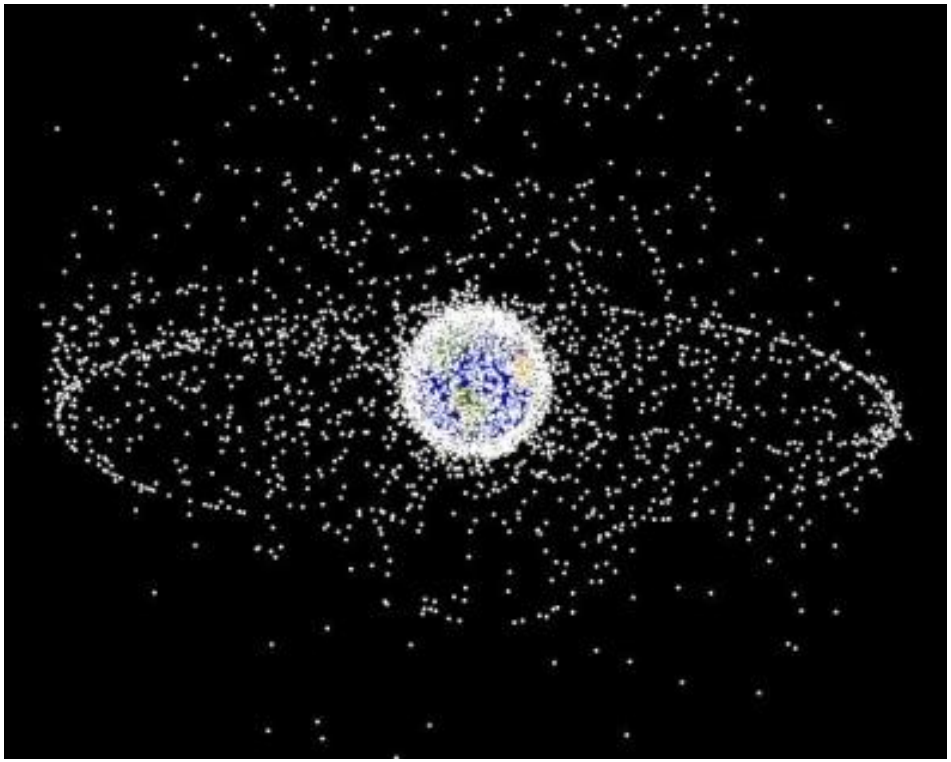
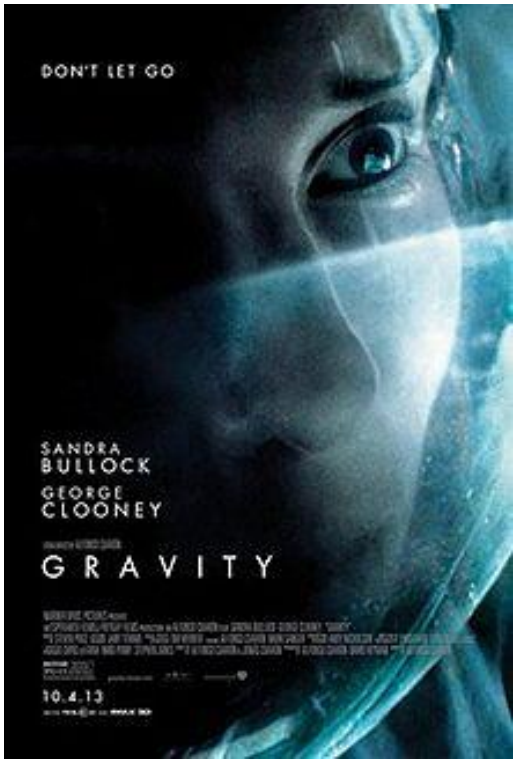
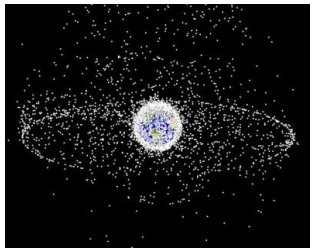
"Gravity" – Great Show, Average Physics

Dr. Darren McKnight, Integrity Applications

9 December 2013





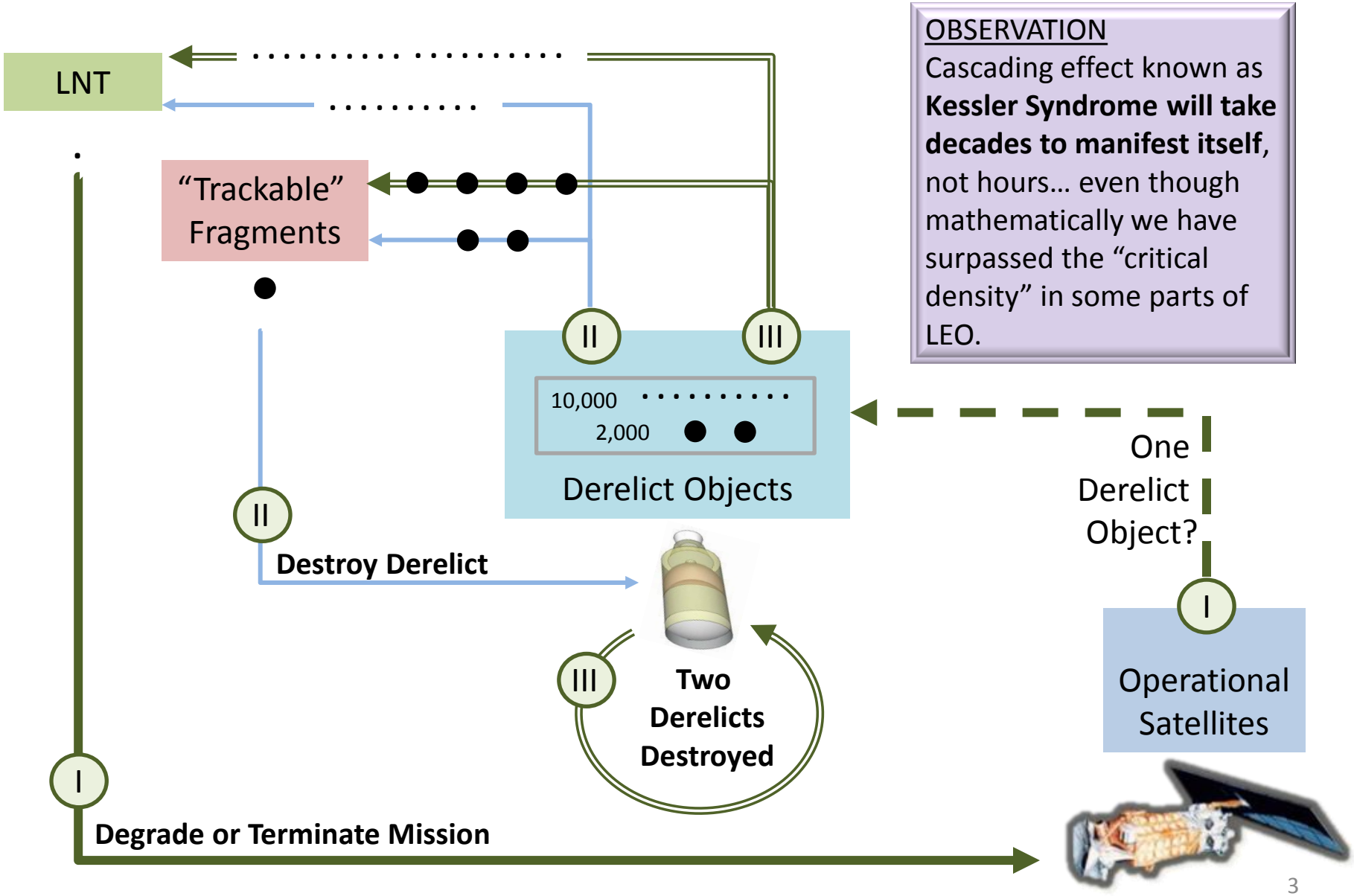


Good News and Bad News

- **Good News**
  - *Sorry to ruin your fun but…* The exact sequence of events portrayed in "Gravity" has zero probability of occurring
    - Wrong orbits for several objects – altitudes and inclinations
  - The general sequence of events portrayed in "Gravity" has a very near zero probability of occurring (~1/100,000,000)
    - Will calculate probabilities for one breakup directly hitting the ISS multiple times
      - The Gravity-depicted chain reaction is many orders of magnitude less likely…
- **Bad News**
  - Over 200 explosions and collisions that have occurred in space have produced an impact hazard from orbital debris in many regions
  - The hazard will continue to increase if current mitigation practices are not followed closely and then followed with derelict collision prevention (e.g. active debris removal, ADR) operations

Potential Encounters → Flight Safety → Instability

LEO: VR ~ 10 km/s



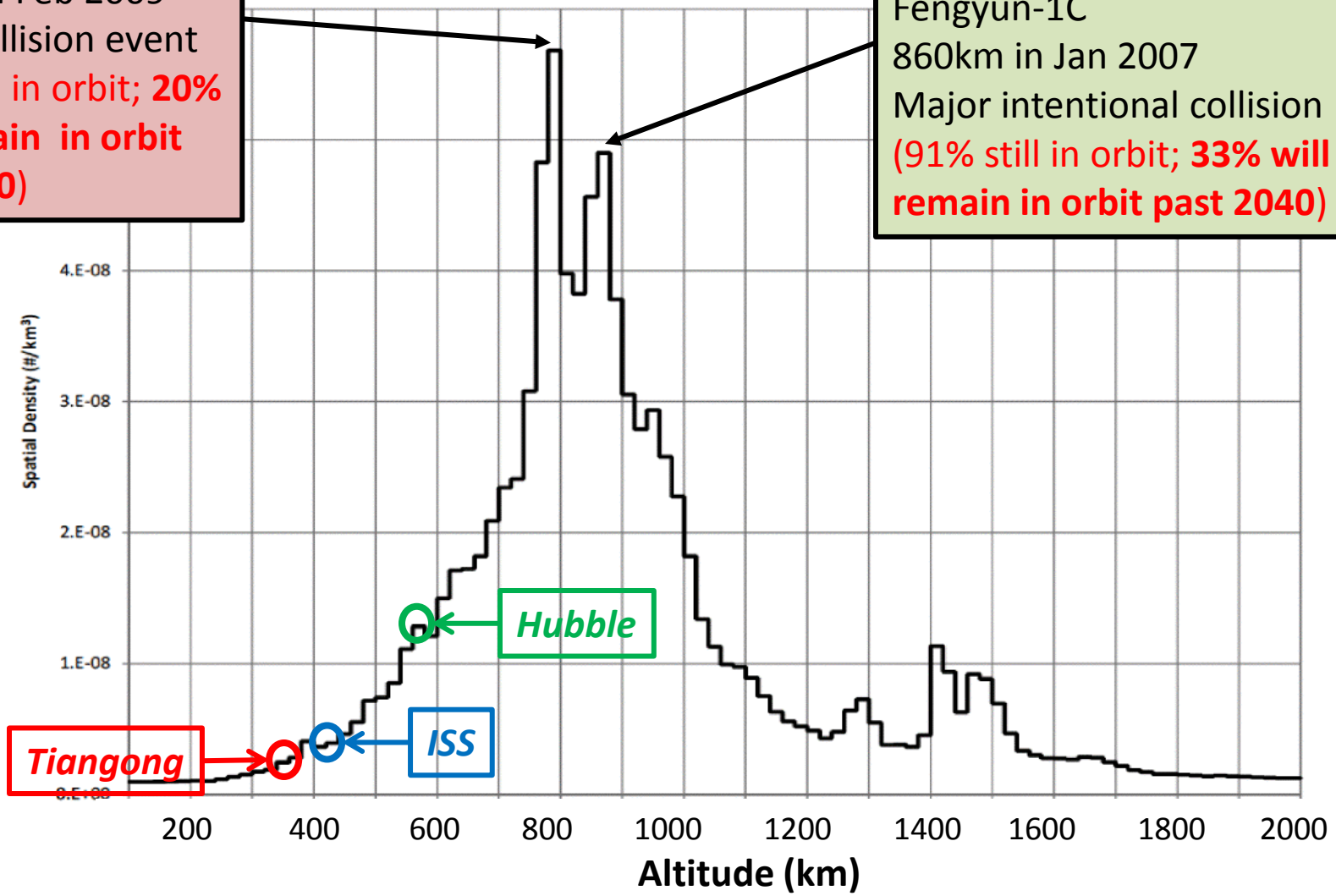
Source: McKnight and Di Pentino, "Controlling the Future Growth of Orbital Debris", ISU Space Sustainability Conference, Strasbourg, France, February 2012

Mapping of Space Debris

Iridium and C2251
790km in Feb 2009
Major collision event
(80% still in orbit; **20% will remain in orbit past 2040**)

Chinese breakup event
Fengyun-1C
860km in Jan 2007
Major intentional collision
(91% still in orbit; **33% will remain in orbit past 2040**)

Trackable (Catalog) **Spatial Density** (#/km^3)



Data plot courtesy of NASA/JSC

Fengyun-1C vs “Gravity”

Fengyun-1C (Reality)

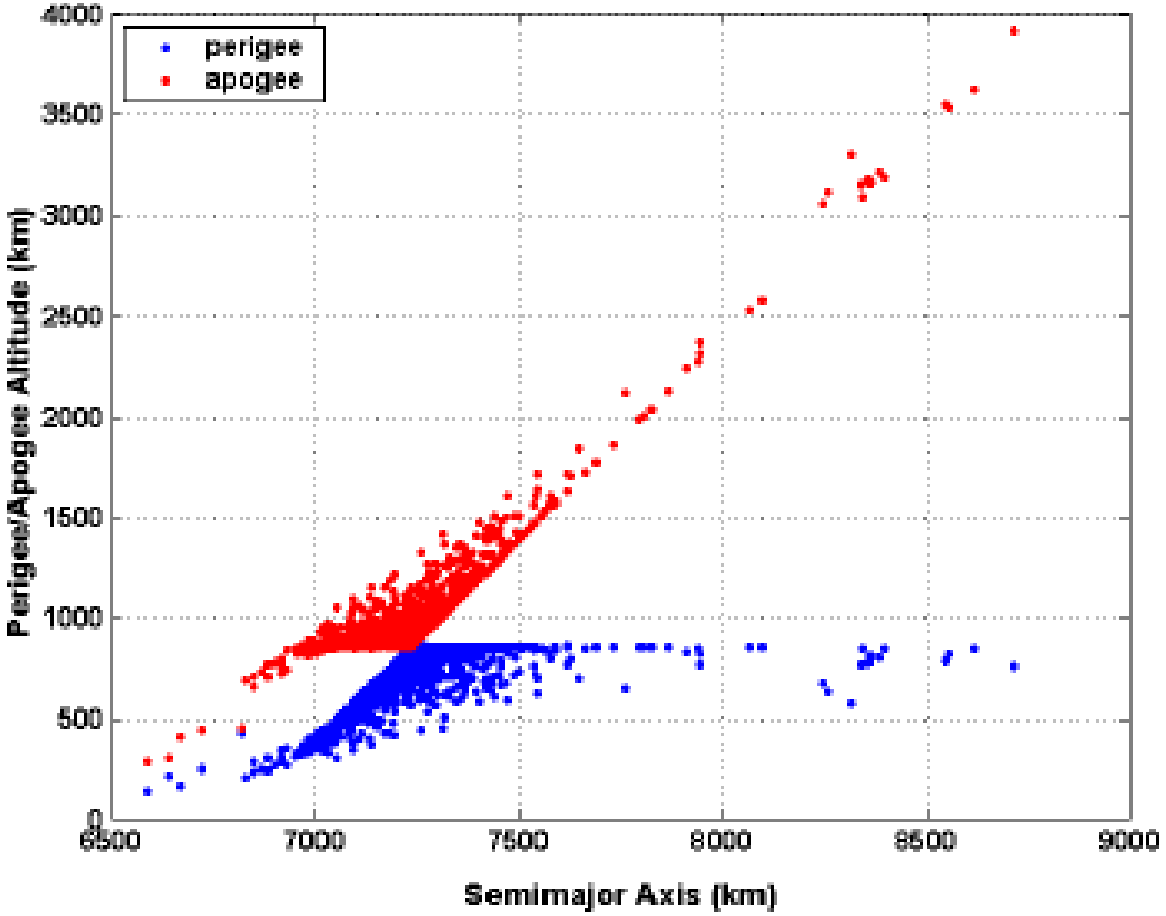
- 860km/750kg
- 3,000 cataloged pieces
- Altitude range of initial debris spread 0-4000km but ± 150km for about 75%
- Potential “targets” are many operational satellites whose aggregate collision cross-section exceeds ISS
- No collisions between resulting trackable debris and other cataloged objects over last six years

Gravity

- **420km**/750kg
- 3,000 cataloged pieces
- Altitude range of initial debris spread ± 150km from 2,500 of them
- Same spread of debris would put half onto reentry trajectories within 2 weeks
- Two collisions occurred within several hours
  - ISS shown getting struck multiple times

Debris is Distributed In Altitude

Gabbard Diagram for Fengyun-1C



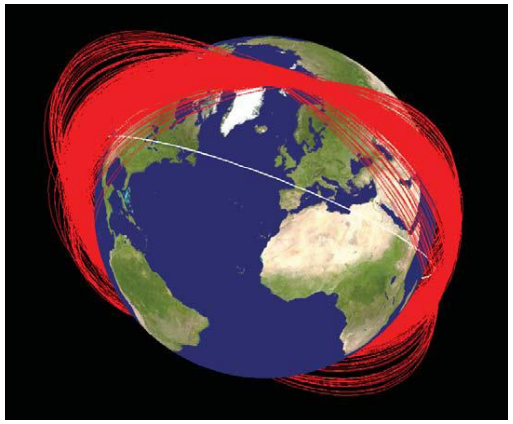
- Debris distributed across wide range of altitudes
  - Reentry to 4000km
  - Majority of debris stayed within ± 150km
- Collisions spread debris significantly
  - This is both good and bad…

Source: Pardini, C. and Anselmo, L., "Evolution of the Debris Cloud Generated by the Fengyun-1C Fragmentation Event"

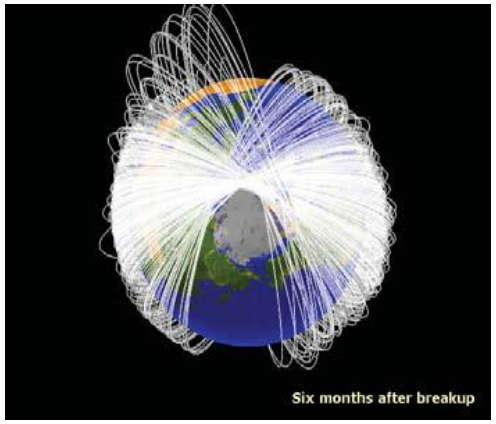
LEO Breakup Evolution

Fengyun-1C Cloud

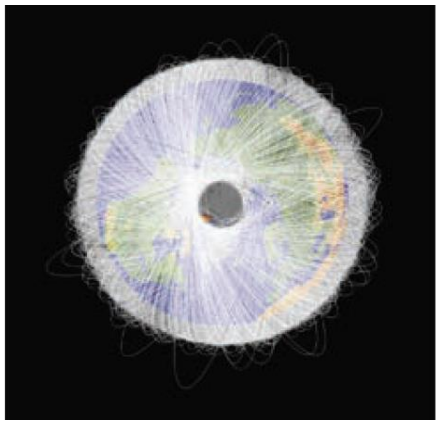
- Depending on orbit…
  - Cloud → Torus → Clam shell → Truncated shell
    - Pinch point remains for weeks
  - Evolution rate in LEO depends on inclination and magnitude of breakup



One Month



Six Months

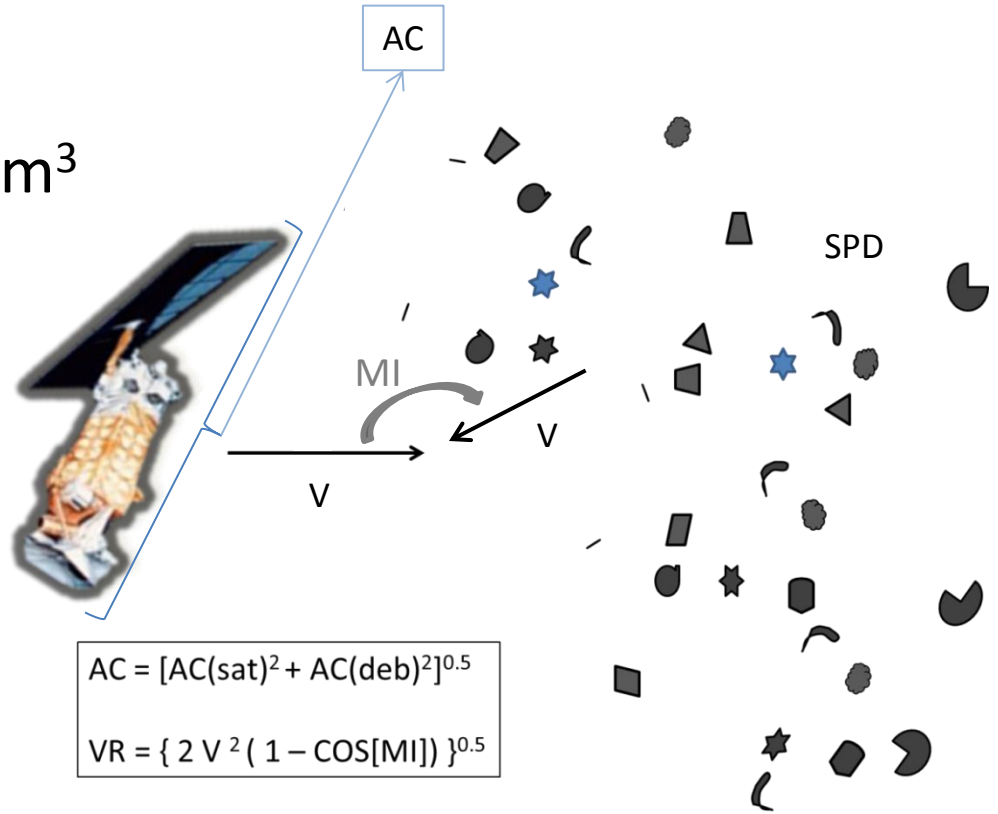


One Year

Figure compliments of NASA/JSC

Probability of Collision (PC)

- **PC = VR * SPD * AC * T**
  - PC = probability of collision
  - VR = relative velocity
  - SPD = spatial density
    = number of objects per km^3
  - AC = collision
    cross-section
  - T = time over which
    PC is determined
- **Gravity Scenario**
  - VR = 10 km/s
  - AC = 900 m^2 (ISS only) or
    7500m^2 w/solar arrays



Collision Hazard Evaluation/Evolution

Worst Case: Used high-end ISS size and debris cloud counts

- Probability of one strike >>> probability of two or more impacts (as shown in the movie)
- Cloud of debris is a large undulating ellipsoid that dismantles over time

Total PC = Probability of Encountering Cloud * Probability of Collision While in the Cloud

Time After Fragmentation	Total PC	Probability of Encountering Cloud	PC Within Cloud	Number of Fragments Used (Out of 3000)	Time in Cloud
10 sec	**4×10^{-11} One pass**	5×10^{-11}	~0.75	3000	0.1 sec
75 min (3/4 orbit)	**4×10^{-8} One pass**	9×10^{-5}	4×10^{-4}	2500	~30 sec
6 months	**4×10^{-6} Per orbit**	1	4×10^{-6}	1500	~90 min

Debris will rapidly decay at this altitude so hazard will diminish quickly over time

Alternative Context for *"Gravity" To Increase Physical Validity of Plot*

Proposed by Don Kessler

- **Scenario could have been set up with:**
  - The orbits of major assets were different than they are now.... plus, not only did no one follow the 25-year rule, the usage of satellites in LEO had significantly increased.
    - NASA stopped using TDRS in GEO and switched to something like Iridium for communication.
  - At great expense, NASA changed the orbital inclination of Hubble to match that of the ISS so that Hubble could be easily serviced by the ISS.
    - China liked that approach and launched as planned in 2020, but into a near-by orbit.
  - Hubble had proven so successful that not only was servicing it a matter of national pride, the Space Shuttle was put back into service so that when Hubble was finally retired, it could safely be returned to Earth to go into the Smithsonian.
  - **All these events provided a perfect target for *some adversary* to conduct an anti-satellite test that would create debris specifically to disable these three systems to (re)establish their leadership in space... as the result of an "accident".**
    - For this scenario to have been effective, it still would have required a significant anti-satellite system and a lot of luck

Derelict Collision Prevention Options

Debris Mitigation
-Deorbit in 25 yrs
-Do not create

Collision Avoidance (CA)
-Daily JSpOC Warnings
-Typical propulsion

By Self
-Only for op. objects

By Other
-Variety of options
-Spacebased
-Groundbased

Active Debris Removal (ADR)
-ID-Despin/Grapple-Remove
-Requires large number
-Requires large impulse
-Over decades
-Manage reentry risk
STRATEGIC - Statistical

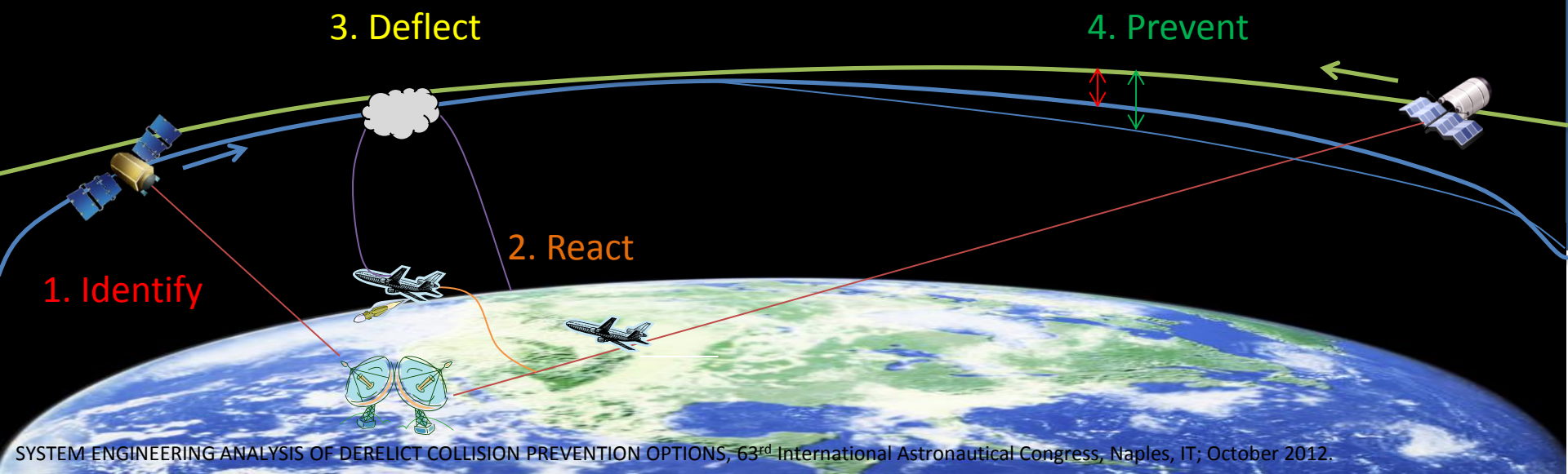
Just-In-Time CA (JCA)
-ID-Intercept-Move
-Want low false alarms
-Enhanced el set accuracy
-Hourly/daily response
-No reentry risk
TACTICAL - Deterministic

Source: McKnight and Di Pentino, "Controlling the Future Growth of Orbital Debris", ISU Space Sustainability Conference, Strasbourg, France, February 2012

JCA Operations:
Prevent imminent orbital collision w/o going into orbit

1. Identify: Ground and orbital systems detect imminent collision.
2. React: Air-launch system is mobilized with JCA system on board.
3. Deflect: JCA system is deployed to induce a slight change in the orbit of one of the objects involved by deploying cloud of high density gas.
4. Prevent: If the object's orbit is changed enough the collision will be prevented.

Original Orbit
Ground Detection
Aircraft Trajectory
Launch Vehicle Trajectory
New Orbit



SYSTEM ENGINEERING ANALYSIS OF DERELICT COLLISION PREVENTION OPTIONS, 63rd International Astronautical Congress, Naples, IT; October 2012.

Summary

- **Go and see "Gravity" immediately**
  - **Compelling and captures general starkness and wonder of spaceflight**
  - **Introduces issue of orbital debris risk to millions who may not have been aware previously**
- Do not base funding decisions or engineering options on the portrayal of events in "Gravity"
  - Not accurate cause and effect sequences
  - Reinforces some bad physics that may be difficult for the uninformed to differentiate from reality
- **Orbital debris is a growing hazard that needs to be addressed soon to prevent a measurable degradation in operational lifetimes of LEO satellites in the future**
  - **Hazard growth is uncertain due to lack of empirical collision data and the large range of potential collision events**
    - **Watch for "massive collision" analysis in 2014**