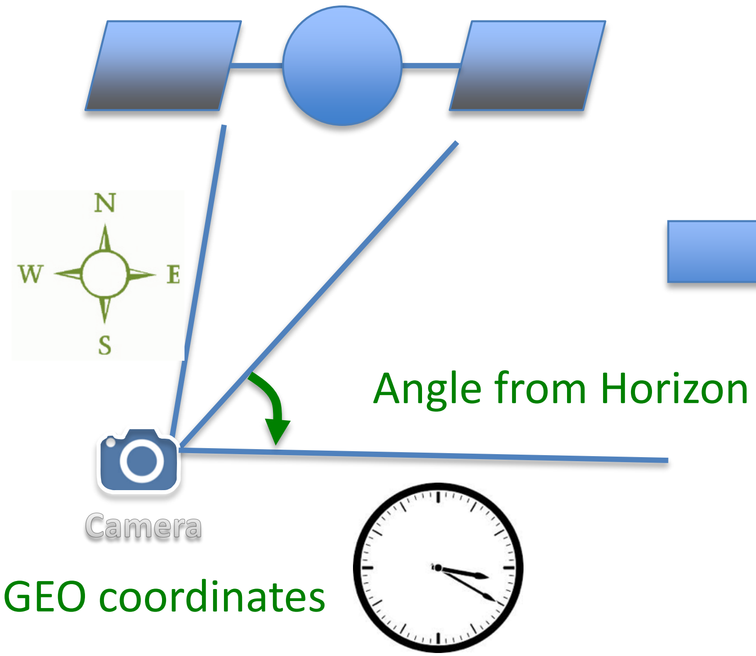
The Space Catalog Mission and Conjunction Analysis

Seth Harvey

Air Force Officer Maneuvers satellite and saves the day

who is more realistic....Hollywood or the Air force

Space Catalog ~~101~~ 0.1
Orbit Analysis



If you take a picture of a satellite and you know a few things about your location, orientation and time

you can determine where a satellite is in relation to the earth

Space Catalog ~~101~~ 0.1
Orbit Analysis

With enough observations, you can determine the orbit path of the satellite around the earth

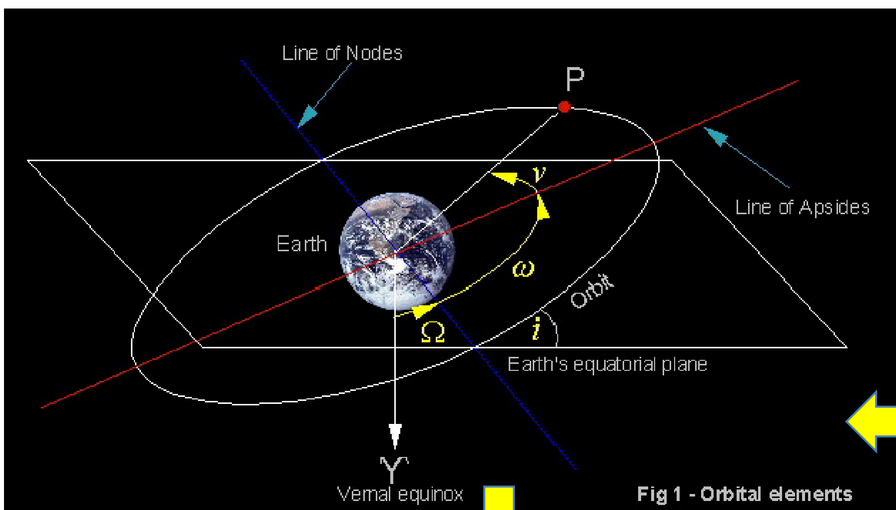
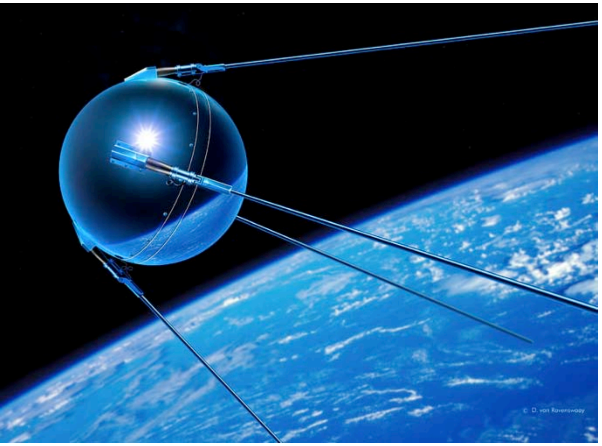


Fig 1 - Orbital elements

The orbit path can be described using orbital parameters and represented as a Two Line Element set (TLE or Elset)

ISS (ZARYA)
1 25544U 98067A   08264.51782528 -.00002182 00000-0 -11606-4 0 2927
2 25544 51.6416 247.4627 0006703 130.5360 325.0288 15.72125391563537

The Genesis of the Space Catalog mission



Sputnik 1- Launched Oct 4th 1957

- Spacetrack was started in 1957 to by two scientists to track Russian spacecraft
- Relied on any observations they could find….usually voice reported
- Initial orbital analysis was done using mechanical calculators

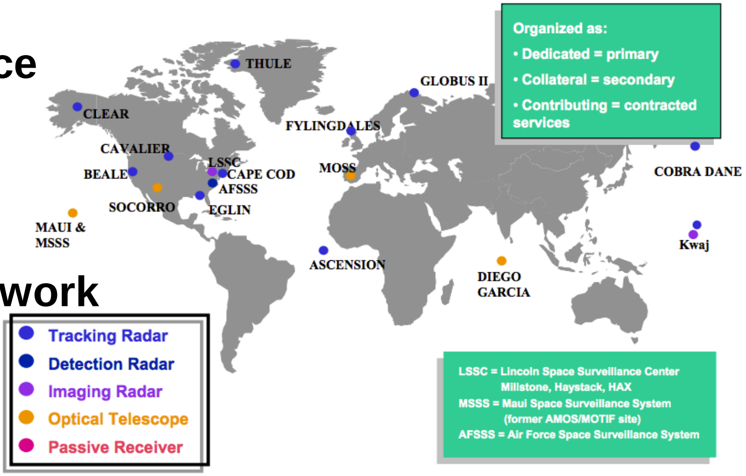
- In 1959 DARPA funded the project and Spacetrack received its first computer….The IBM 610

Ford Aerospace did most of the programing

Space catalog mission today

Tasks the Space Surveillance Network For Observations

Transmits Observations Via global point to point network



SPADOC – Current C4 System responsible for maintaining the space catalog

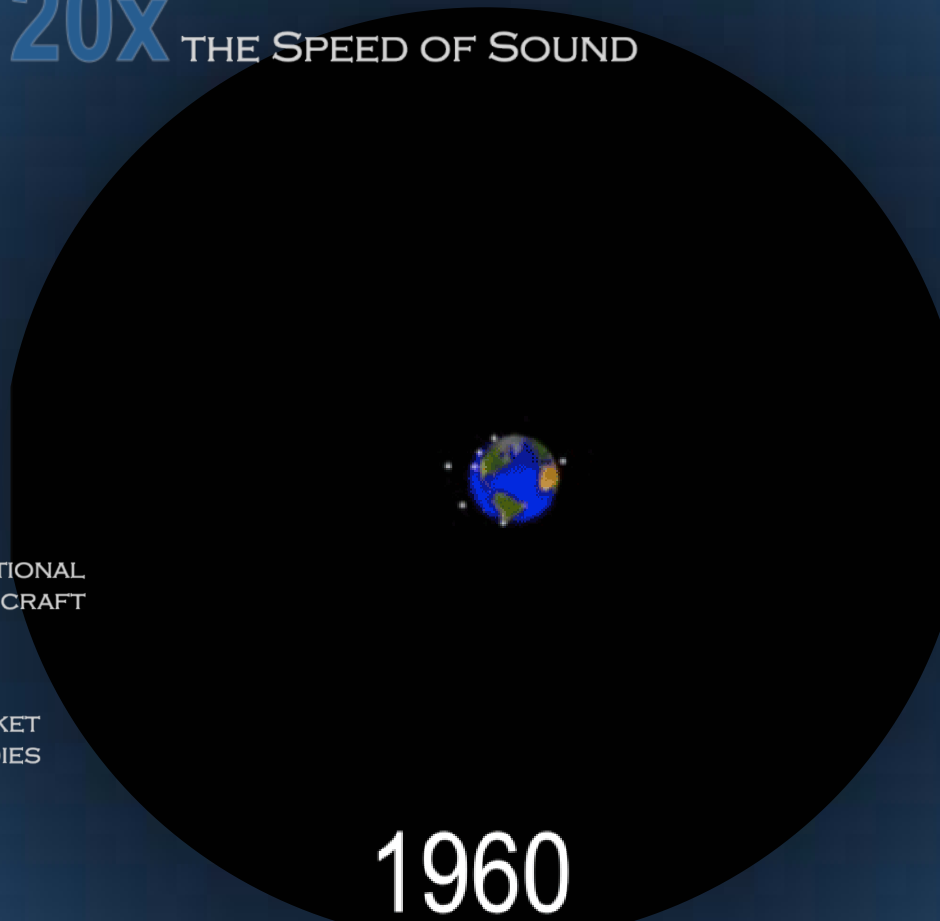
- It produces an updated space catalog once every 8hrs
- It was Last upgraded in 1991, with IBM 3090-200J Mainframes.
- It publishes 6700 messages an hour to over 370 user organizations worldwide via legacy comm.
- It is hard coded to track at most 69,999 space objects.
- It currently receives 700,000 observations a day or 250% more than originally designed.
- It is 17 years past end of life.
- Cost $1.2 billion in 1980 which is equivalent to $3,448,275,862 today.

Space Catalog Objects by the numbers

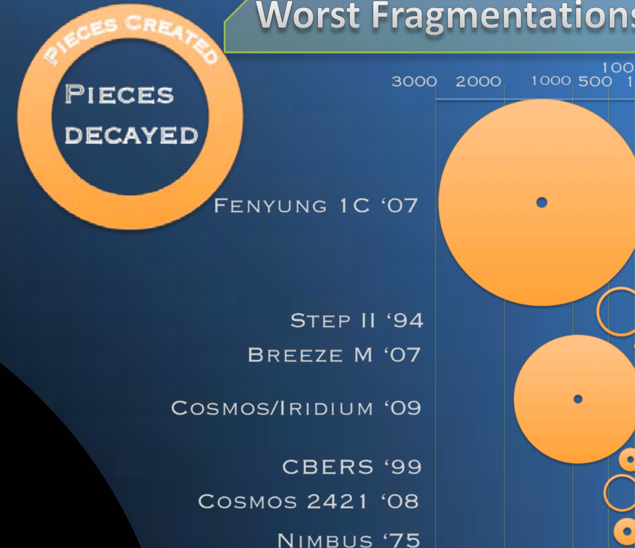
22,000
TRACKED OBJECTS IN
EARTH ORBIT
LARGER THAN 10 CM
ESTIMATED TO GROW OVER
100K
IN THE NEXT 10 YEARS

ORBITAL SPEED OF ISS APPROX. 7.7 KM/S
ASSUMING AN ALTITUDE OF 370KM

OR OVER 18,000 MPH WHICH IS
20x THE SPEED OF SOUND



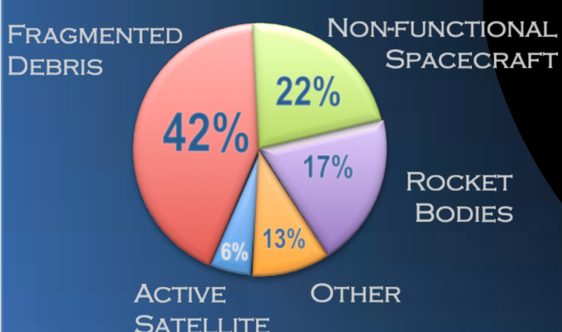
Worst Fragmentations



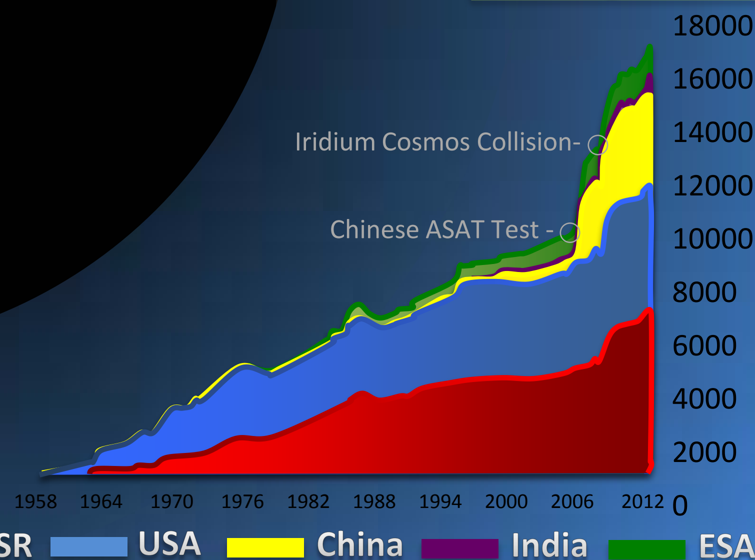
Passing By

OVER 40,000 EVENTS OCCUR EACH DAY WHERE ONE OBJECT PASSES WITHIN 5 MILES OF ANOTHER

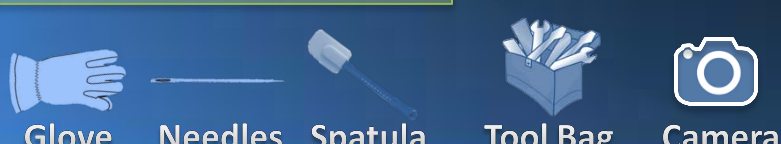
Catalog demographics



Catalog Growth



Strange orbiting objects



The Space Catalog Mission of the Future

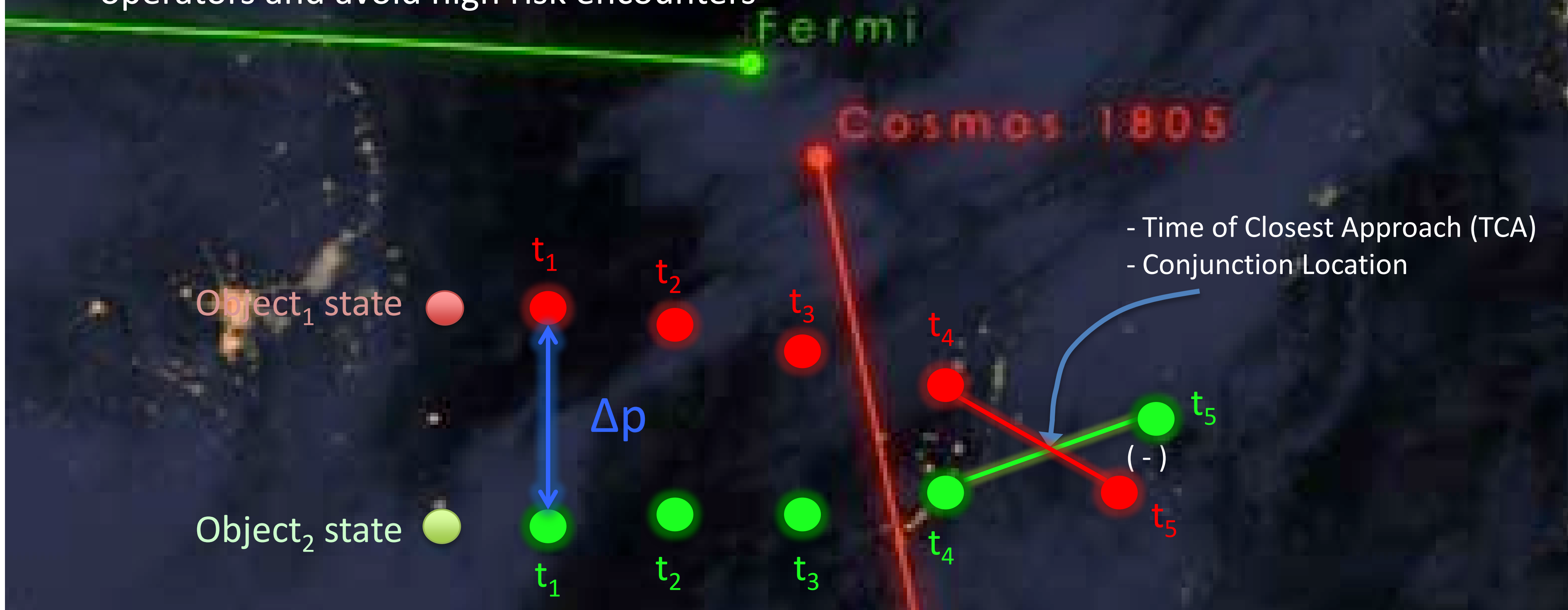
- The Air Force developed a second non-operational system to help off load processing from SPADOC called CAVENet.
- CAVENet Cannot keep pace with catalog and Space Situational Awareness (SSA) processing demands.

- The JSpOC Mission System (JMS) is being developed to transition the catalog and SSA missions off of the legacy SPADOC and CAVENet systems
- JMS will:
  - **Replace SPADOC for 1/12 the money in ½ the time**
  - **Process the catalog in real time vs 8 hr batch processing**
  - **Process 3,000,000 observations a day vs 700,000**
  - **Be capable of tracking 1,000,000,000 objects vs 69,999**
  - **Be capable of all on all catalog collision assessment in <3 hrs for 100,000 catalog vs 8 hrs for active satellites against todays 22,000 object catalog**

The JMS Collision Assessment KPP was widely though to be impossible 4 years ago

Conjunction Analysis

The Process of predicting upcoming object encounters in an effort to notify satellite operators and avoid high risk encounters

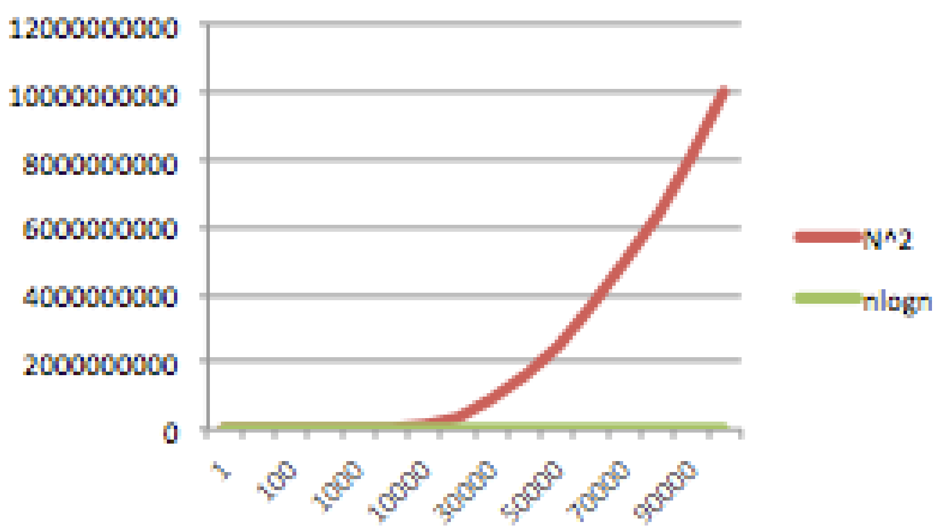


- Take the last orbital state and propagate two objects some distance into the future
- At each time step, find the difference of the predicted positions for the object pair
- A conjunction is detected when the sign changes on the difference calculation
- Determine the exact location and time of conjunction by interpolating between points

Why was this considered ~~impossible~~ difficult

- An AFRL prototype Joint Situational Awareness and Reasoning System (JSARS) integrated an Aerospace computational system called CSIEVE, In 2008 it was considered state of the art for CA processing
- CSIEVE was capable of performing all v all on a 11K catalog using SP data in under 17 Minutes
- It scaled by n^2 as new objects where included in the run

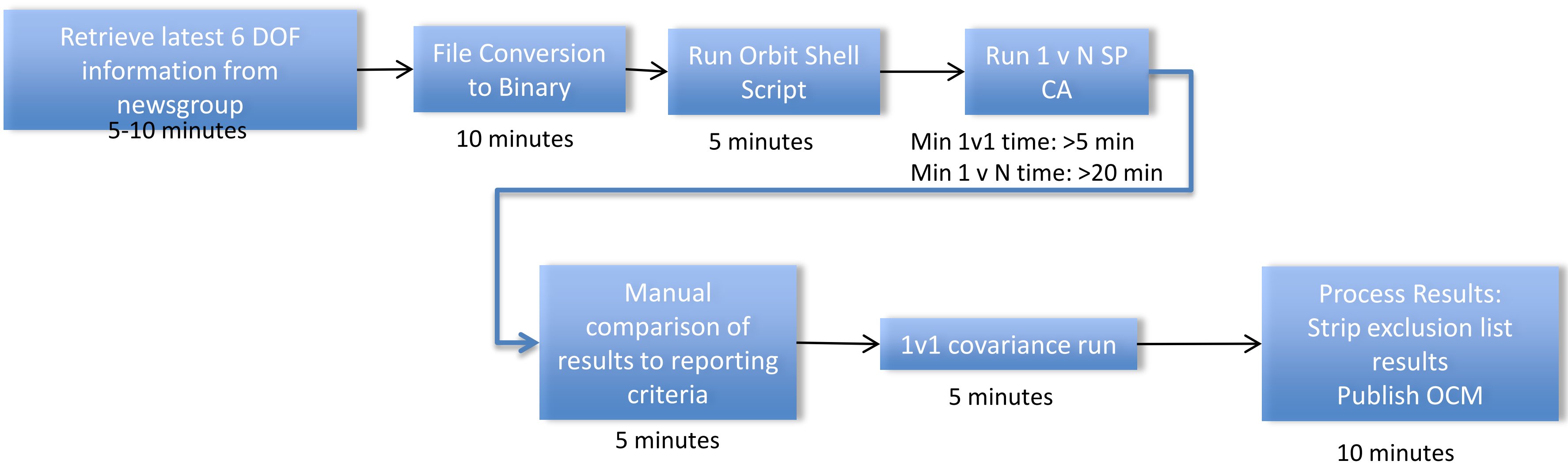
As you can see the Processing time grows very quickly as objects are added to the catalog



This is still much faster than today's JSpOC runs

JSpOC CA workflow

- Today a CFE cell's shift consists of 27 operators. 4-5 operators Per shift (3 shifts per day) conduct SP CA analysis on 1200 v All
- These runs are broken up into smaller runs, and all 1200 active satellites are screened 3 times a day.
- DOD assets are treated uniquely



TOTAL time for 1 v N SP CA run: > 60 minutes

Research Objects

The JSARS prototype highlighted the need for more research In the area of CA.

Approach: Analyze a traditional Aerospace problem from a computer science perspective

Requirement #1: Increase the speed of CA (critical as catalog grows)

- Characterize the CA problem
- Breakdown CSIEVE to understand the current speed bottle necks
- Investigate new Compute Architectures

Requirement #2: Develop an extensible framework for future research and improvements to be dynamically added to the system by any effort

- Framework should support dynamic inclusion of new algorithms/data/approaches
- Framework should allow for dynamic configuration of algorithms/data/approaches

Requirement #3: Separate the algorithms from the user interface

Computer Architecture Assessment

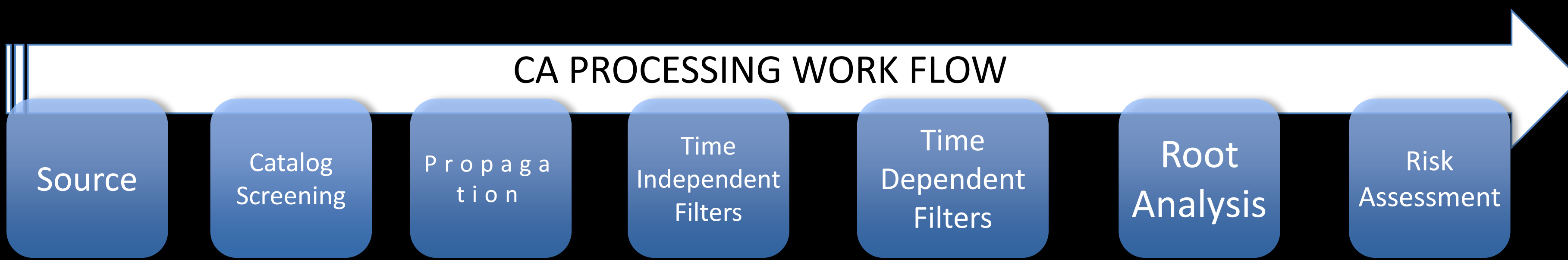
- Cluster Computing - CSIEVE
  - Advantages: Fail-over, scalable hardware, works well on separable problems
  - Disadvantages: Suffers from n^2 data passing in non-separable problems (like CA)

- Cloud Computing - MIT
  - Advantages: Massive data processing/storage, Rapid access to data, data redundancy, fail-over, scalable hardware, large number of nodes, works well on separable problems,
  - Expensive
  - Disadvantages: Suffers from n^2 data passing in non-separable problems (like CA)

- GPU Computing - AI Solutions
  - Advantages: Designed for the types of computation that CA requires (vector math), reduces transmission overhead
  - Disadvantages: Limited on-board memory requires tedious memory transfers between host and device, not as mature as other architectures

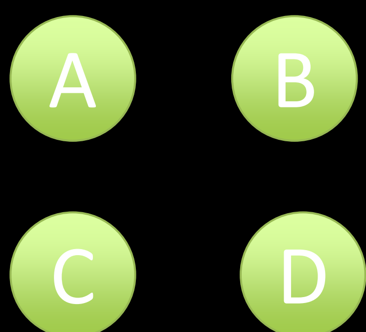
1st Research Discovery

Conjunction Analysis is easily parallelizable however it is also massively **I/O Bound** when parallelized

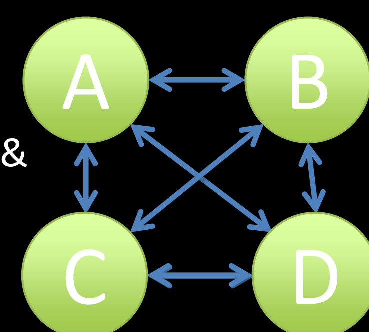


Separable | Separable | Separable | **Inseparable** | **Inseparable** | Separable

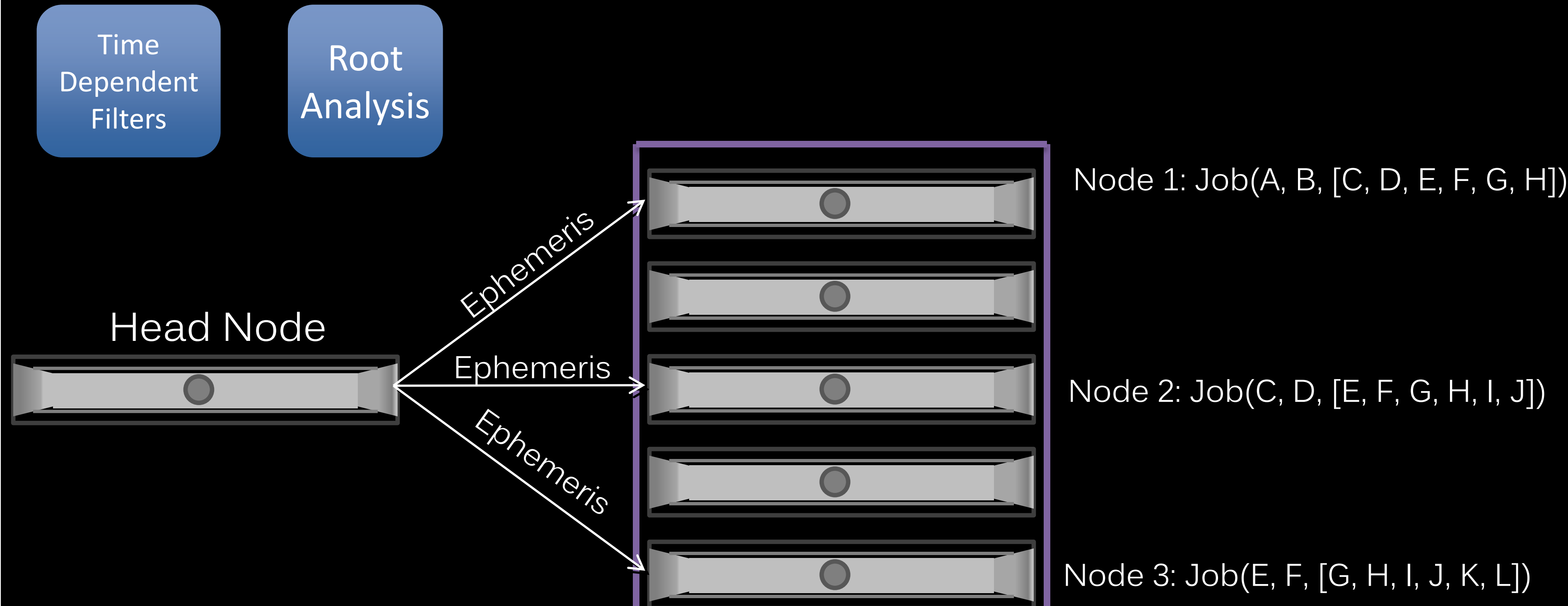
Parallelizable & separable



Parallelizable & Inseparable



PARALELLIZING A NON-SEPERABLE PROBLEM



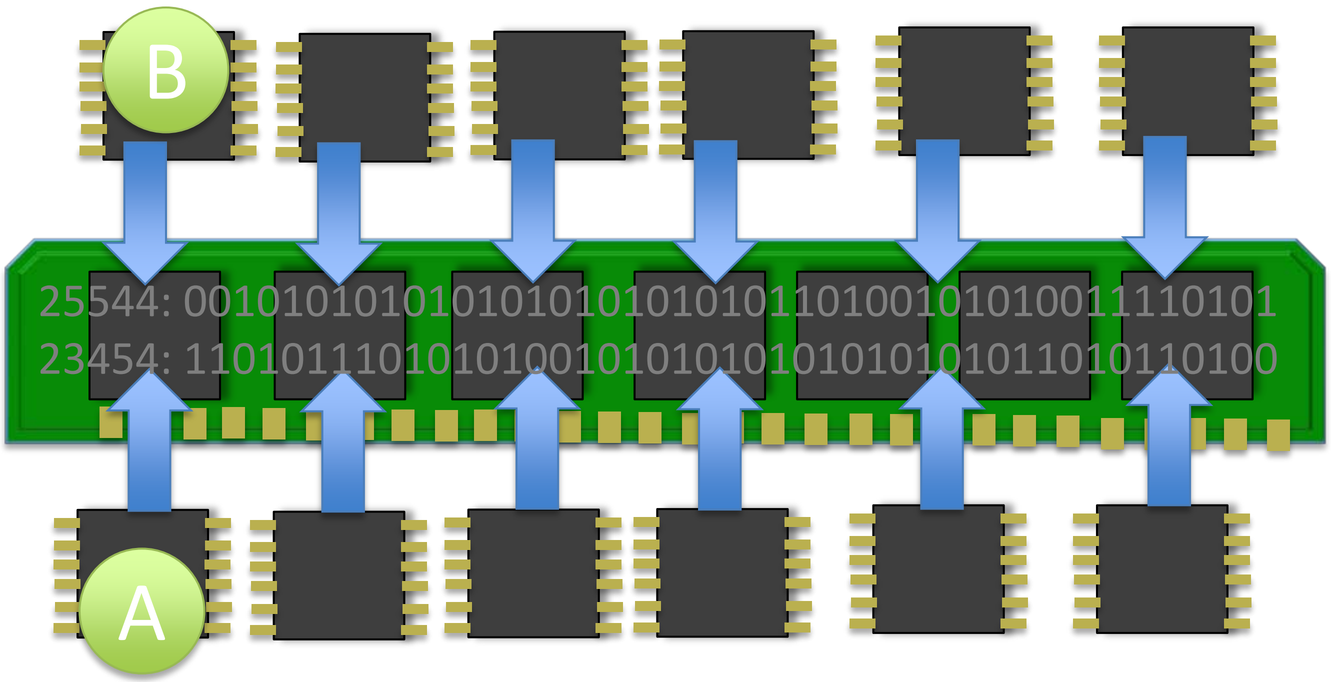
In this simple example, the ephemeris for objects E, F, G and H are sent to
every compute node

NOW REPLICATE THIS PROBLEM BY 100,000

Chosen System Architecture

CA Performed on single
2U Blade Server

Cisco Server: 1TB RAM
48 processors



- Ephemeris is loaded into RAM and shared by multiple threads
- Avoids N^2 Message Passing
- Immutable data minimizes data hazards

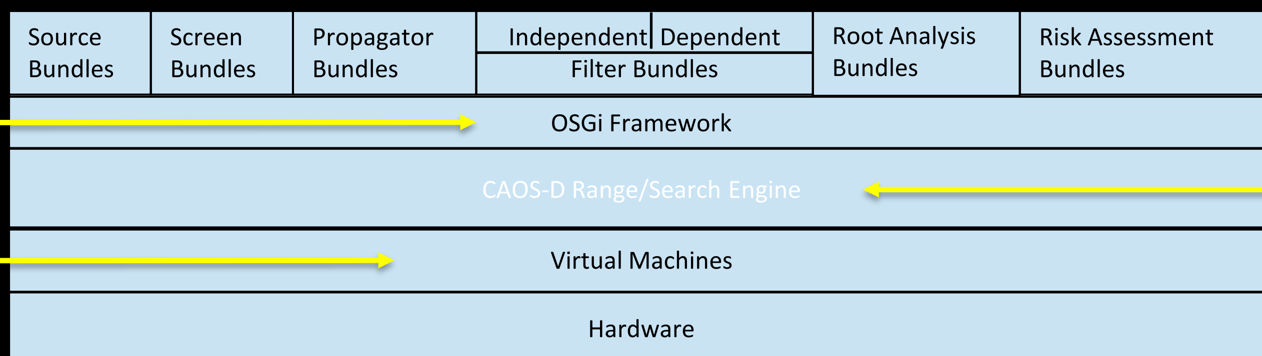
Software Architecture

Dissected CA into 7 Major stages

CAOS-D started w/ CSIEVE, but has since incorporated many prominent CA solutions as plugins

0040 Plugins added

Aerospace CSIEVE:	12 plugins
ESA SmartSieve:	13 plugins
AFSPC Astro Std:	2 plugins*
SuperCOMBO:	7 plugins**
And others…..	10+



Developed pluggable framework capable of dynamic plugin addition

Built on JMS Locked down VMs

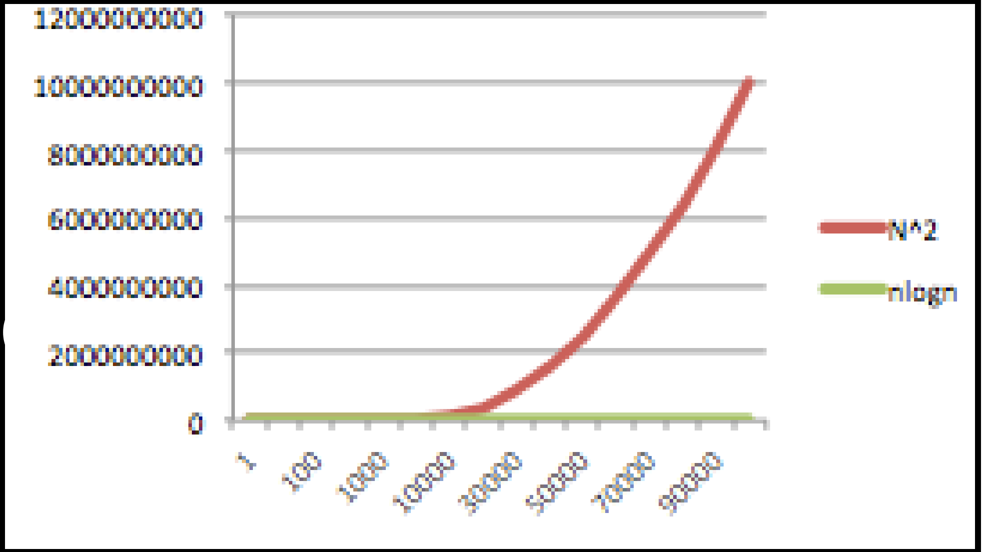
Coupled with range/search engine to make it fast!

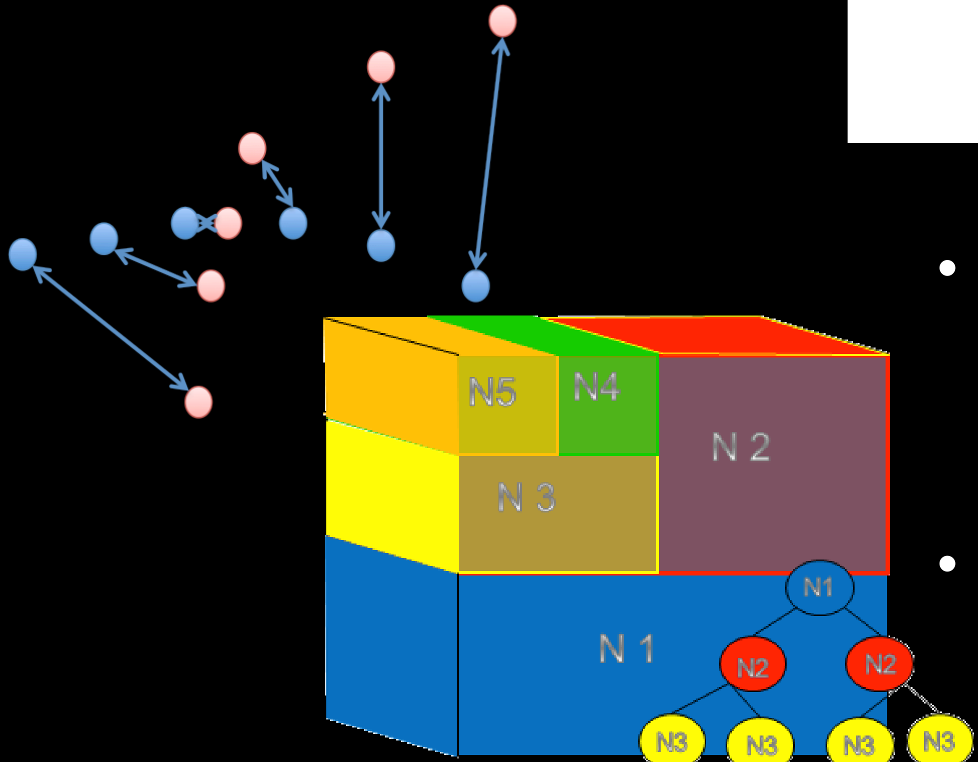
Capable of performing all versus all (20k objects) CA in under 10 minutes but that still didn't meet the JMS requirement

2nd Research Discovery

Conjunction analysis is a range/search problem

- A sort and search is performed at each time step (range search)
- **Most CA solutions out there perform with computational complexity O(**





- Range Search problems are often encountered in the gaming industry, fluid dynamics and molecular research Industries (collision of spaces)
- **R/S problems are known to be lower bound with Complexity O(n logn)**

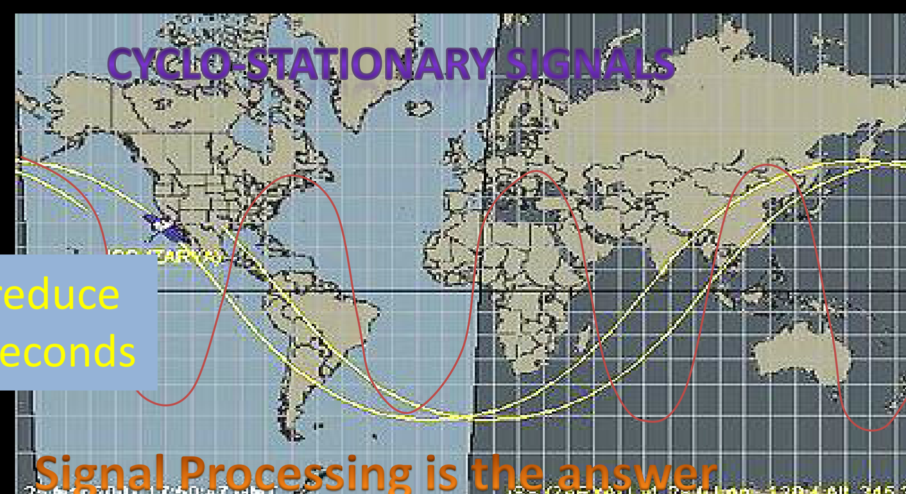
Current State of the Research

- Capable of screening todays catalog in under **45 seconds**
- Capable of screening a future 100k catalog in under **20 minutes**
- But there is still room for vast improvement!

Still Work to be done…CA is still brute force

Objects are compared at every time step regardless of where they are at

We can reduce time to seconds



Questions

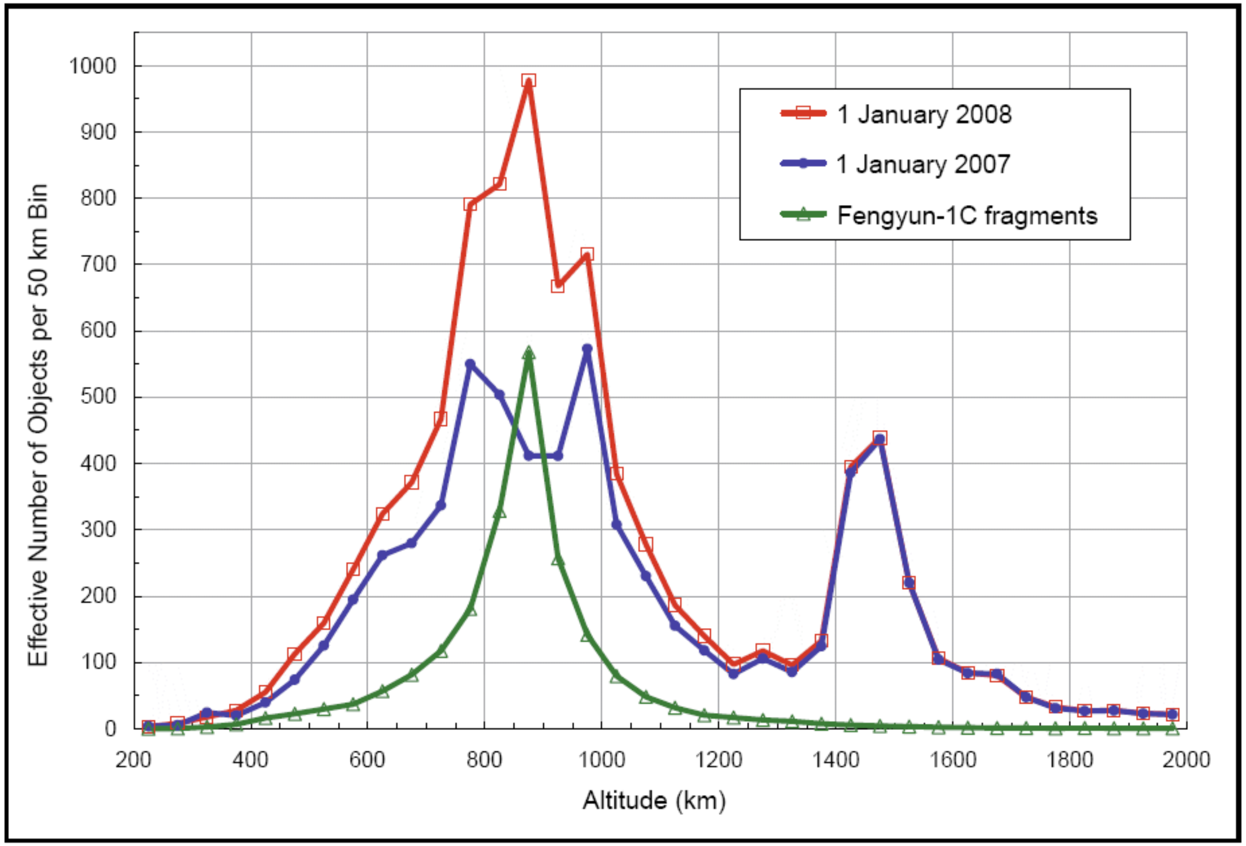


Figure 1. Distributions of the catalog populations in the low Earth orbit region in January 2007 (blue), January 2008 (red), and the officially cataloged Fengyun-1C fragments.

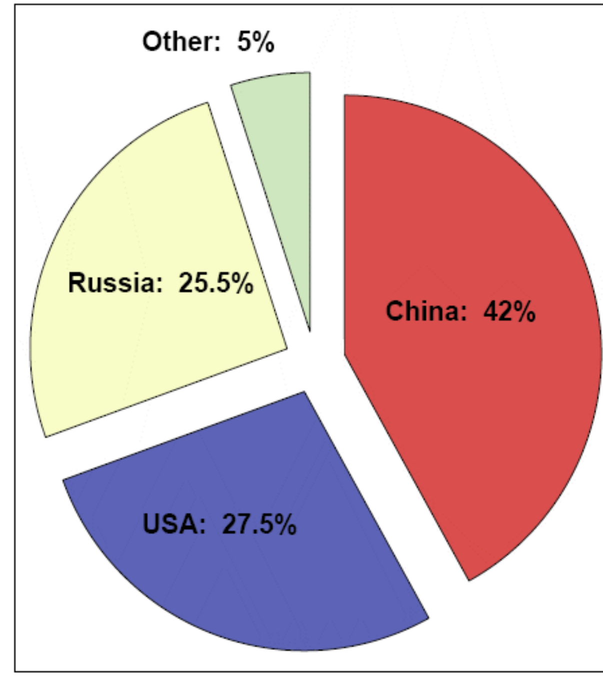
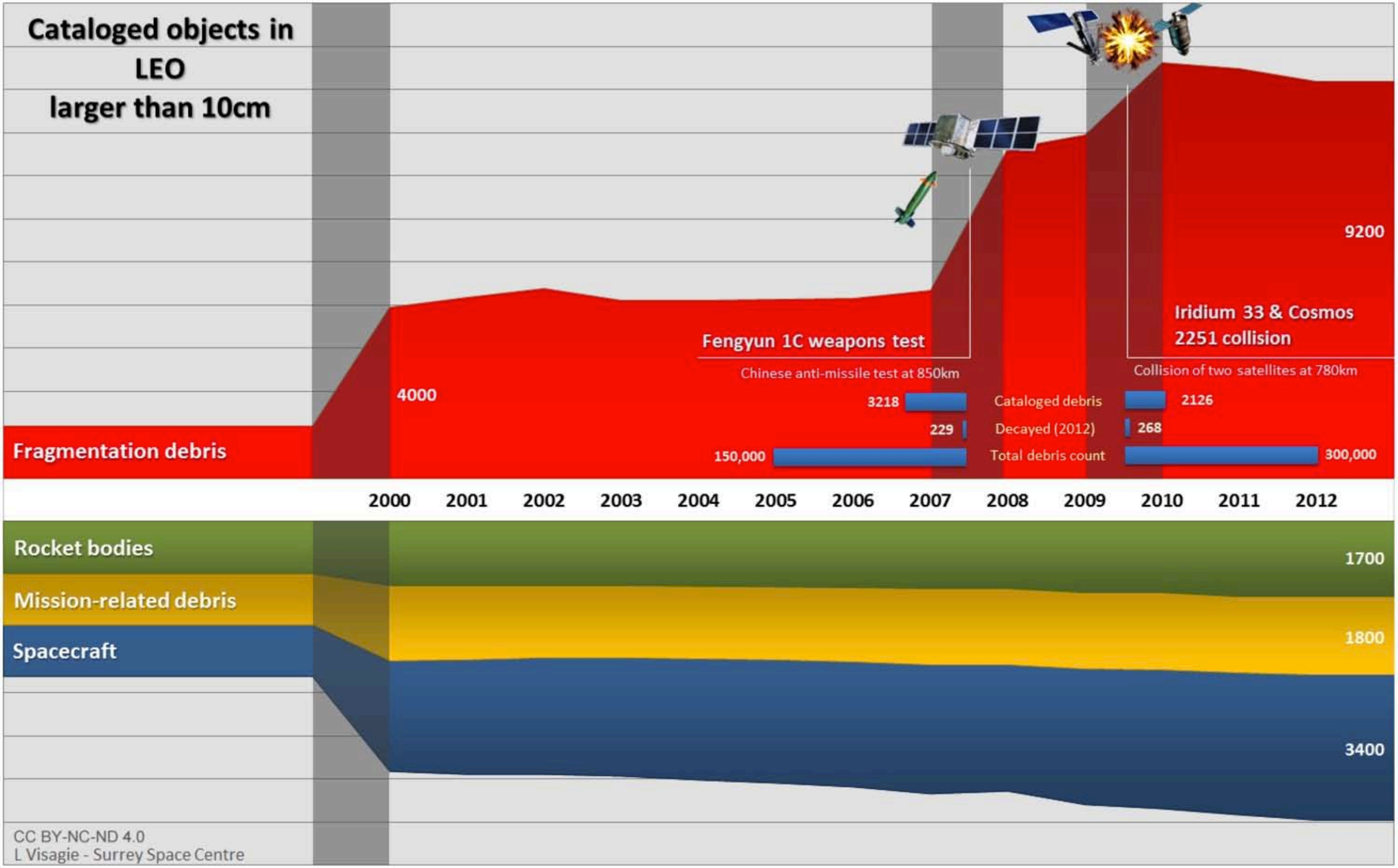


Figure 2. The People's Republic of China was responsible for nearly half of all known satellite breakup debris in orbit as of 1 January 2008. The primary source of this debris was the intentional destruction of the Fengyun-1C spacecraft.



Cataloged objects in LEO larger than 10cm
Fragmentation debris
4000
Fengyun 1C weapons test
Chinese anti-missile test at 850km
3218
229
150,000
Cataloged debris
Decayed (2012)
Total debris count
Iridium 33 & Cosmos 2251 collision
Collision of two satellites at 780km
2126
268
300,000
9200
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Rocket bodies
1700
Mission-related debris
1800
Spacecraft
3400

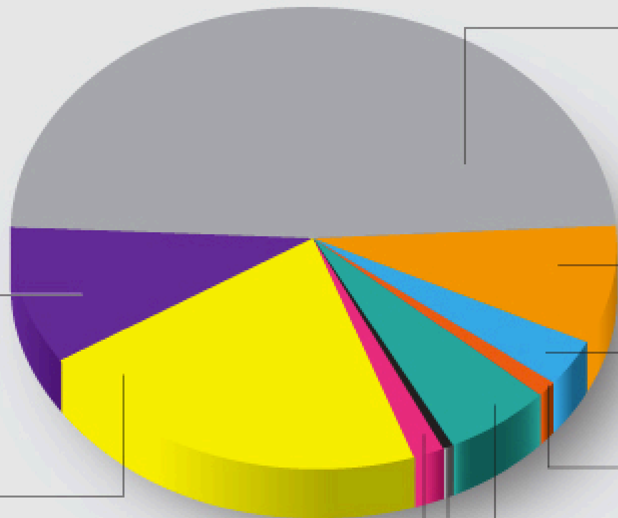
70 Percent of Geostationary-orbiting Objects Are Garbage

The population of objects — satellites and rocket stages — in the geostationary arc over the equator was 1,369 as of January. But only 30 percent of the objects were known satellites that were at least partially controlled by their owners, according to a European Space Agency analysis of U.S., Russian and European radar data.

Nearly half the objects were drifting around the arc. Another 12 percent had collected in one of two sinks — libration points — at 75 degrees east and 105 degrees west.

The European analysis of the state of debris mitigation efforts in geostationary orbit in 2012 showed that just nine of the satellites retired that year were placed into correct graveyard orbits. The owners of four others raised their satellites' orbits somewhat, but not enough. One satellite appears to have been abandoned.

Status: Jan. 8
Total: 1,369



Source: European Space Agency

SPACENEWS GRAPHIC

This large amount of space hardware has a total mass of more than 6 300 tonnes. Not all objects are still intact. More than 23 000 space objects Earth orbits (as of September 2012) in total are regularly tracked by the US Space Surveillance Network and maintained in their catalogue, which covers objects larger than approximately 5 to 10 cm in low Earth orbit (LEO) and 30cm to 1m at geostationary altitudes (GEO).

The Chinese Feng-Yun 1C engagement in January 2007 alone increased the trackable space object population by 25%.

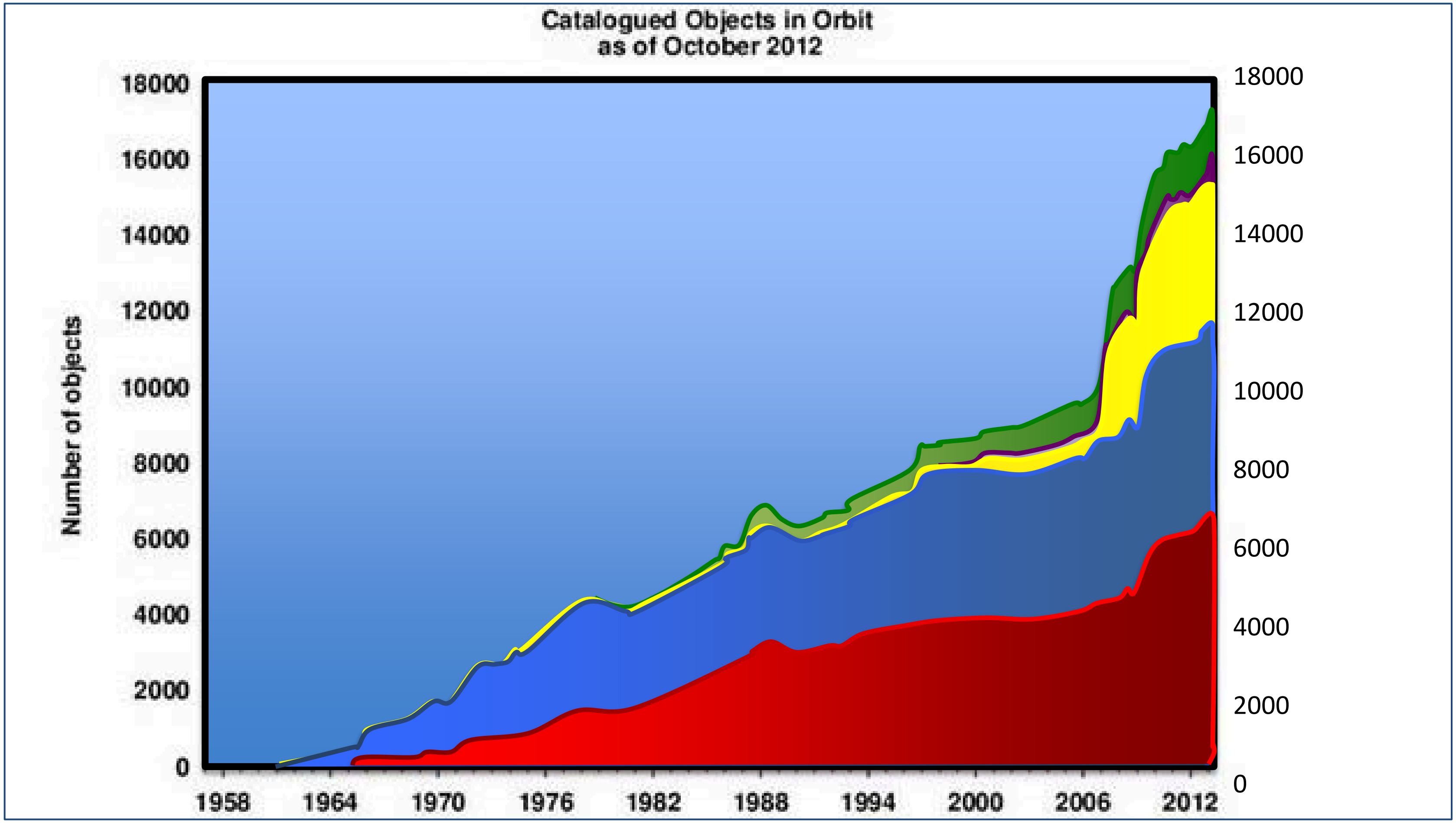
Other sources of debris fragments

The 66 Iridium communications satellites orbiting 500 miles (800 kilometers) above Earth's surface have created a stir on many fronts. Iridium LLC, the original owner of the satellites, spent $5 billion to build and deploy the machines, then sold them for $25 million in 1999 when the company went bankrupt. Then, in 2009, Iridium 33 collided with a decommissioned Russian satellite over Siberia

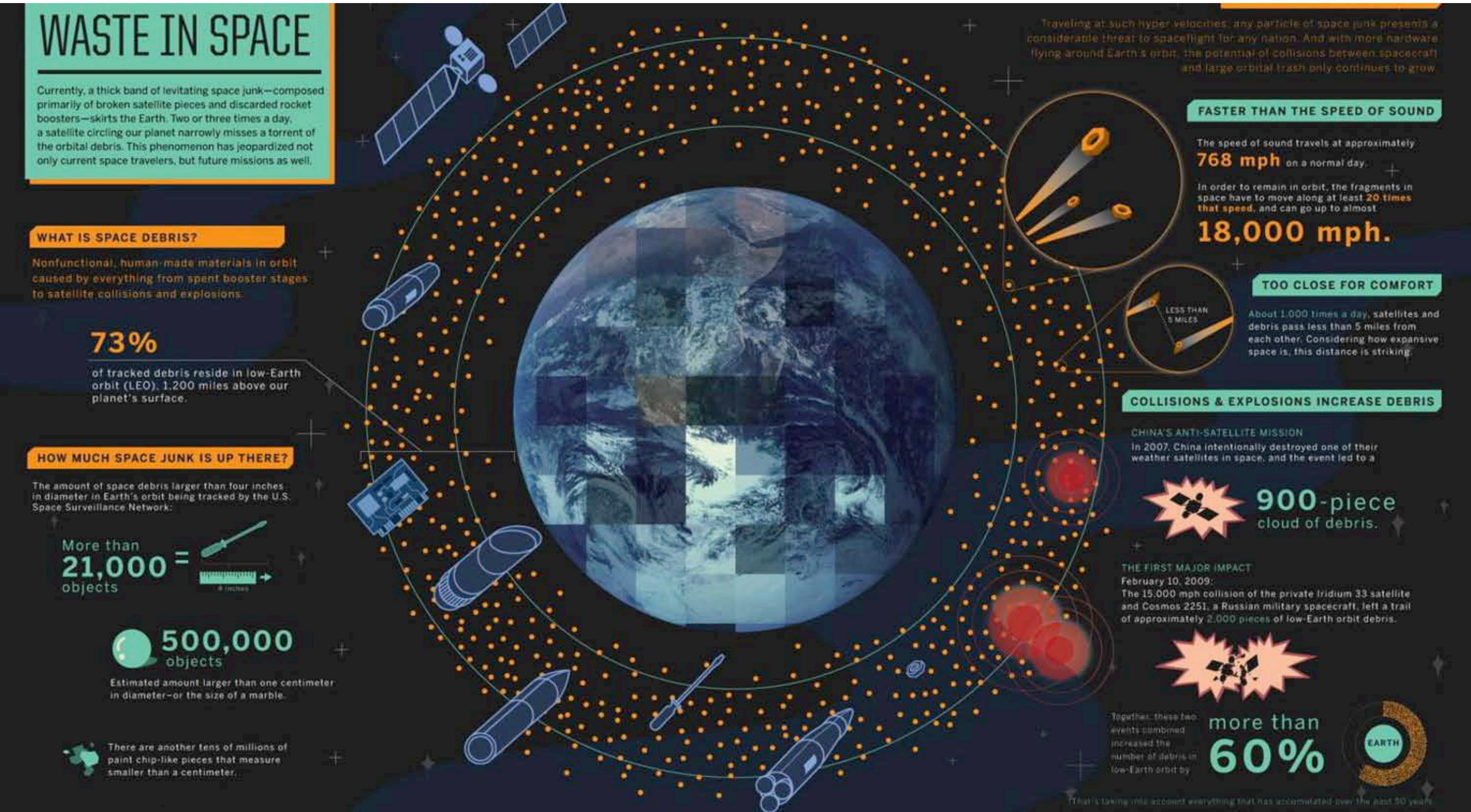
Only 6% of the catalogued orbit popula operational spacecraft, while about 30 can be attributed to decommissioned satellites, spent upper stages and missi related objects (launch adapters, lens c etc.).

The first-ever accidental in-o between two satellites occur 10 February 2009, at 776 km Siberia. An American private communication satellite, Irid Russian military satellite, Kos collided at a relative speed o Both were destroyed, and m trackable fragments were ge

Distribution of catalogued ob global view



Catalogued Objects in Orbit
as of October 2012
Number of objects
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1958
1964
1970
1976
1982
1988
1994
2000
2006
2012
18000
16000
14000
12000
10000
8000
6000
4000
2000
0


WASTE IN SPACE
Currently, a thick band of levitating space junk—composed primarily of broken satellite pieces and discarded rocket boosters—skirts the Earth. Two or three times a day, a satellite circling our planet narrowly misses a torrent of the orbital debris. This phenomenon has jeopardized not only current space travelers, but future missions as well.
WHAT IS SPACE DEBRIS?
Nonfunctional, human-made materials in orbit caused by everything from spent booster stages to satellite collisions and explosions.
73%
of tracked debris reside in low-Earth orbit (LEO), 1,200 miles above our planet's surface.
HOW MUCH SPACE JUNK IS UP THERE?
The amount of space debris larger than four inches in diameter in Earth's orbit being tracked by the U.S. Space Surveillance Network:
More than 21,000 objects =
500,000 objects
Estimated amount larger than one centimeter in diameter—or the size of a marble.
There are another tens of millions of paint chip-like pieces that measure smaller than a centimeter.
Traveling at such hyper velocities, any particle of space junk presents a considerable threat to spaceflight for any nation. And with more hardware flying around Earth's orbit, the potential of collisions between spacecraft and large orbital trash only continues to grow.
FASTER THAN THE SPEED OF SOUND
The speed of sound travels at approximately 768 mph on a normal day.
In order to remain in orbit, the fragments in space have to move along at least 20 times that speed, and can go up to almost
18,000 mph.
TOO CLOSE FOR COMFORT
LESS THAN 5 MILES
About 1,000 times a day, satellites and debris pass less than 5 miles from each other. Considering how expansive space is, this distance is striking.
COLLISIONS & EXPLOSIONS INCREASE DEBRIS
CHINA'S ANTI-SATELLITE MISSION
In 2007, China intentionally destroyed one of their weather satellites in space, and the event led to a
900-piece cloud of debris.
THE FIRST MAJOR IMPACT
February 10, 2009:
The 15,000 mph collision of the private Iridium 33 satellite and Cosmos 2251, a Russian military spacecraft, left a trail of approximately 2,000 pieces of low-Earth orbit debris.
more than 60%
EARTH

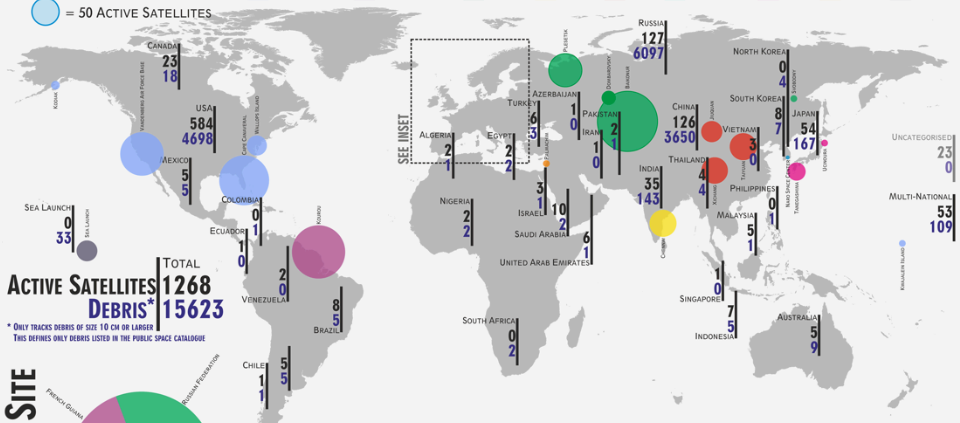
SPACE: 2014

UNIVERSITY OF SOUTHAMPTON
ASTRONAUTICS RESEARCH GROUP

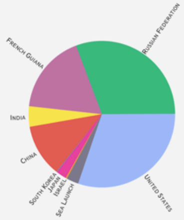
Overview

From Public Space Objects Catalogue — Data Correct as of Jan. 2014

Number of Active Satellites (by launching site): 329 United States 190 French Guiana 332 Russia 49 India 126 China 1 South Korea 25 Japan 3 Israel 29 Sea Launch



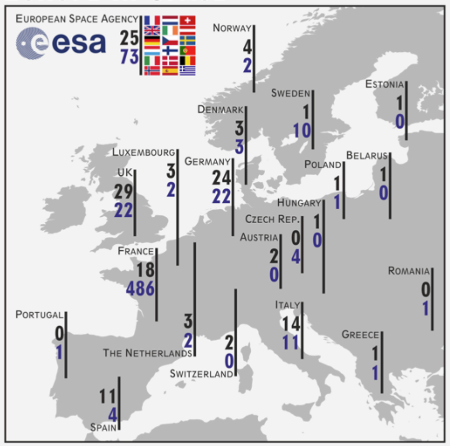
Launching Site



Space Debris is the population of defunct objects in Earth's orbit, including failed or non-operational satellites, rocket stages and fragments from explosions & on-orbit collisions

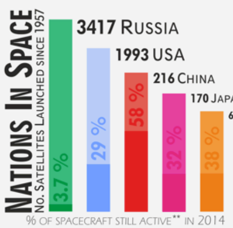
Since orbits may overlap with those of spacecraft, debris can collide with satellites and/or manned vehicles; posing a threat to safety of operational spacecraft

Europe In Space



Spaceflight Since Sputnik

From Public Space Catalogue



** Satellites which are not classified as "active" may include those which have decayed in altitude to burn up in the atmosphere, and those which have come to the end of their operational lifetime

According to the public satellite catalogue, **7579** satellites have been launched since 1957

The oldest object still in Earth orbit is **Vanguard 1 (1958)**

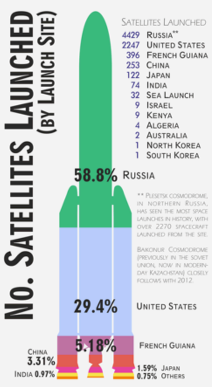
It is expected to remain in orbit for another **200 years**

Total Spacecraft Operated (by Country)

Algeria	2	32	Italy
Argentina	13	170	Japan
Austria	2	6	Luxembourg
Australia	14	6	Malaysia
Azerbaijan	1	10	Mexico
Belarus	1	7	Netherlands
Bermuda	0	5	Nigeria
Bolivia	1	1	North Korea
Brazil	13	7	Norway
Canada	39	4	Pakistan
Chile	2	2	Poland
China	216	1	Portugal
Colombia	1	1	Romania
Czech Republic	6	3417	Russia
Denmark	6	2	Singapore
Ecuador	2	3	South Africa
Egypt	4	17	South Korea
European Space Agency	66	17	Spain
Estonia	1	2	Switzerland
France	66	8	Thailand
Germany	62	9	Turkey
Greece	2	7	United Arab Emirates
Hungary	1	56	United Kingdom
India	66	2118	United States
Indonesia	13	2	Venezuela
Iran	4	5	Vietnam
Israel	15	175	Multinational

No. Satellites Launched (by Launch Site)

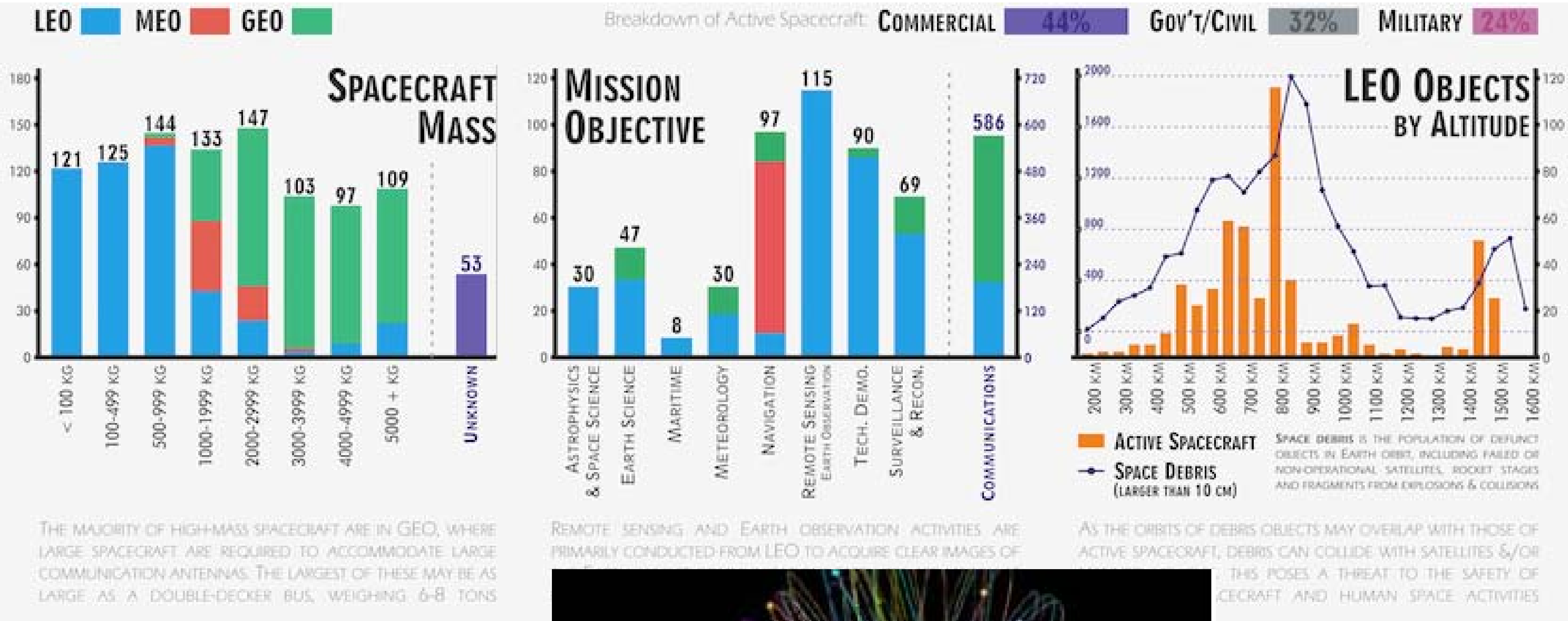
Satellites Launched
4429 Russia**
2247 United States
396 French Guiana
253 China
122 Japan
74 India
32 Sea Launch
9 Israel
9 Kenya
4 Algeria
2 Australia
1 North Korea
1 South Korea



** Plesetsk Cosmodrome, in northern Russia, has seen the most space launches in history, with over 2270 spacecraft launched from the site.

Baikonur Cosmodrome (previously in the Soviet Union, now in modern-day Kazakhstan) closely follows with 2012.

University of Southampton // Astronautics Research Group — More Information: www.southampton.ac.uk/aerospace — Designed by Simon George // Assisted by Benjamin Schwarz



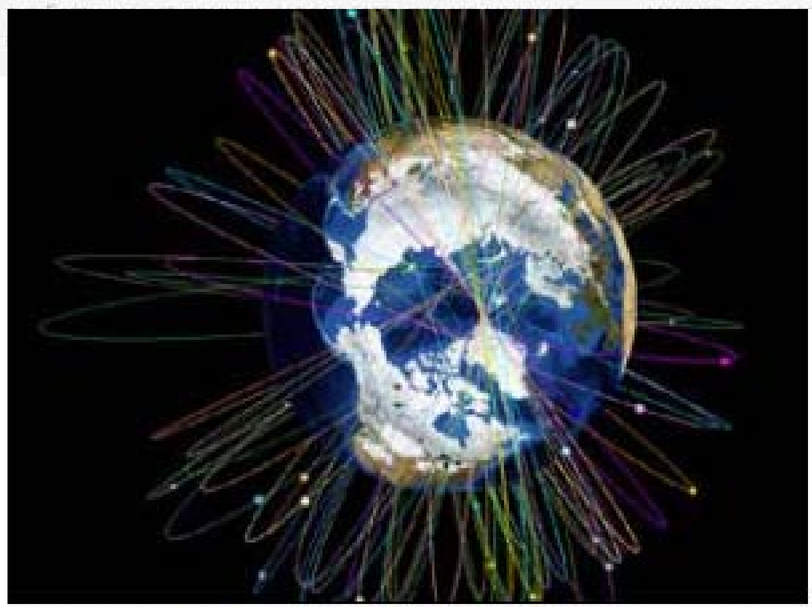


Figure 3. Today only 46 clumps of Project West Ford needles are known to be in orbit. Their orbits are illustrated with this simulated