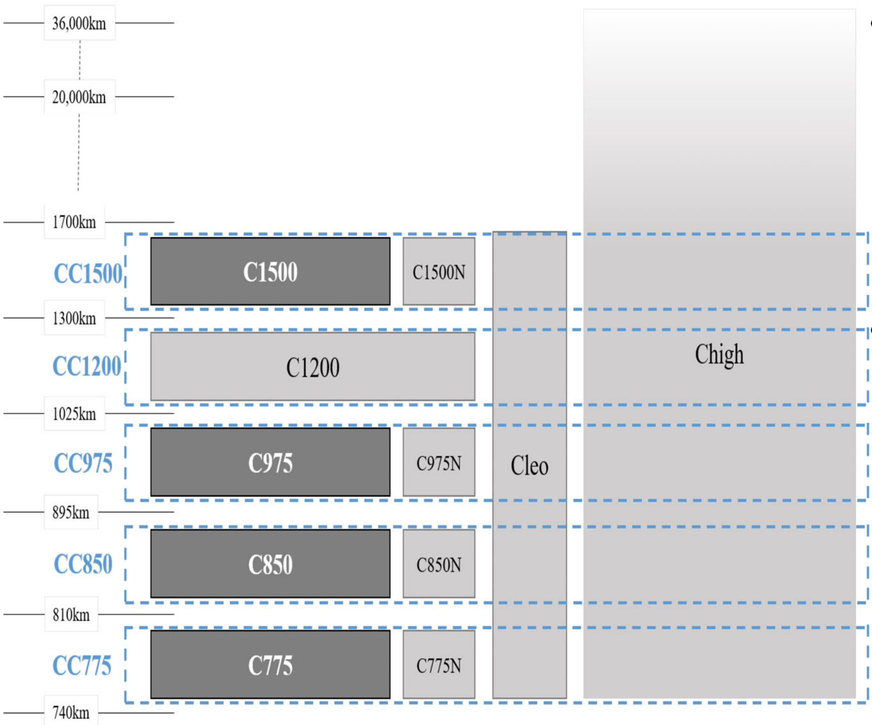
Darren has served on the **National Research Council's** Committee on NASA's Orbital Debris and Micrometeoroid Program; **Defense Science Board** Summer Study on 21st Century Strategic Technology Vectors; and **IBM's Global Innovation Outlook** (GIO) Team. He has coauthored **five books** ranging from space debris and spacecraft operations to soccer coaching and innovation. Darren has authored over **100 technical papers and presented them in 16 countries.** He has appeared on tens of TV, radio, and newspaper interviews including with Discovery Channel, BBC, CBC, Space News, The Space Show, etc.

Dr. McKnight received his Bachelor's Degree from the **United States Air Force Academy** in Engineering Sciences, his Master's Degree from the **University of New Mexico** in Mechanical Engineering, and his **Doctorate from the University of Colorado in Aerospace Engineering Sciences.** He and his wife, Alison, have two daughters, Olivia and Grace.



Expanded Massive Collision Monitoring Activity (MCMA)

Compelling → Complete



- Went from…
  - ✓ #500 →#800 objects
  - ✓ 0.8 Mkg→1.6 Mkg
  - ✓ All Russian → all launching states
- Chigh contains ~200 RBs of ~530,000 kg
  - ✓ Mostly GTO
  - ✓ “Cross-contaminating” risk

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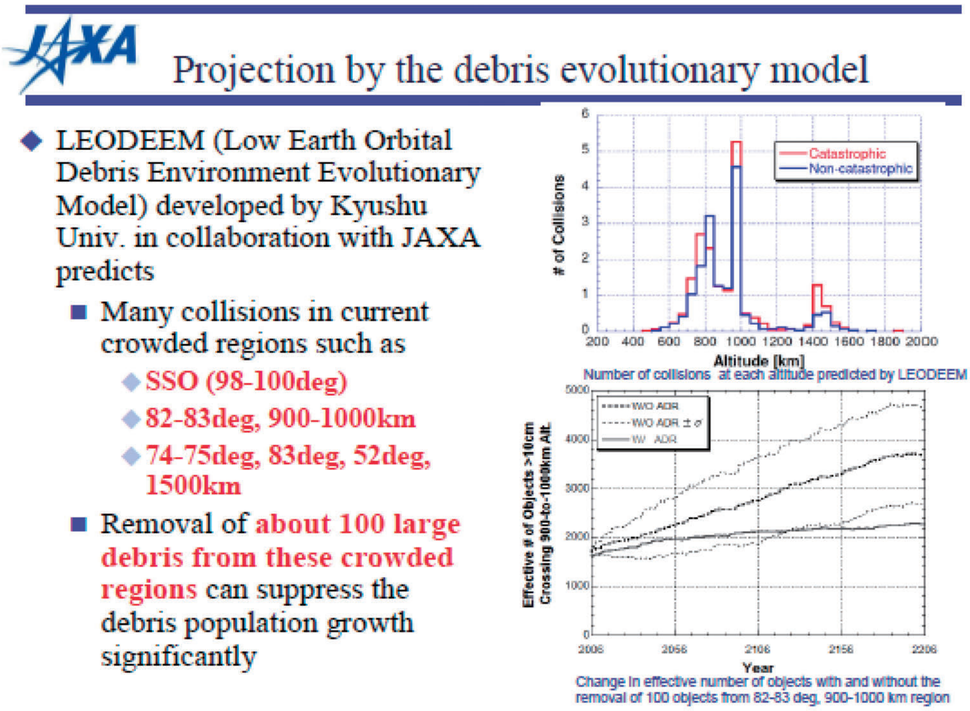
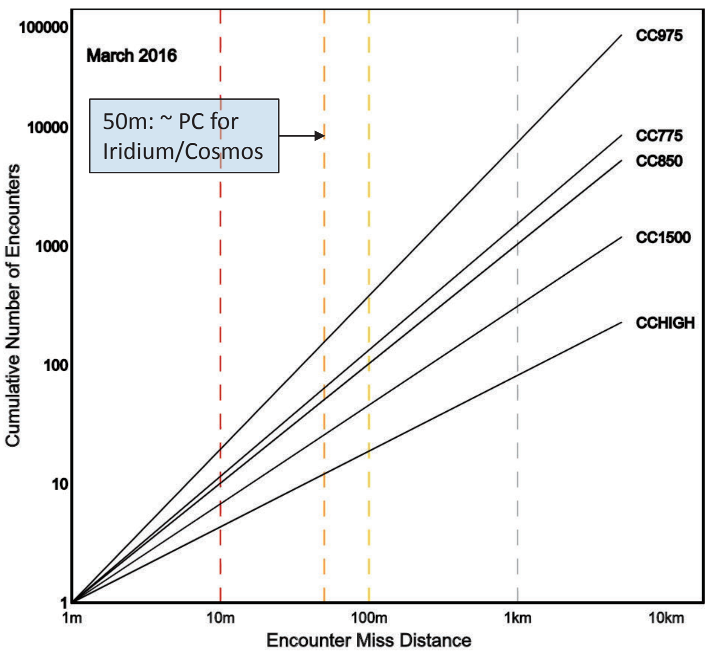
JAXA Said This in 2009

NASA/DARPA Workshop 2009 and ISTC Workshop 2010 by S. Kibe, S. Kawamoto, et al



Massive-on-Massive Dynamics

Animation by Seth Speaks



- Diagonals depict average collision rate
  - Dots provide animation of actual conjunctions
    - 2,000 per month < 5 km
    - 80 per month < 1 km
  - 50m was miss distance estimated for Iridium/Cosmos collision
- Collision of this population will produce 5,000-20,000 trackable debris
  - 50,000-250,000 lethal nontrackable debris
- Mathematical certainty that two of these objects will collide
  - When?

Monthly PC ≥ PC (Iridium-33 and Cosmos 2251) Events would create 2x-10x more debris

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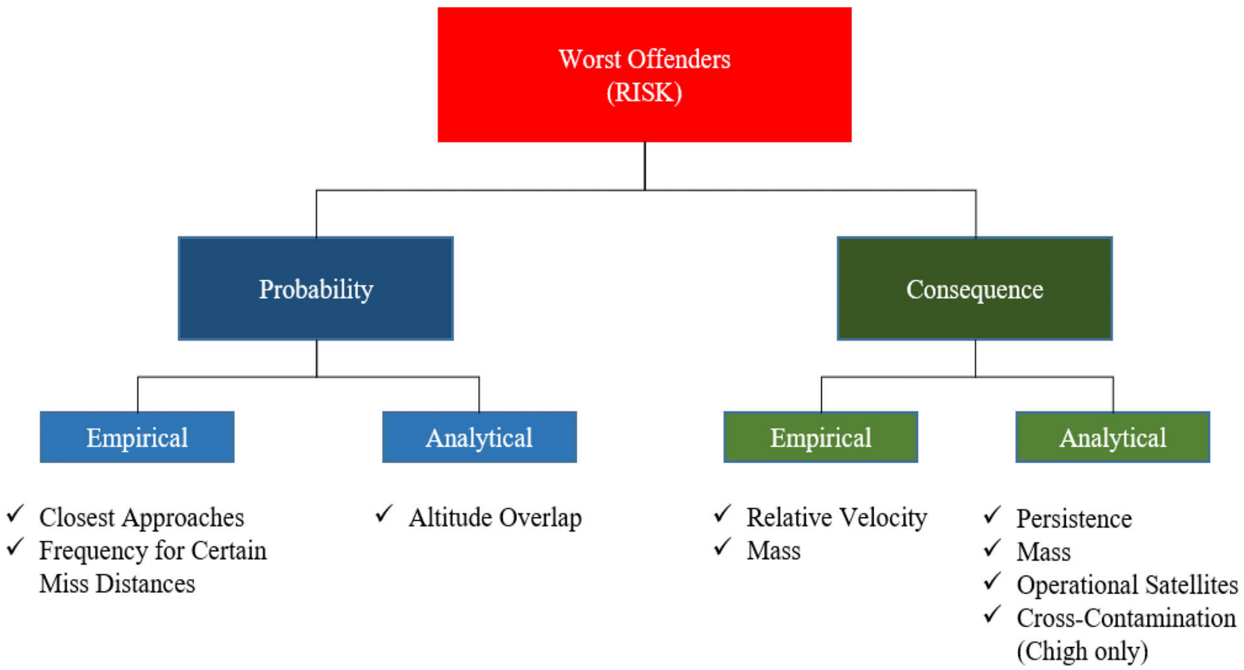
Worst Offenders Process



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Worst Offenders Results - LEO

- 17/20 were monitored in "pure" clusters
- Top two are newly monitored objects
  - Massive objects each in middle of an "SL-8 swarm"
  - Envisat performed 10 collision avoidance maneuvers in three years before it died…???
- Removal of top five massive derelicts would reduce debris-generating potential in LEO by 8-10%
  - Prevent potential 30,000 future trackable fragments

	Worst Offenders	
	Object	Cluster
1	**27006 / SL-16 R/B**	***975**
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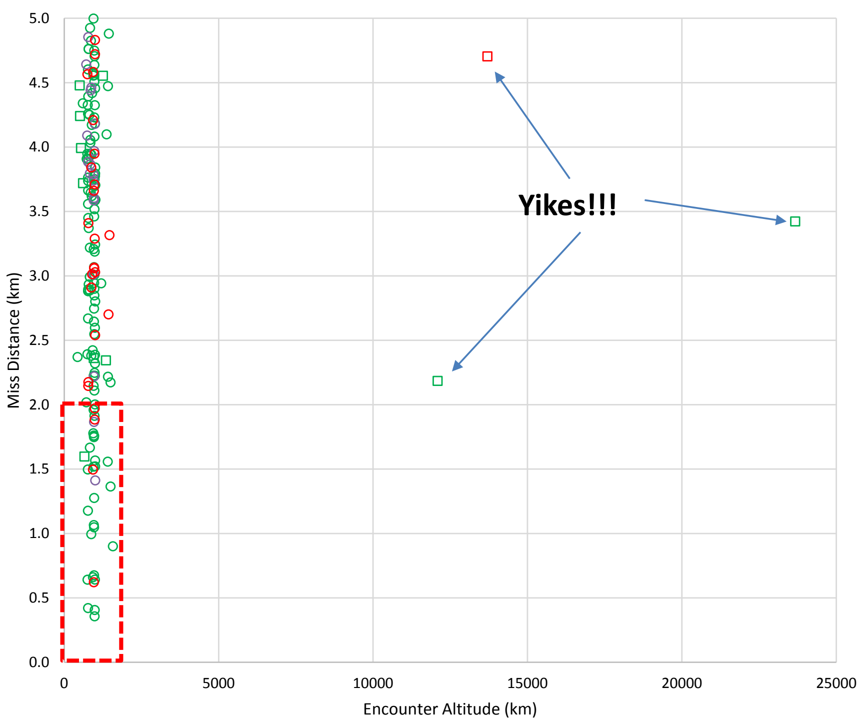
GTO/MTO are Unique

- "What happens in Vegas stays in Vegas!?!?!"
- "What happens in LEO may not stay in LEO!"
  - Examine:
    - Inclination and apogee
    - Argument of perigee

- Collisions between massive derelicts in GTO/MTO and LEO pose unique cross-contaminating hazard

Chigh Encounters – Big Picture

Miss Distance and Altitude of Chigh Object Encounters



○ = Chigh/LEO

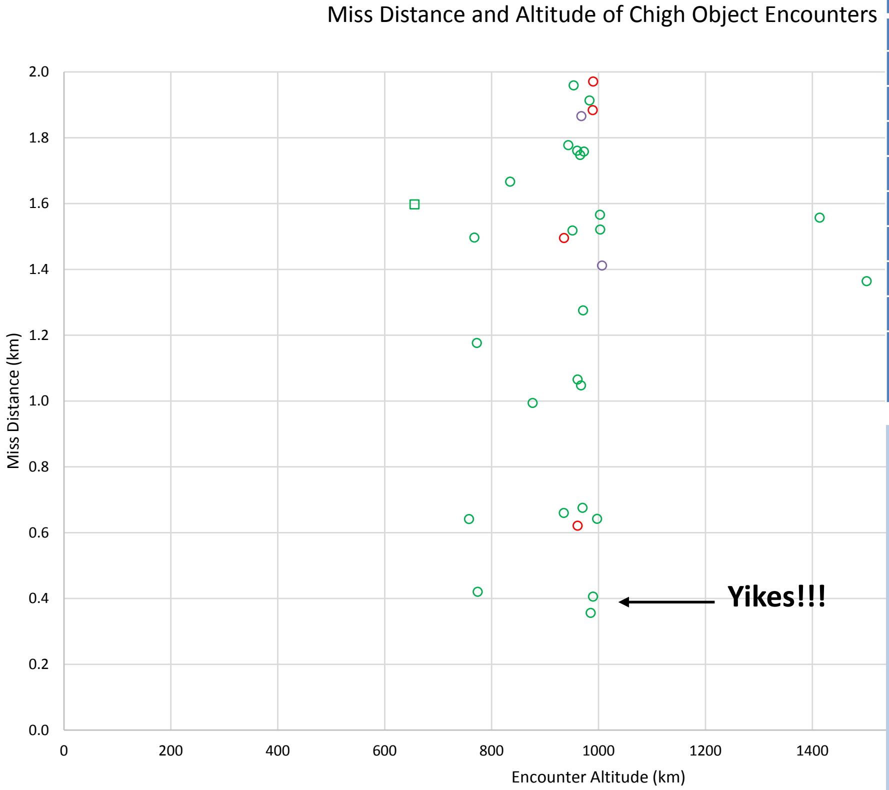
□ = Chigh/Chigh

Red = VR > 6km/s; i <15° and Apogee near GEO (±300km) or Apogee near MEO (±500km)

Green = VR < 6km/s; **not** near GEO or MEO

Yellow = Else

Chigh Encounters – Drill Down



	Chigh Worst Offenders
1	**40270--PSLV R/B**
2	6797--ATLAS CENTAUR R/B
3	39618--ARIANE 5 R/B
4	26762--BLOCK DM-SL R/B
5	28138--BLOCK DM-SL R/B
6	41593--ARIANE 5 R/B
7	36832--ARIANE 5 R/B
8	25405--CZ-3B R/B
9	40750--CZ-3B R/B
10	10722--ATLAS CENTAUR R/B

180 objects only had 175 encounters over 2 years

Five spacefaring entities represented:
> India
> ESA
> Russia
> China
> US

Conjunctions Since 1 May 2018:

+50% More Sub-100m Misses (18/yr vs 12/yr)

Objects		Date	Miss (m)	VR (km/s)	Clusters	
C1959	Meteor-2	2 Jul	16	14.3	975	975
SL-8	SL-24	5 Jul	15	14.7	975	LEO
SL-8	Cosmos 1344	8 Aug	98	14.6	975	975
Cosmos 858	Cosmos 1048	15 Aug	120	14.3	775	775
Worldview-2	Cosmos 2112	24 Aug	137	14.8	775	775
COBE	Meteor 1-11	12 Sep	67	11.7	850	850
ENVISAT	Cosmos 773	2 Oct	78	14.4	775	775
SL-8	Cosmos 614	14 Oct	82	12.9	775	775
Cosmos 1898	Ariane 5 RB	17 Oct	560	10.7	775	**GTO**
SL-8	Cosmos 951	**29 OCT**	47	10.7	975	975
SL-8	Cosmos 726	**29 OCT**	70	14.3	975	975
SL-16	Cosmos 2428	4 NOV	71	11.0	850	850

Thinking About Risk Uncertainty…

Risk = probability x consequence

For orbital debris, usually probability and consequence are fairly uncertain so risk is even more uncertain

"All models are wrong; some models are useful."
by George E. P. Box

"Near-miss events are too often perceived as successes rather than warning signals of a system's vulnerability."
by Dr. Robin Dillon-Merrill

"The odds of Black Swans [low probability, high consequence events] may not be computable!"
by Taleb Nassim

"Should the uncertainty in our risk calculations motivate action or inaction?"
by Dr. Darren McKnight

Backup Slides

Summary

Reported in 2017	Features	Reported in 2018
~# 500 / ~800,000kg	Derelicts	~#800 / ~1,600,000kg
Four "pure"	Clusters	Five "complete" plus GTO/MTO
One	Years of Data	Two
	#Conjunctions	
~ 25,600	< 5km / yr	~ 28,000
~ 1,100	< 1km / yr	~ 1,200
~ 6	< 100m / yr	~ 12
	KEY OBSERVATIONS	
11% probability of SL8/SL8 collision @ 975km: add ~4,500 1% probability of SL16/SL16 collision @ 850km: add ~16,000 10 worst offenders are Russian rocket bodies at 850km and 975km		"Getting lucky" (i.e., PC ~ Iridium collision) monthly at 975km 180 derelicts in GTO/MTO had 3 encounters < 500m with LEO derelicts Remove 20 worst offenders reduces probability of massive collision by 15-30%; top five reduces risk by 8-10%
4 "pure" clusters have vast majority of encounters; two new objects situated in the middle of CC775 and CC975 are top two worst offenders: Envisat and SL-16 rocket body (#27006).		

Hypothesis: Response to MCMA Results Depends on Perspective

- **Environmental Bent : ACT LATER**
  - Metric: Instability over centuries
  - Tendency: Average across diverse population
  - Assessment: Individual collisions less important than aggregate population
  - Response: Study evolution over long-term
- **Space Safety Focus : ACT NOW**
  - Metric: Mission loss now and near future
  - Tendency: Focus on individual space system failures
  - Assessment: Individual collisions may be unacceptable, especially if they occur where there are many operational payloads
  - Response: Accelerate debris remediation (e.g., ADR and JCA)
- **Responsible Behavior Norm : MEET NOW**
  - Metric: Actions are acceptable
  - Tendency: Marginalize outcomes
  - Assessment: No one is responsible for derelict-on-derelict events, examine new behaviors to follow
  - Response: Discuss new norms of behavior

Future Debris Hazard → Mass

FengYun @ 850 kg → +3,200 fragments

1	ISS	<400km	417,000
2	TIANGONG 2	<400km	8,900
3	ENVISAT	~765km	8,506
4	ZENIT R/B	~845km	8,300
5	ZENIT R/B	~845km	8,300
6	ZENIT R/B	~845km	8,300
7	ZENIT R/B	~845km	8,300
8	ZENIT R/B	~845km	8,300
9	ZENIT R/B	~845km	8,300
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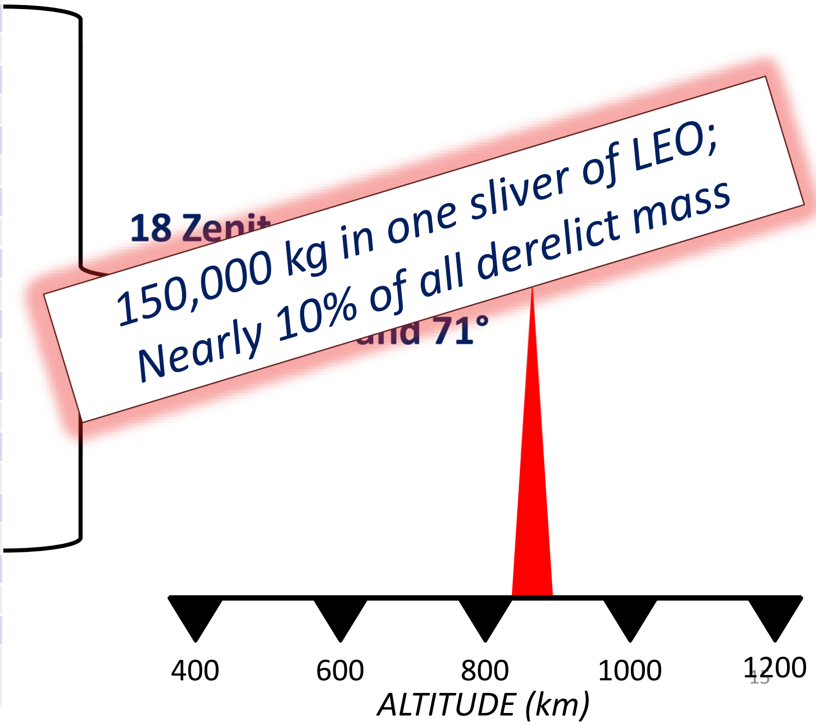
17	ZENIT R/B	~845km	8,300
18	ZENIT R/B	~845km	8,300
19	ZENIT R/B	~845km	8,300
20	ZENIT R/B	~845km	8,300
21	ZENIT R/B	~845km	8,300
22	ZENIT R/B	~765km	8,300
23	ZENIT R/B	~765km	8,300
24	ZENIT R/B	~765km	8,300
25	COSMOS 2441	~High-e LEO	7,800



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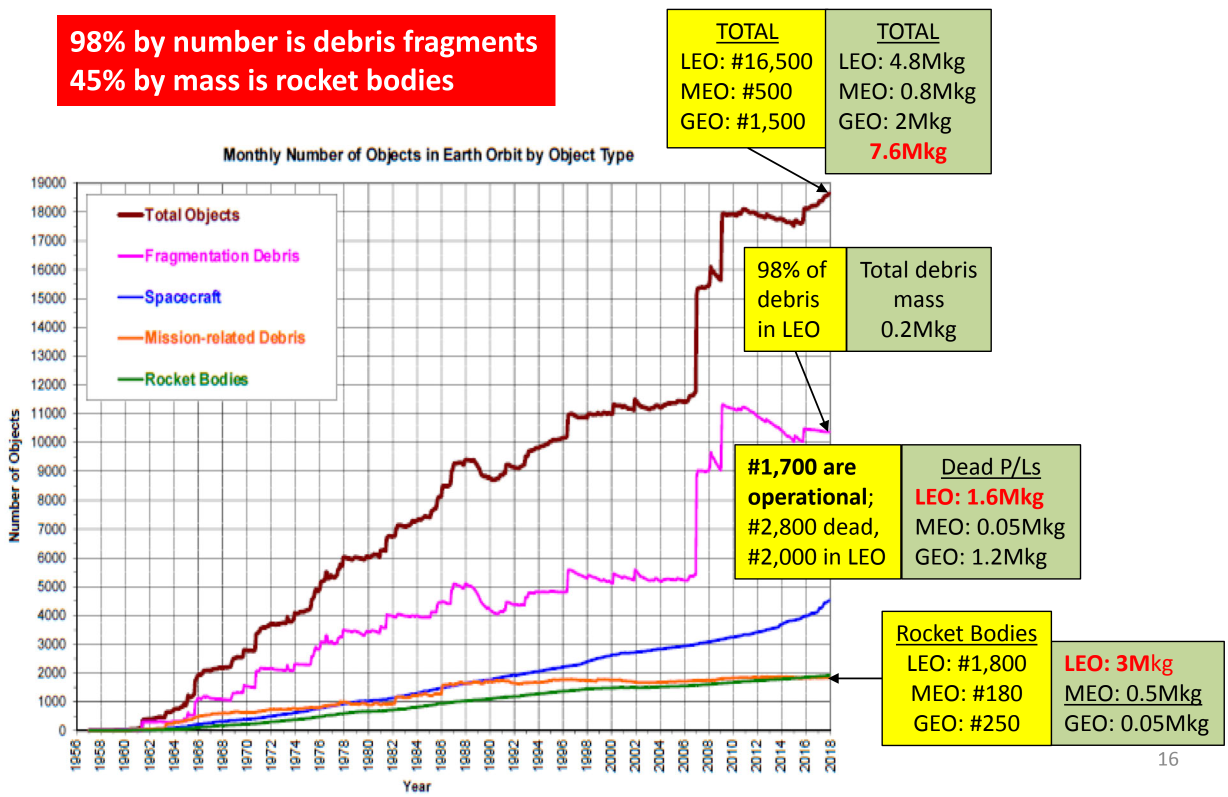
Context – Like Peeling an Onion

98% by number is debris fragments
45% by mass is rocket bodies



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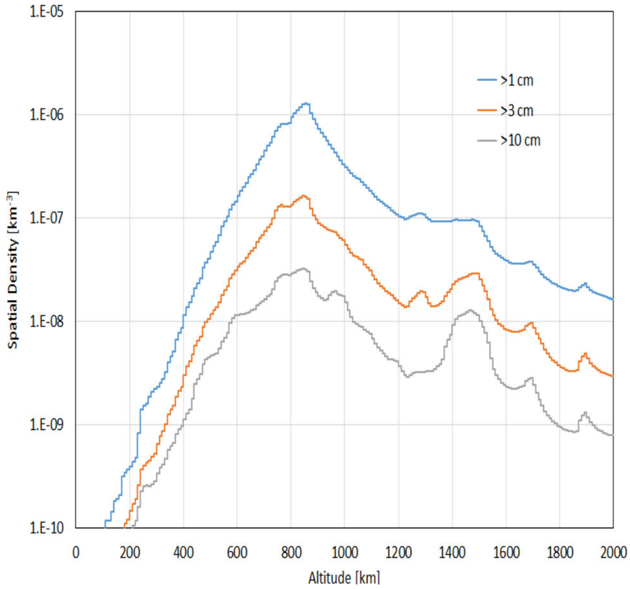
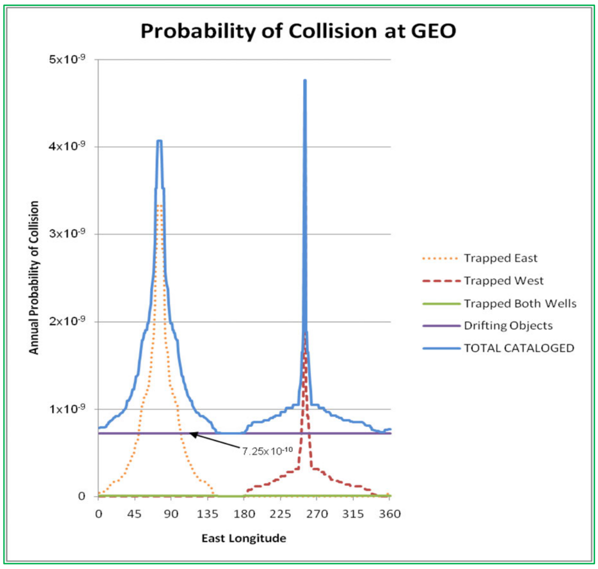
Orbital Debris: *LEO vs GEO*

LEO
High relative impact velocities (~10km/s)
Collisions more likely at extreme latitudes
~16,500 cataloged objects (>10cm)
Peaks at 790km and 850km
~500,000 lethal nontrackables (~<5mm)

GEO
Low relative impact velocities (~500m/s)
Collisions more likely during “rush hours”
~1,500 cataloged objects (>1m)
Peaks at 75°E and 105°W
~1,000 lethal nontrackables (~<50cm)



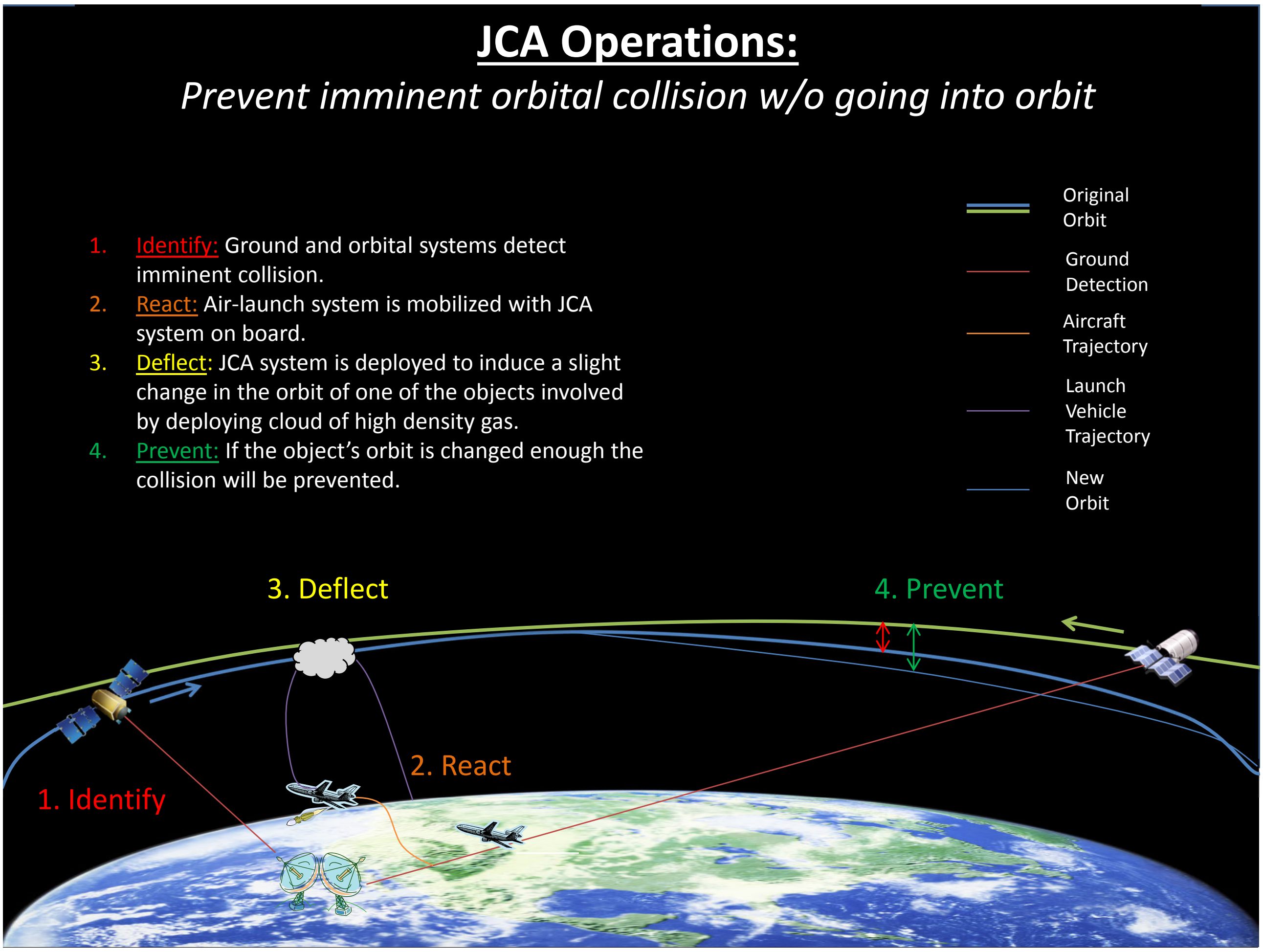


Change Way of Thinking

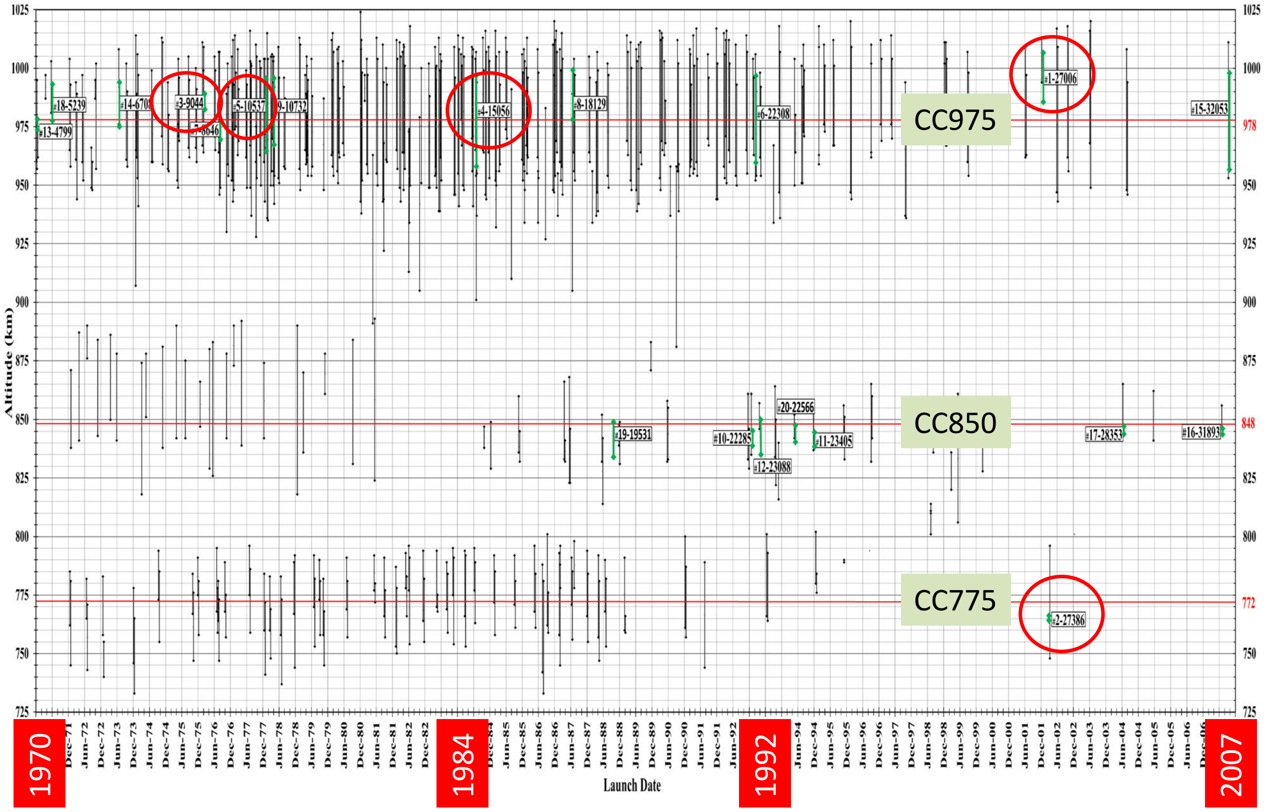
~~*Study, wait, and hope…*~~

Monitor, characterize, and act

- Should “ambiguous uncertainty” drive us to act or to wait (and hope)?
  - ✓ The most likely event to occur… is likely not the next event to occur



"Stock Ticker": Making of the Clusters…



Two Years of Monitoring

1MAY2016 – 30APR2018

	Monitored Derelicts			Encounters < 5km		
Cluster	Original # (Added #)	Total Derelicts	% Increase	Original Encounters (New Encounters)	Total Encounters	% Increase
CC775	88 (13)	101	15%	4,958 (1,192)	6,150	24%
CC850	36 (39)	75	108%	1,217 (2,240)	3,457	184%
CC975	301 (13)	314	4%	42,746 (2,146)	**44,892**	5%
CC1200	0 (8)	8	---	0 (52)	52	---
CC1500	65 (4)	69	6%	849 (69)	918	8%
Cleo	0 (22)	22	---	0 (1,897)	1,897	---
Chigh	0 (180)	180	---	0 (175)	175	---
Total	490 (279)	769	57%	49,770 (7,771)	57,541	16%

Once a month have an encounter with greater probability of collision then when Iridium-33 and Cosmos 2251 collided in 2007 → events would be 2x larger

Space Vision: Global Space Operations Assurance

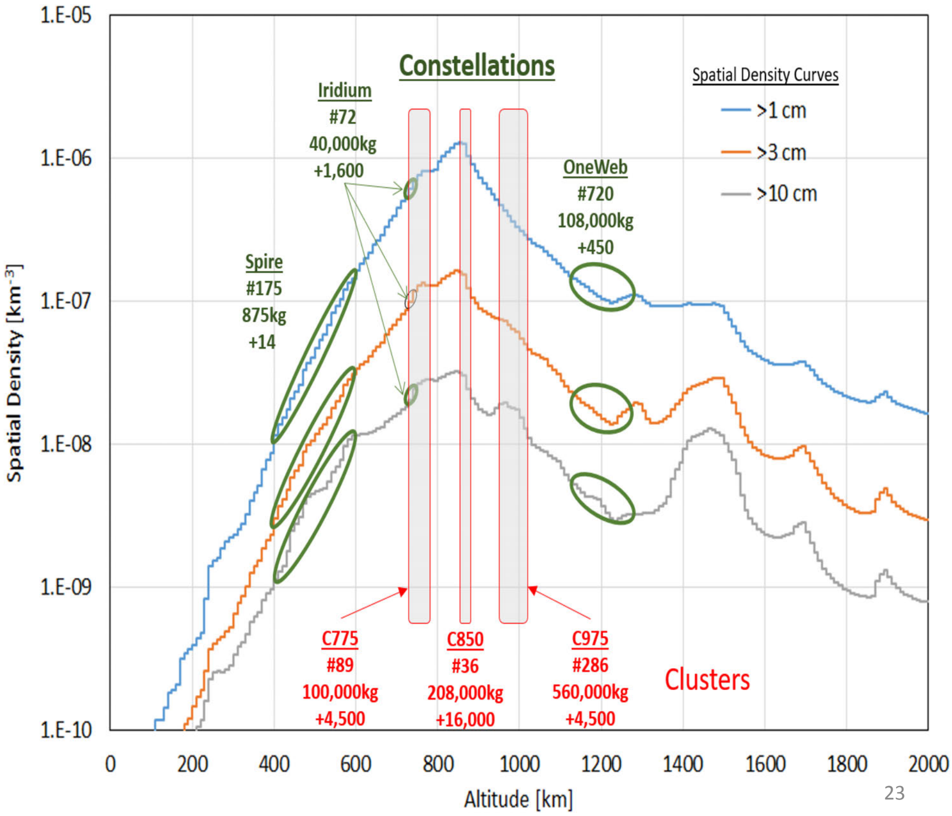
Maximize probability of all spacefaring entities to execute the objectives of their space systems to support scientific, economic, and national security missions
Via: procedures, regulations, design standards, approved conops, laws, treaties, etc.

Category	**Lethal Nontrackable (LNT) Debris and Space Weather (what you cannot see can kill you)**	**Trackable Hazards: Abandoned Hardware and Large Debris Fragments**	**Operational Satellites**

Specific Problem	- Predict and characterize effects from severe space weather events
	- Model LNT creation via degradation of large derelicts, breakup modeling, etc.
	- Characterize LNT environment
	  - via *in situ* sensors
	  - via S/C anomalies & failures monitoring and attribution
		← Large derelicts colliding create significant LNT and trackable fragments that pose hazard to operational satellites →
		- Create and distribute catalog of trackable (i.e., "large") objects
		  - Avoid collisions between trackable objects and operational satellites →
			- License and deploy satellites and constellations to maximize success of all
			  - Architecture design (e.g., altitude, frequency, etc.) adjudication
			    - RFI, physical separation, etc.
			  - Operational systems sharing ephemeris data in proper format in timely fashion to:
			    - Prevent RFI
			    - Prevent collisions
			    - Prevent cross-contamination
			- Minimize Dead On Arrival (DOA) failures, especially for constellations
			- Eliminate/minimize adversarial actions

Constellations vs Clusters

- Lots of angst about evolving constellations being deployed and being proposed…
  - Why?
- Strong regulations being suggested…
  - Why?
- Some calling for greater oversight for this threat to space operations…
  - Why?



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Examining Four LEO Clusters of Massive Derelicts

Double cataloged population +18,000 trackables

Create > 4,000 trackable

Cluster	Cluster Member	Mass (kg)	Number	Apogee (km)	Perigee (km)	Inclination (deg)
C775	SL8 RB	1,434	44	793	733	74
	SL8 PL	850	44	802	742	74
C850	SL16 RB	8,300	18	860	814	71
	SL16 PL	3,250	18	868	823	71
C975	SL8 RB	1,434	144	1020	935	83
	SL8 PL	800	142	1024	934	83
	Other PL	1500	15	997	905	64
C1500	SL8 RB	1,434	17	1660	1330	74
	SL14 RB	1,407	24	1530	1363	83
	SL14 PL	2477	24	1507	1381	83
TOTAL		**~756k**	**490**			

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"Worst" Clusters

	Probability (CR/yr)	Consequence (Trackable Debris Created)	"Risk" (Probability x Consequence)	Persistence (lifetime, yrs, for $0.01m^2/kg$)
C775	1/413	3,500	~9	300
C850	1/578	16,000	~28	500
C975	1/92	4,000	~43	1,800
C1500	1/1345	6,000	~5	20,000

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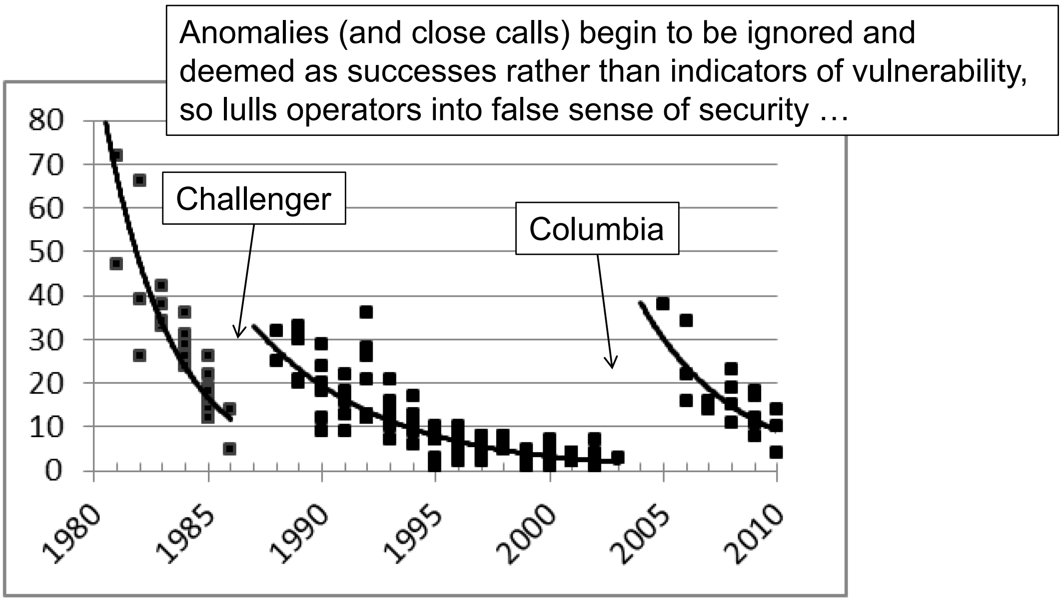
In-Flight Anomalies Reported for each NASA Space Shuttle Mission (1981-2010)



Cognitive Bias:

Normalization of Deviance

Professor Robin Dillon-Merrill (rld9@Georgetown.edu)

Georgetown University
McDonough School of Business

Spacecraft Anomalies and Failures Workshop, Chantilly, VA, 2015