# Orbital Mechanics Seminars, Module 4: Space Debris

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## Abstract

The Orbit Mechanics Seminars series is a collection of introductory material covering orbit mechanics and related topics. It was assembled with an engineering audience in mind, though no prior knowledge of orbit mechanics is required. The series begins with an overview of orbits, geometry, and perturbations, and progresses to more advanced topics such as Maneuvers, Collision Avoidance, and Space Debris.

Guidance for using this material:

The material assumes a basic understanding of physics.

The content is best understood with the accompanying audio track, but the slides are useful as reference material and as points for discussion and further study.

# *Outline of Presentation*

- What is Space Debris
- How Much and What Size
- Is Space Debris Really a Problem
- Can we Protect Spacecraft
- Predicting Collisions
- What Happens When Objects Collide
- What Happens When Space Objects Reenter
- Examples
  - *Iridium/Cosmos*
  - *Other known collisions*

# WHAT IS SPACE DEBRIS?

Obsolete spacecraft, parts of satellites or rockets

AND

Fragments of spacecraft that have broken up or collided

# HOW MANY BREAKUPS AND COLLISIONS?

Prior to 1 May 2022, there have been 268 fragmentations and 87 anomalous events[1]

Most of the debris comes from propellant explosions and deliberate action

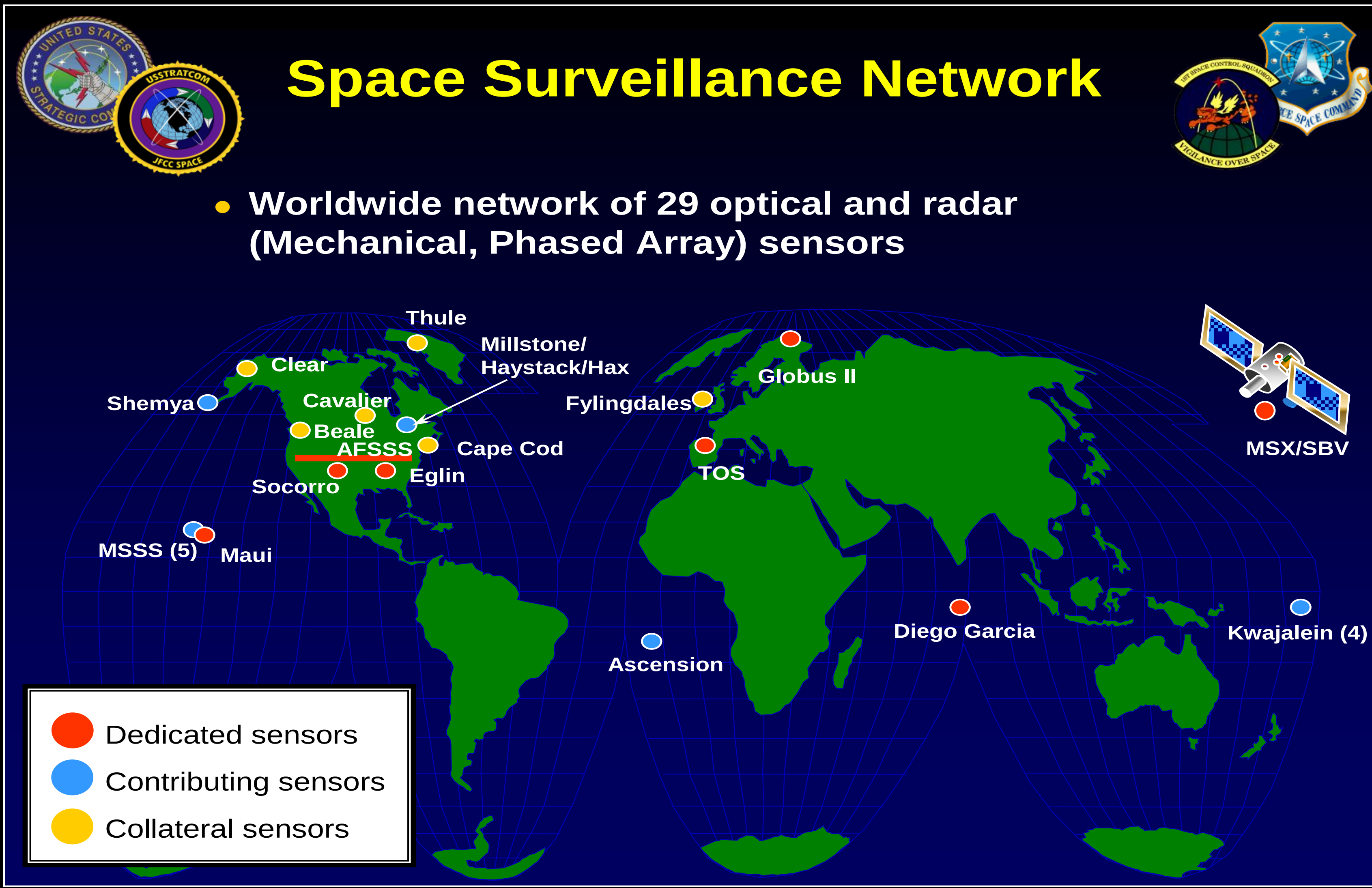
| | |
|---|---|
| 61 | were deliberate |
| 129 | were accidental: 112 propulsion, 11 battery, 6 collisions |
| 78 | have unknown causes |

The have been only 4 known collisions between tracked objects

| | |
|---|---|
| 1991 | Cosmos 926 debris and Cosmos 1934 (inactive) (not discovered until 2005) |
| 1996 | Cerise active satellite and Ariane 1 Debris |
| 2005 | Thor Burner 2A debris and CZ-4 Debris |
| 2009 | Iridium 33 active satellite and Cosmos 2251 (inactive) |

[1] History of On-Orbit Satellite Fragmentations 16th ed., NASA Orbital Debris Program Office, December 2022

# HOW DO WE KNOW ABOUT SPACE DEBRIS?

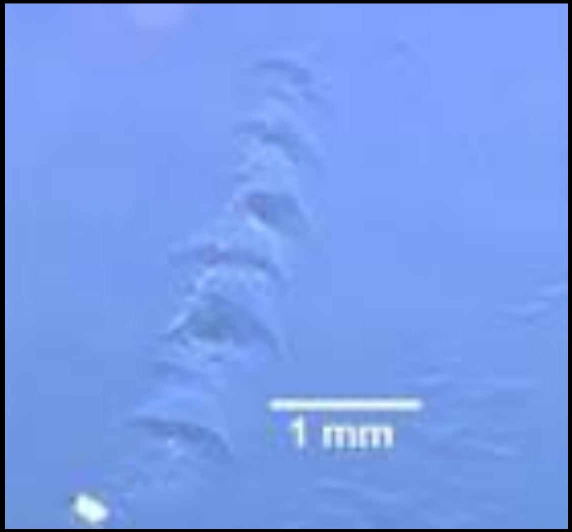



Graphic from USSTRATCOM Space Control and Space Surveillance Fact Sheet

# SPACE DEBRIS COMES IN ALL SIZES

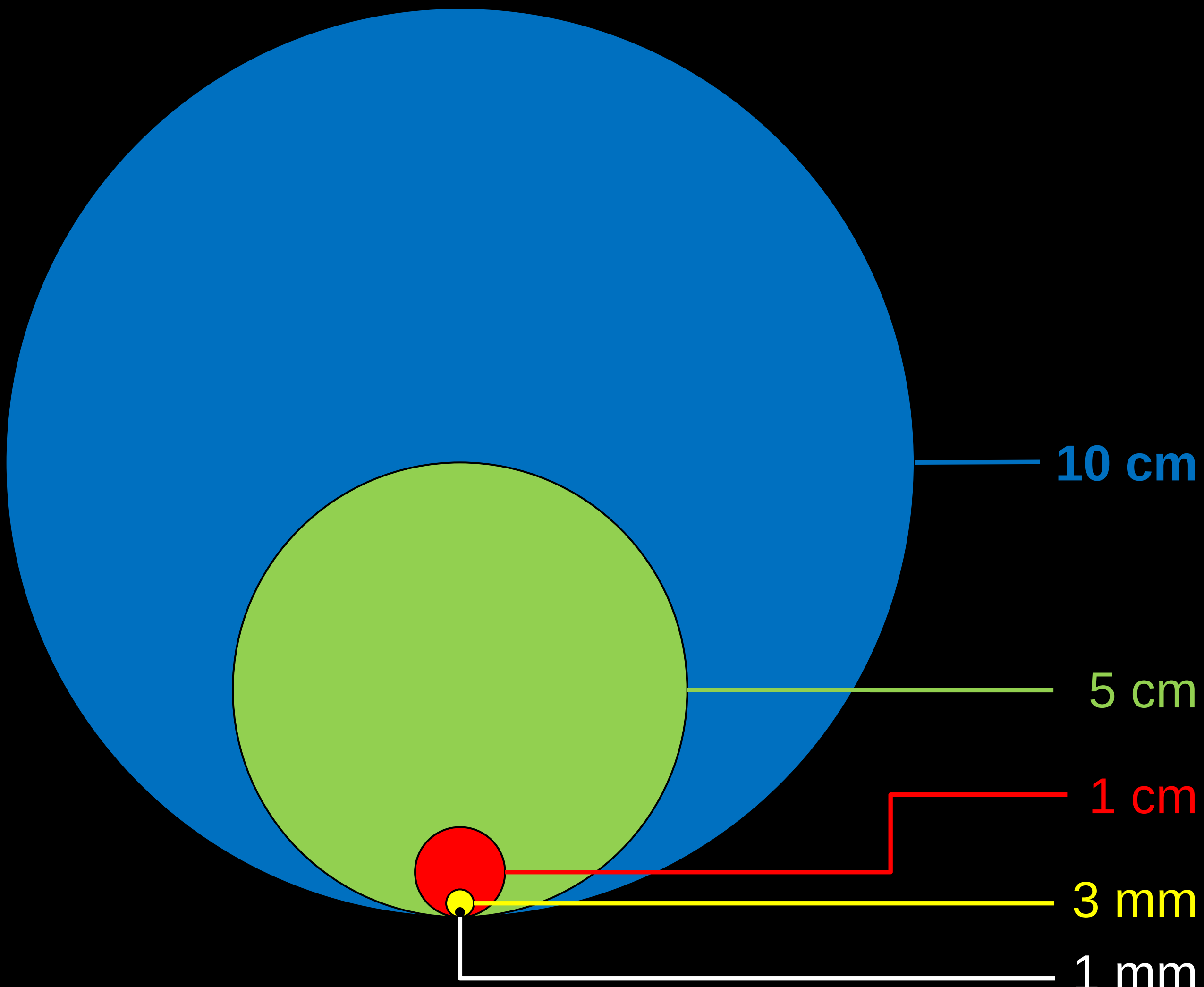
From microscopic particles

To obsolete spacecraft and rocket bodies tens of feet in length




Photographs Courtesy of NASA

# BUT WE CAN ONLY TRACK “LARGE” OBJECTS



# HOW MUCH SPACE DEBRIS IS THERE?

| Size Class | Quantity | Collision Risk |
|---|---|---|
| ~10 cm or larger | Over 29,000 | • Catastrophic damage<br>• Tracked and cataloged<br>• We can try to avoid these |
| 1 cm to ~10 cm | Over 500,000[2] (estimated) | • Most can’t be tracked<br>• Major to catastrophic damage<br>• Constant daily risk to satellites |
| 1 mm to 1 cm | Over 100,000,000[2] (estimated) | • Can’t be tracked<br>• Localized damage<br>• 3 mm = upper limit of shielding<br>• Constant but lower risk |

[2] https://orbitaldebris.jsc.nasa.gov/faq/#, NASA Orbital Debris Program Office

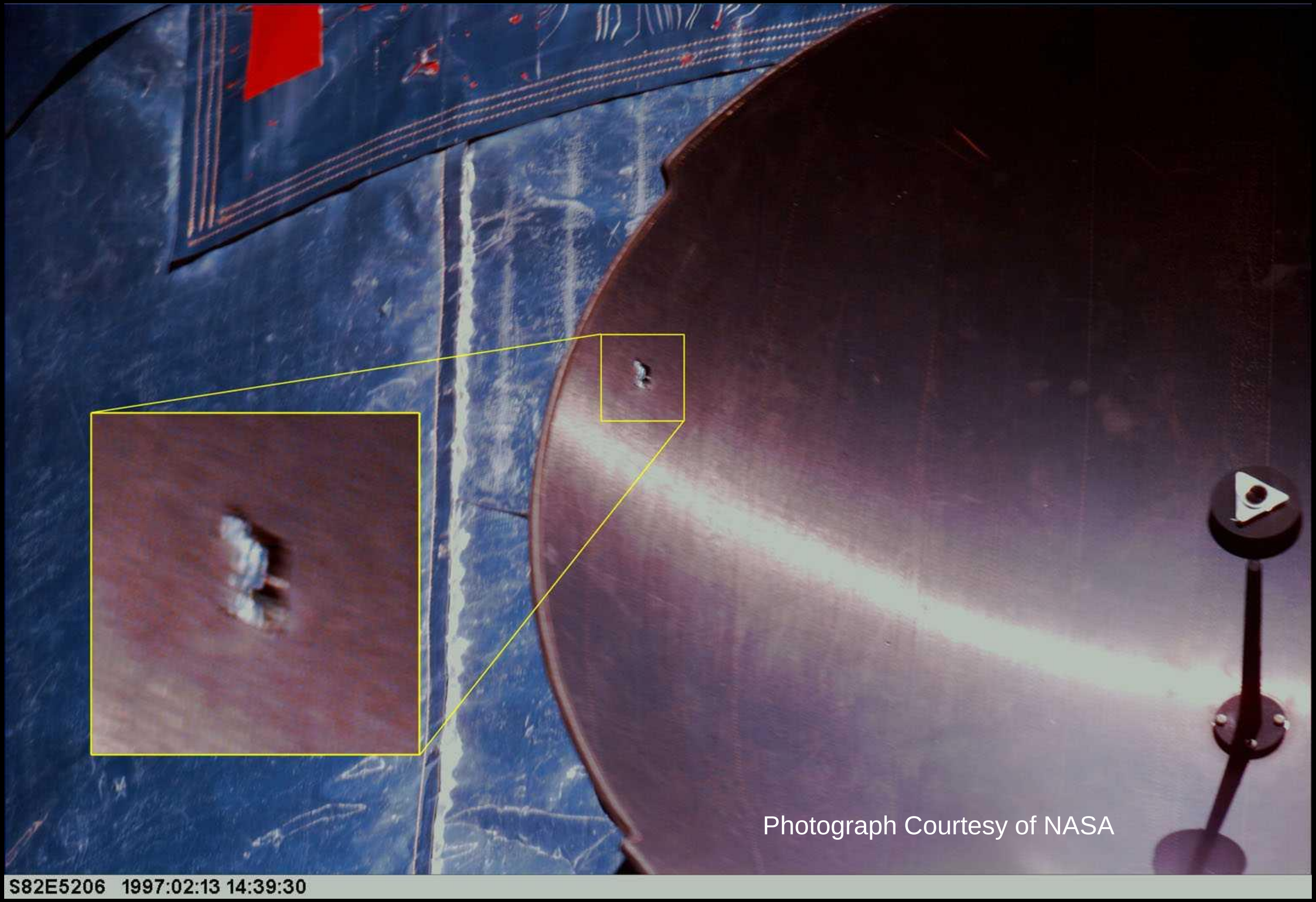
# IS SMALL DEBRIS REALLY A PROBLEM?

It may be small, but it is moving at 17,000 mph!

That kind of energy can damage anything it hits

# IS SMALL DEBRIS REALLY A PROBLEM?

Hubble Space Telescope antenna damage



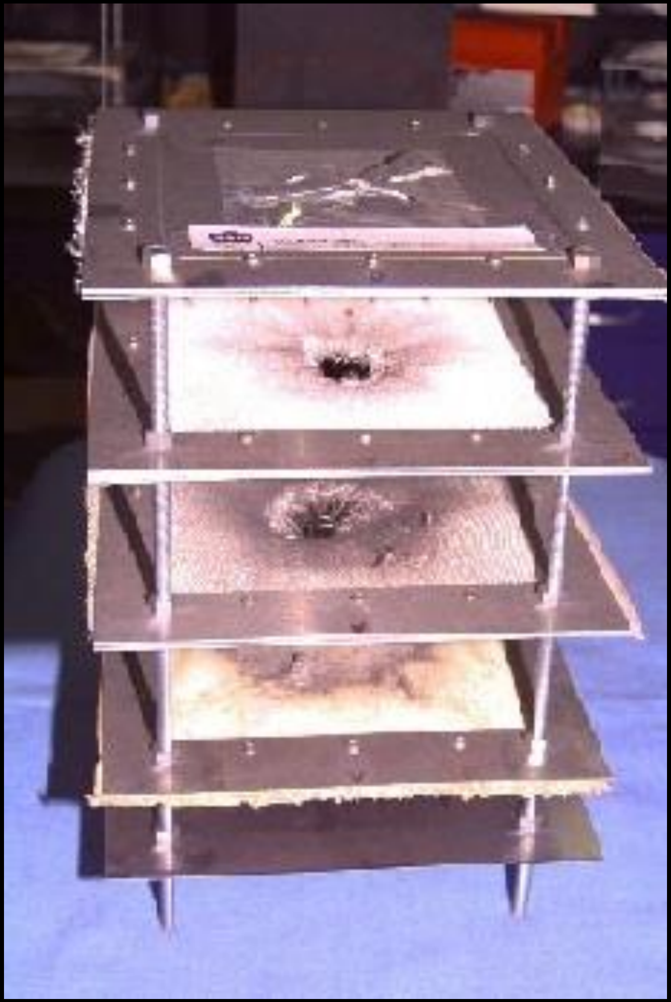
# IS SMALL DEBRIS REALLY A PROBLEM?

This panel, returned from the Hubble Space Telescope after 7 years in space , has 69 space debris impacts


Photograph Courtesy of NASA

# HOW CAN WE PROTECT SPACECRAFT?

For very small debris, an outer shield can protect critical components



Photograph Courtesy of NASA

# HOW CAN WE PROTECT SPACECRAFT?

For very small debris, an outer shield can protect critical components

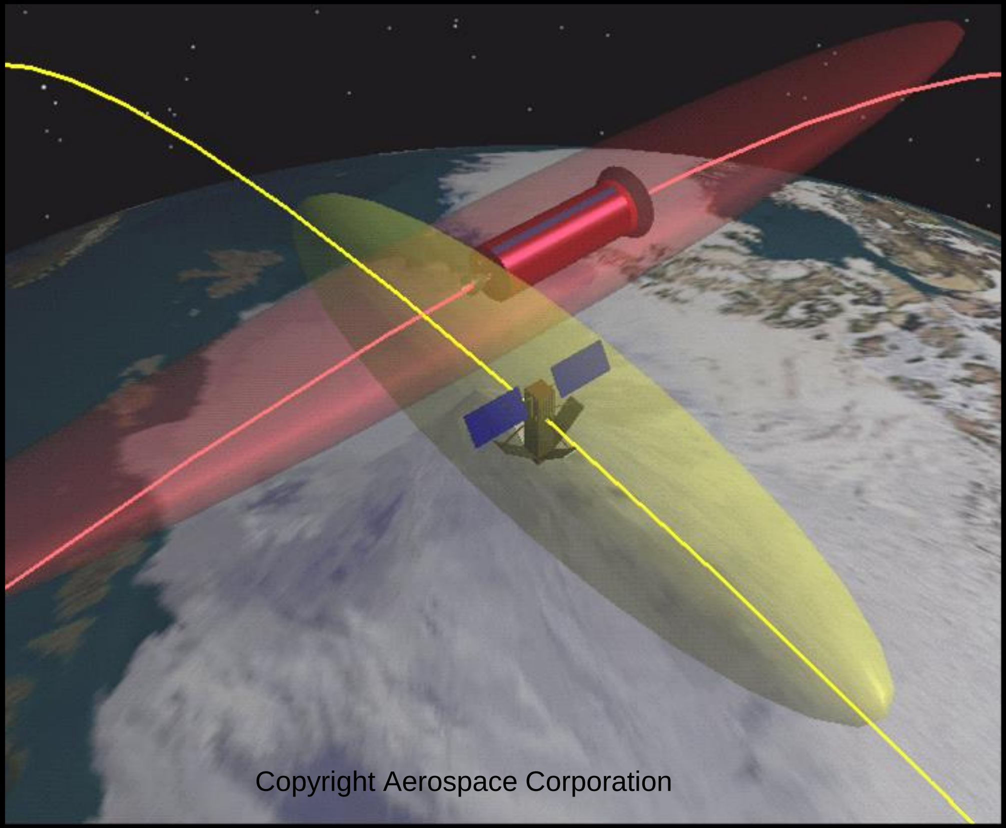
For large debris, maneuvering out of the path is the only option

| Debris size | Mass (g) aluminum sphere | Kinetic Energy (J) | Equiv TNT (kg) | Energy similar to |
|---|---|---|---|---|
| 1 mm | 0.0014 | 71 | 0.0003 | Baseball |
| 3 mm | 0.038 | 1,910 | 0.008 | Bullets |
| 1 cm | 1.41 | 70,700 | 0.3 | Falling anvil |
| 5 cm | 176.7 | 8,840,000 | 37 | Hit by bus |
| 10 cm | 1,413.7 | 70,700,000 | 300 | Large bomb |

# PREDICTING COLLISIONS

Not a yes/no result, we have to work with probabilities

Exact orbits and positions are never known



# REMEMBER THOSE FOUR KNOWN COLLISIONS?

1991 Cosmos 926 debris and Cosmos 1934

- Predicted miss distance 512 meters
- Probability of collision 1.7E-5 (~1 : 59,000)

1996 Cerise active satellite and Ariane 1 Debris

- Predicted miss distance 882 meters
- Probability of collision 5.6E-7 (~1 : 1,786,000)

2005 Thor Burner 2A debris and CZ-4 Debris

- Predicted miss distance 877 meters
- Probability of collision 1.8E-6 (~1 : 556,000)

2009 Iridium 33 active satellite and Cosmos 2251

- Predicted miss distance 584 meters
- Probability of collision 1.3E-5 (~1 : 77,000)

# WHAT HAPPENS WHEN OBJECTS COLLIDE?

- Hyper-velocity collisions cause objects to fragment into tens of thousands of particles
- Fragment sizes are distributed from 10s of cm down to 1 mm
  - Distribution is reflected in the space debris population table (Slide 9)
- Energy imparted to each fragment alters the orbit
  - Essentially an impulsive delta-v
    - Positive delta-v results in higher apogee, perigee at collision site
    - Negative delta-v results in a lower perigee, apogee at collision site
- All fragments have the collision location in common
  - Called the “pinch point” because all orbits pass through this location
  - Perturbations will eventually spread the orbits in right ascension
- Apogee of debris can be thousands of km higher than parent object orbit

# Example: Iridium 33 / Cosmos 2251 Collision

- Only a partial fragmentation of both objects
  - Iridium 33 modeled as a 15% fragmentation
  - Cosmos 2251 modeled as a 55% fragmentation
- Total fragmentation would have been much worse
- Model predictions and actual observed (tracked) debris

| Size Class | Iridium 33 | Cosmos 2251 |
|---|---|---|
| 5 cm or larger | 854 | 1864 |
| 1 cm or larger | 77,544 | 168,328 |
| Tracked Objects | 656 | 1714 |

# Iridium 33 / Cosmos 2251 Collision Animation

- Animation of 1 cm and larger fragments
- Only 49,174 of 245,872 fragments (20%) are shown, it's really 5 times worse!

2009/02/10 13:42:00.0000 UTC


AEROSPACE

# WHAT HAPPENS TO SPACE DEBRIS?

Debris in very low orbits slowly loses altitude and re-enters the atmosphere

Most of time it burns up during re-entry

Sometimes, it survives and lands back on Earth

Debris in higher orbits can remain for hundreds or thousands of years

Photograph Courtesy of NASA

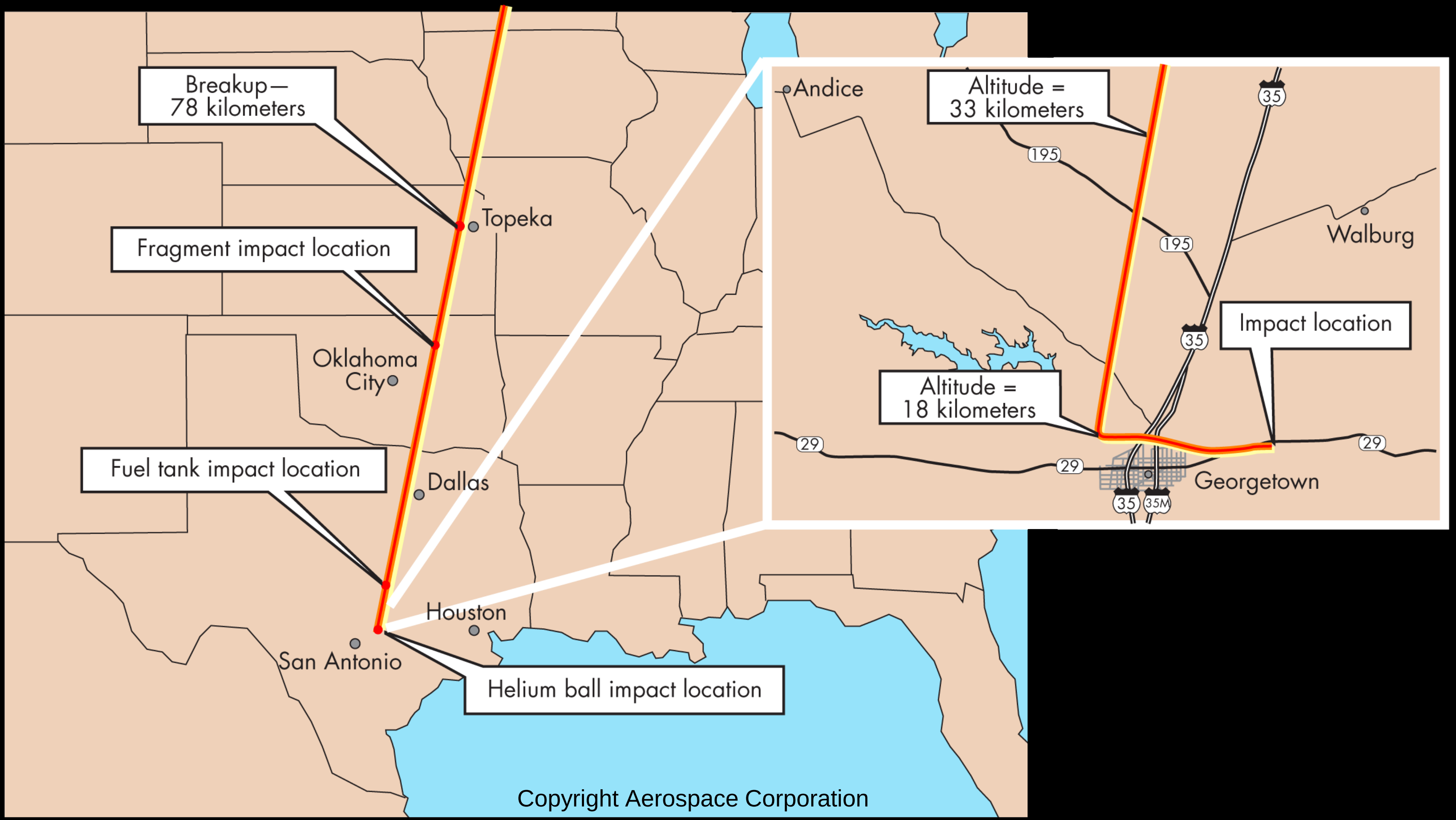
# UNCONTROLLED DEBRIS RE-ENTRY

Objects pose a risk to life and property if they survive re-entry

This tank landed 150 ft from a house

# UNCONTROLLED DEBRIS RE-ENTRY

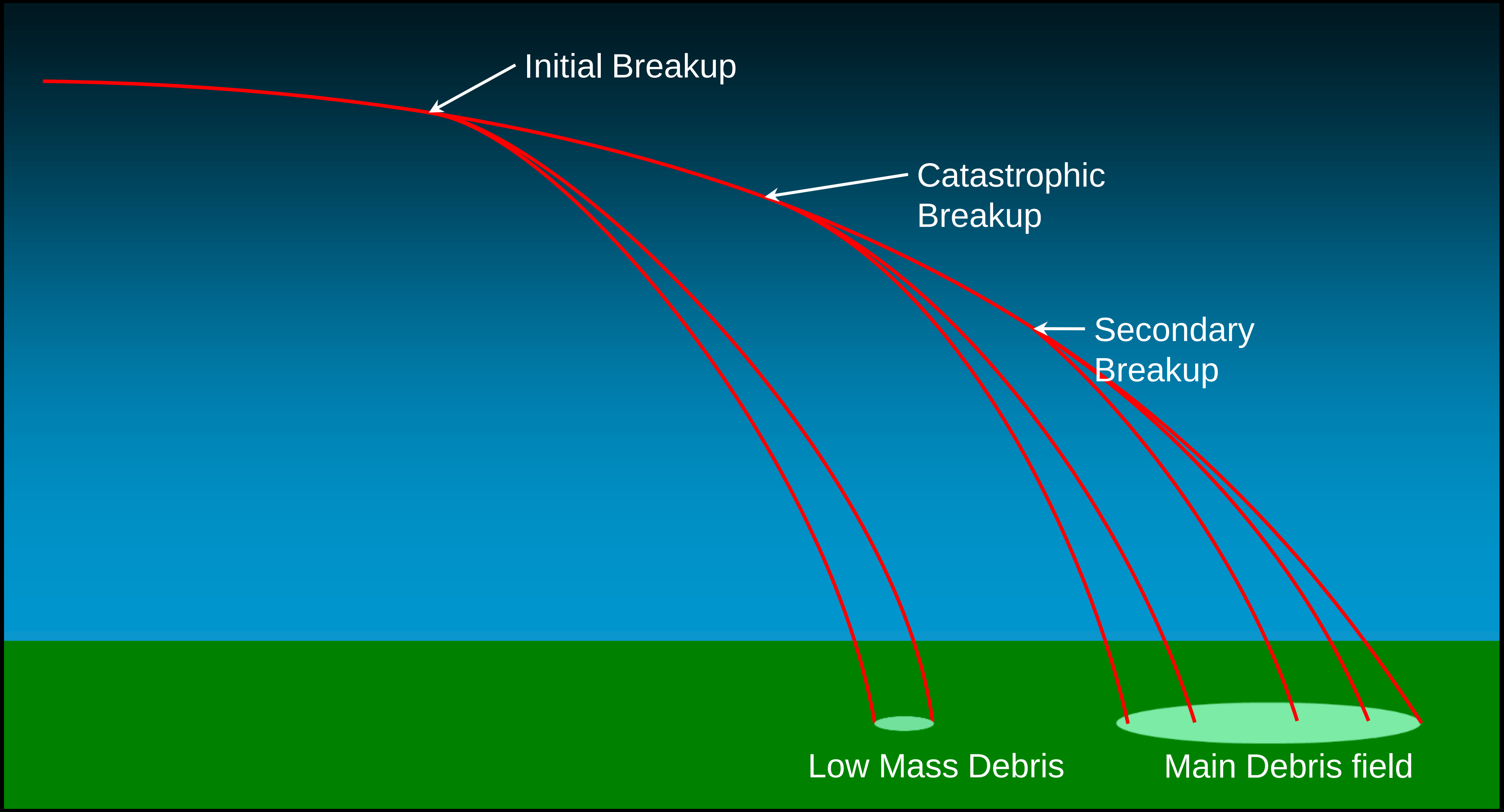
It is impossible to predict exactly where objects will land



# UNCONTROLLED DEBRIS RE-ENTRY

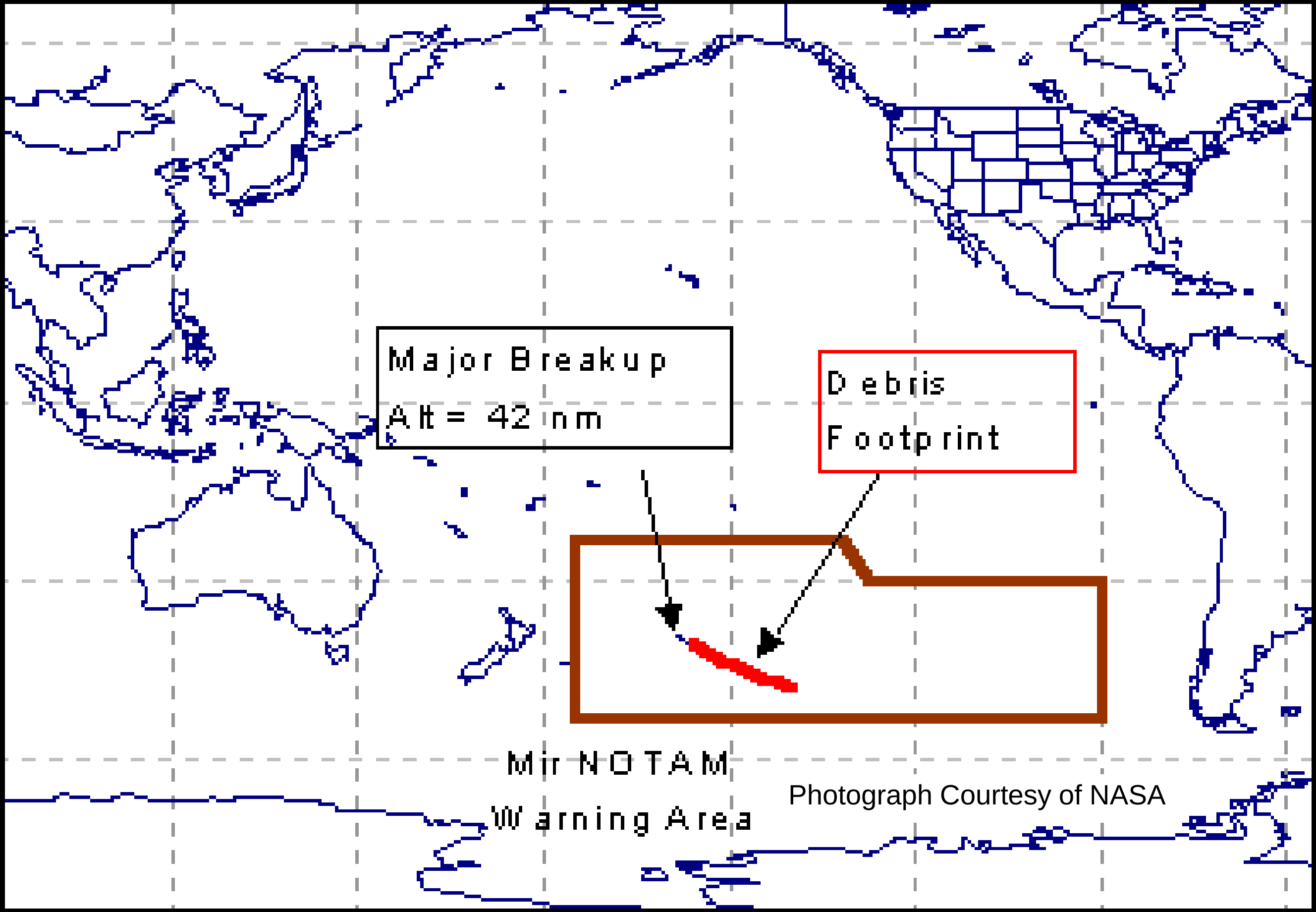
We can calculate a probable impact zone

But it may cover thousands of square miles (28,000 for Columbia)



# CONTROLLED DEBRIS RE-ENTRY

Spacecraft that are no longer needed are sometimes programmed to re-enter and impact in the ocean



Photograph Courtesy of NASA

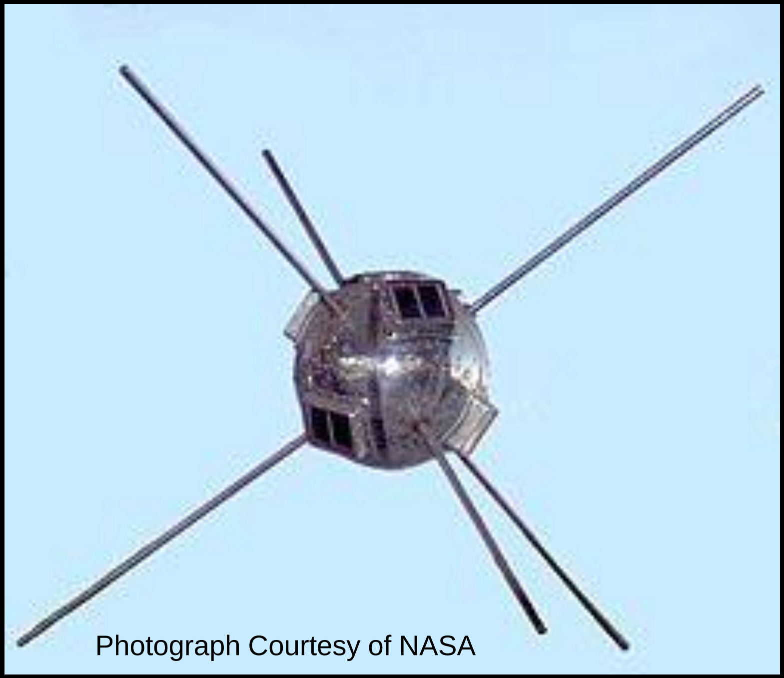
# IT ALL BEGAN WITH SPUTNIK 1 in 1957

As of March 1, 2025, 6,399 missions have been launched

20,613 payloads were delivered, 10,102 in the last 6 years

14,387 are still in orbit, ~11,700 are active.

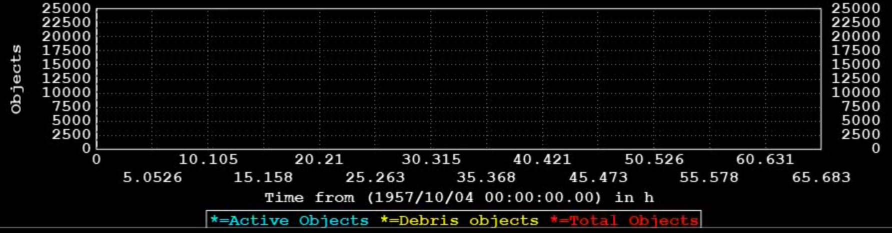
Vanguard 1 (US 1958) is the oldest object still in orbit



Photograph Courtesy of NASA

# Spaceage Timeline

1957




Active Objects, 0
Debris objects, 0
Total Objects , 0