GPS Transponder for Space Traffic Management

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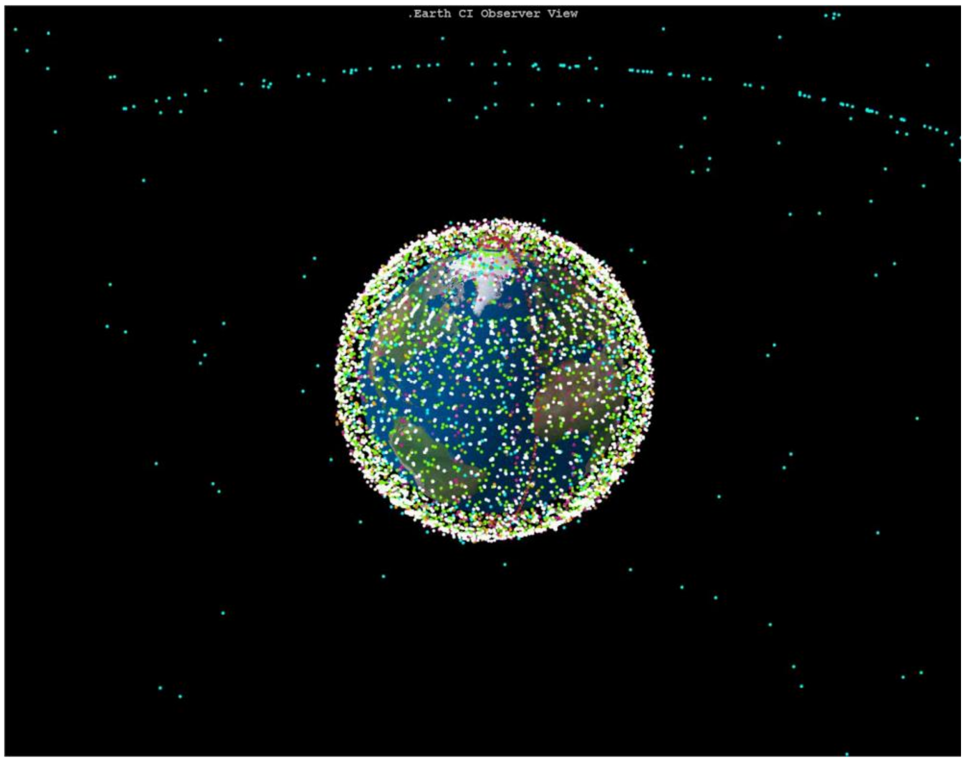
Large Constellations are Proposed

As many as 20,000 new satellites in the next decade

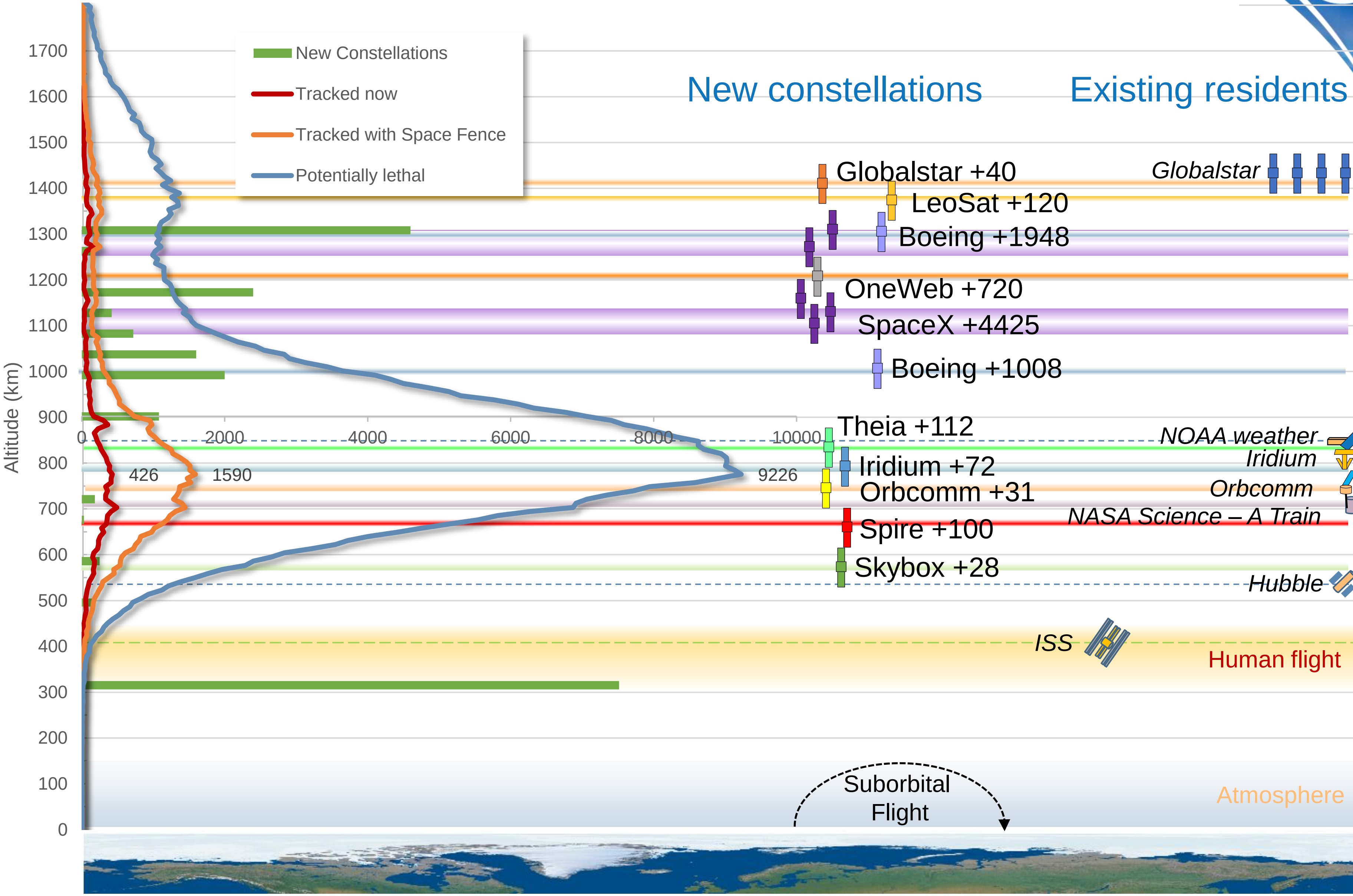


Some possible new constellations

Operator	Num sats	Alt (km)	Incl (deg)
SpaceX V-band	7518	335-345	42-53
Black Sky	60	450	55
Kepler	140	550	97.6
Skybox	28	576	97.8
Yalini	135	600	97.6
Planet	150	675	97.4
Spire	100	651	97.9
Orbcomm	31	750	45
Iridium	72	780	86.4
Theia (3000 kg)	112	800	98.6
Telesat (Canada)	72	1000	99.5
Boeing (1500 kg)	1008	1025	88
SpaceX (400 kg)	4425	1110-1325	53-81
OneWeb (150 kg)	720	1200	88
Telesat (Canada)	45	1248	37.4
Boeing (1500 kg)	1948	1275	45-55
Samsung	4600	1400	99
LeoSat (700 kg)	120	1400	89
Globalstar	40	1410	52

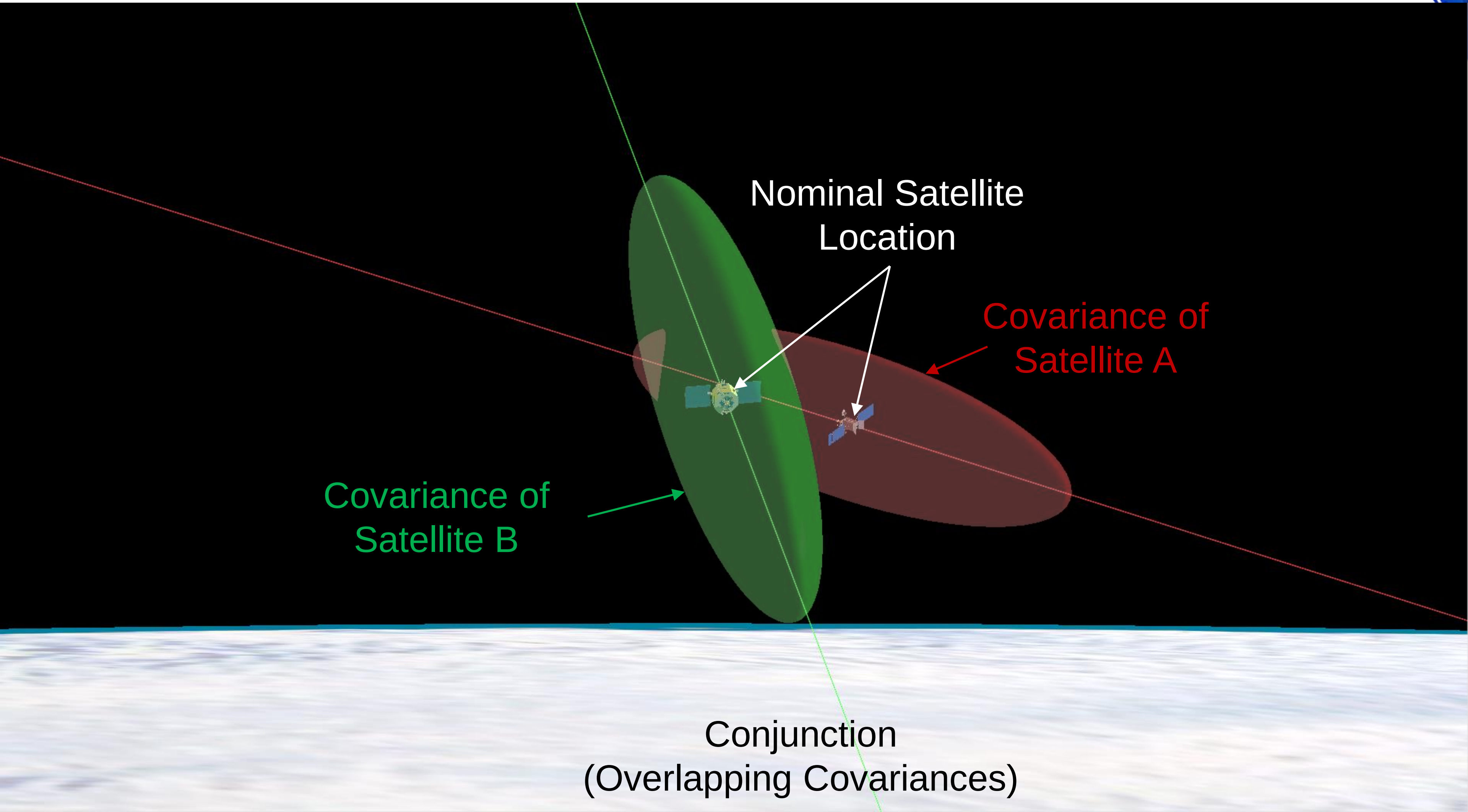
We will see a fundamental change in the LEO environment – Business as Usual will not work anymore

A Combined Threat to Current Missions



Covariance, Conjunction, and Collision Probability

The Positional Uncertainty of a Space Object

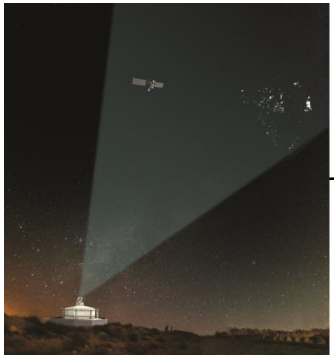


Note: Covariance represents the probability distribution of the object's position (& sometimes velocity).

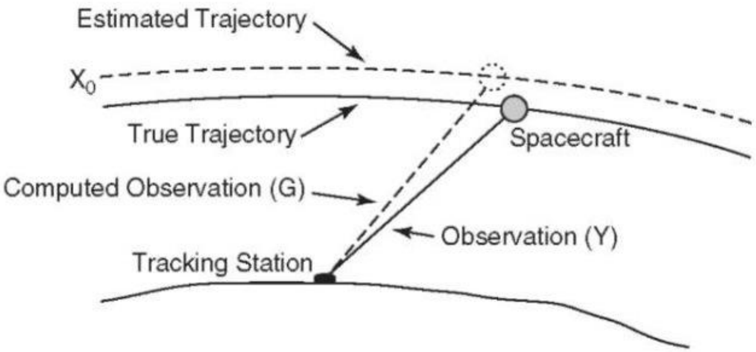
Note: Integrating the overlapping areas of the two covariance's together allows for the calculation of the probability of collision, P_c.

Overview of Current Space Situational Awareness

Non-Cooperative Tracking Network's Current Collision Avoidance Process



Object Observations

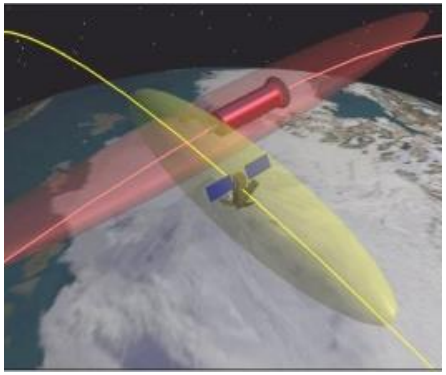


Orbit Determination

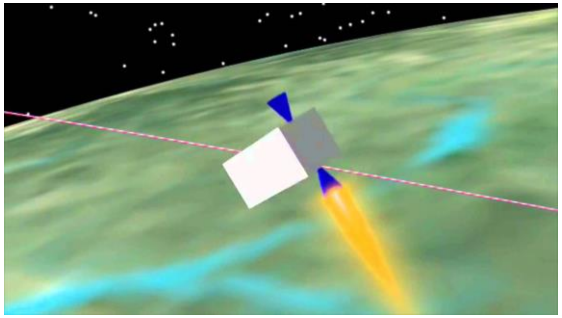
International Designator	SCC Number	Common Name
1957-001A	1	SL-1 R/B
1957-001B	2	SPUTNIK 1
1957-002A	3	SPUTNIK 2
1958-001A	4	EXPLORER 1
1958-002B	5	VANGUARD 1
1958-003A	6	EXPLORER 3

Satellite Catalog Construction

Conjunction Screening



Conjunction WARNING!

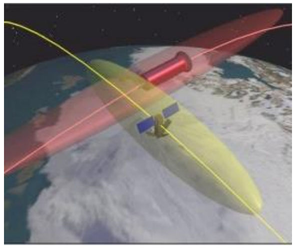


Spacecraft COLA Maneuver

The Problem

Space is Becoming Congested and Contested

- Space is becoming more congested
  - *Launch prices are decreasing; reusability is a game changing technology*
  - *Large constellations of several thousand satellites are planned by multiple companies*
  - *CubeSats are increasingly popular; more are launched each year*
  - *Space Fence is about to be activated (ballooning the catalog by detecting smaller objects)*
- Operators will see a multiple-order-of-magnitude increase in the frequency of conjunction warning messages*
  - *Today they occur once every month; with future traffic they will occur once per day*
  - *It is costly to respond to conjunction warnings*
    - Responding to one conjunction can consume hundreds of man-hours
    - Maneuvering to avoid a collision uses fuel and significantly shortens mission life
    - Maneuvering takes the spacecraft out-of-mission for several hours (mission specific)
- Number of collisions per year also increases
  - *Goes from 1-2 collisions per decade to 1-2 collisions per year*

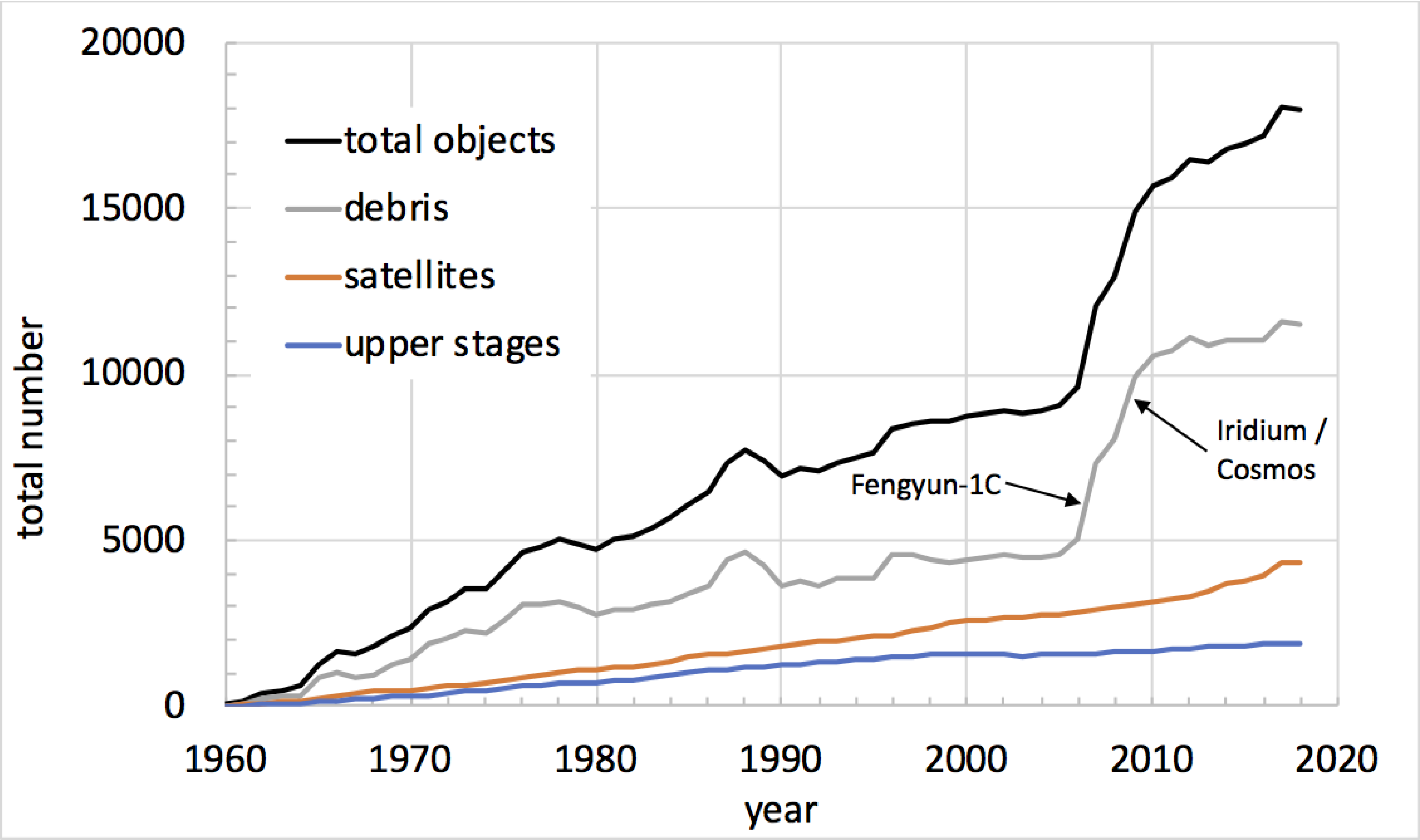


- What can be done?
  - *Either limit the number of space objects launched per year or*
  - *Find a way to safely operate more satellites in the same, highly congested environment*

* Reference: Peterson, Sorge, and Ailor, “Space Traffic Management in the Age of New Space,” CSPS Policy Paper, The Aerospace Corp, April 2018.

The Problem

SATCAT Growth Over Time

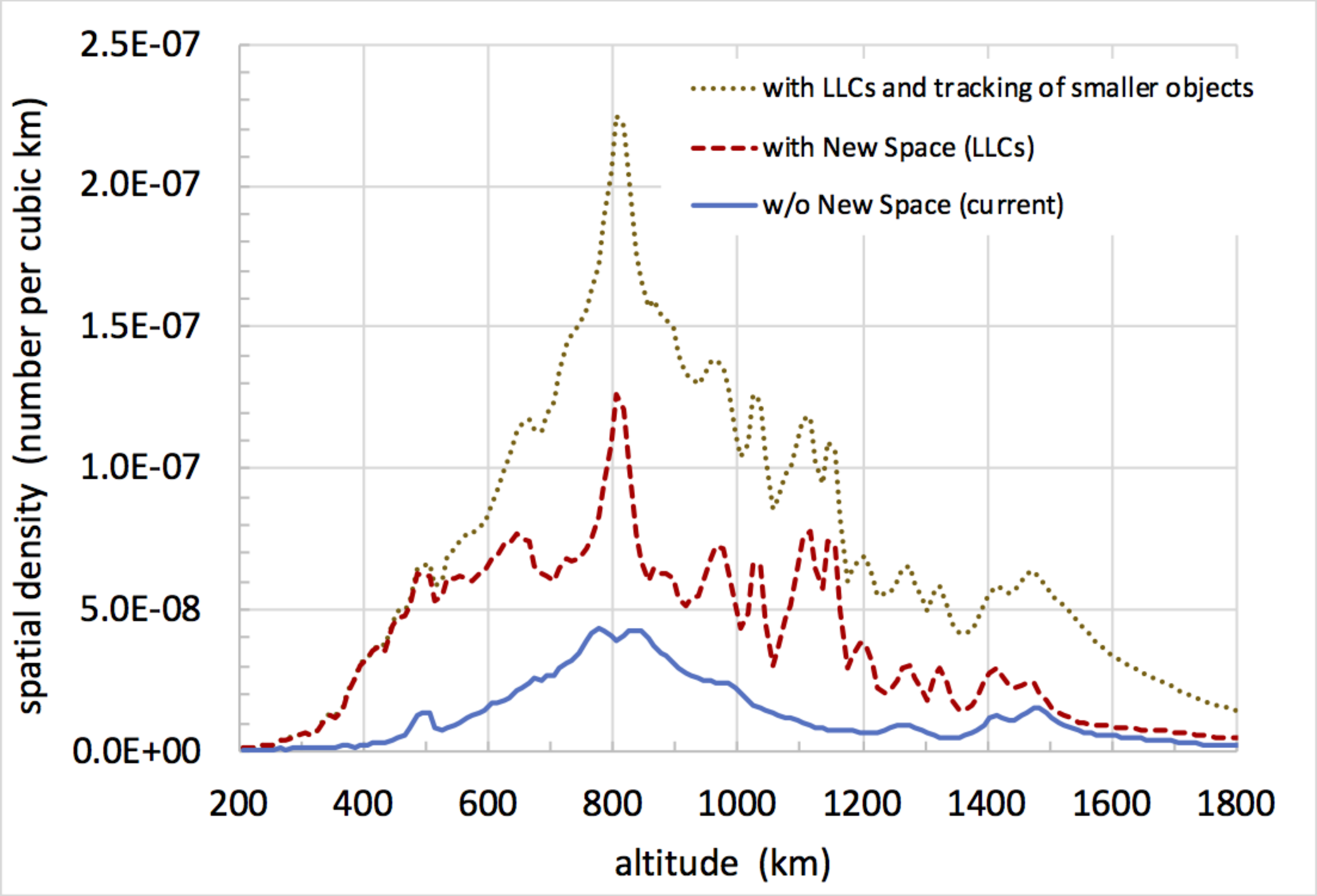


Number of objects in SSN catalog. The number of these objects has increased significantly during the past decade.

Reference: Peterson, Sorge, and Ailor, "Space Traffic Management in the Age of New Space," CSPS Policy Paper, The Aerospace Corp, April 2018.

The Problem

Space Congestion is Increasing and is Better Known

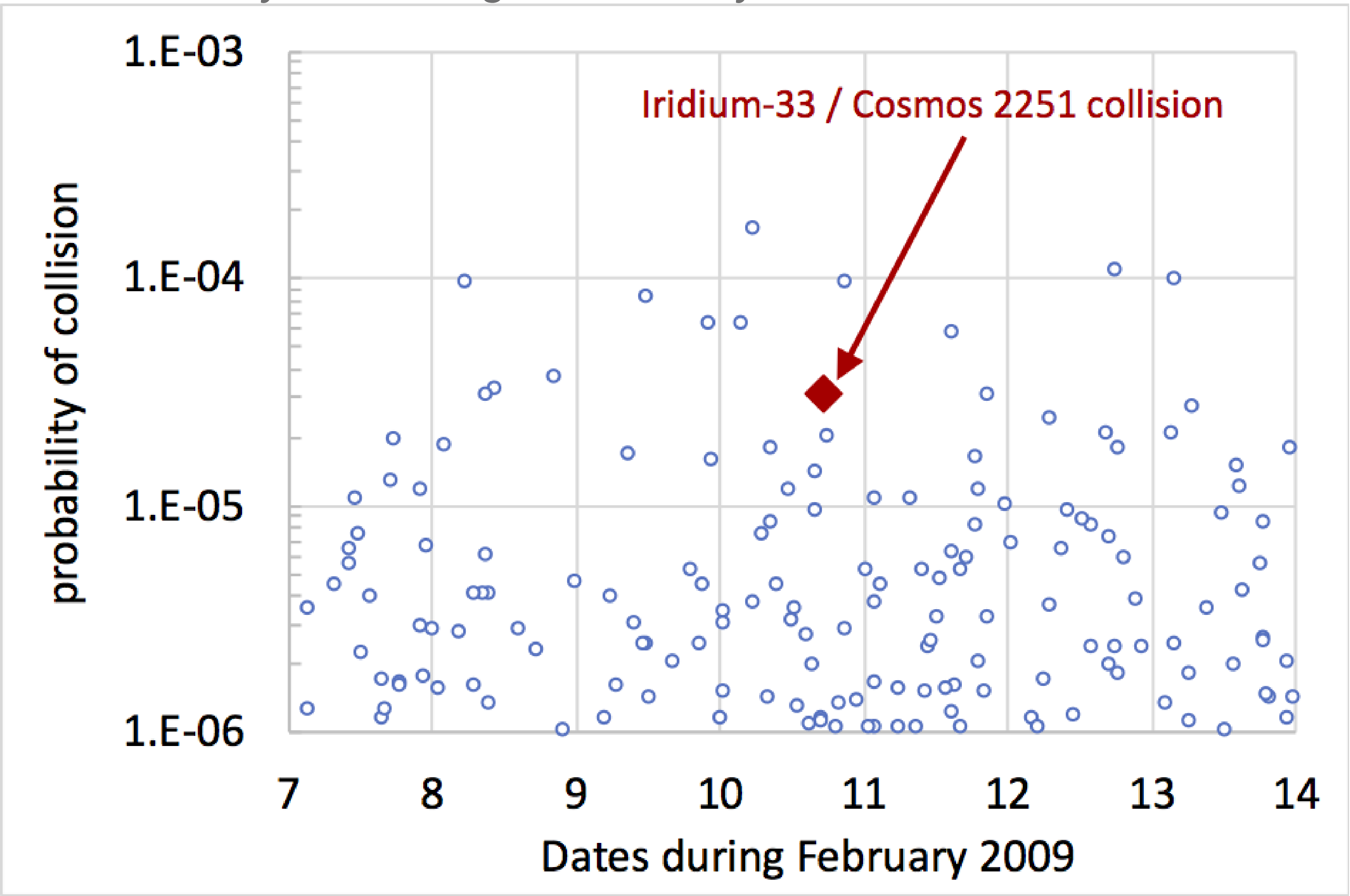


Spatial density of objects in LEO with and without New Space activity. Adding New Space Large LEO Constellations (LLCs) will increase the density at all altitudes due to replenishment, disposal, and failed satellites. Adding the smaller objects that would appear with an improved tracking system could increase the density at all altitudes even more.

 Reference: Peterson, Sorge, and Ailor, "Space Traffic Management in the Age of New Space," CSPS Policy Paper, The Aerospace Corp, April 2018.

The Problem

Collision Probability Screenings Often "Cry Wolf!"

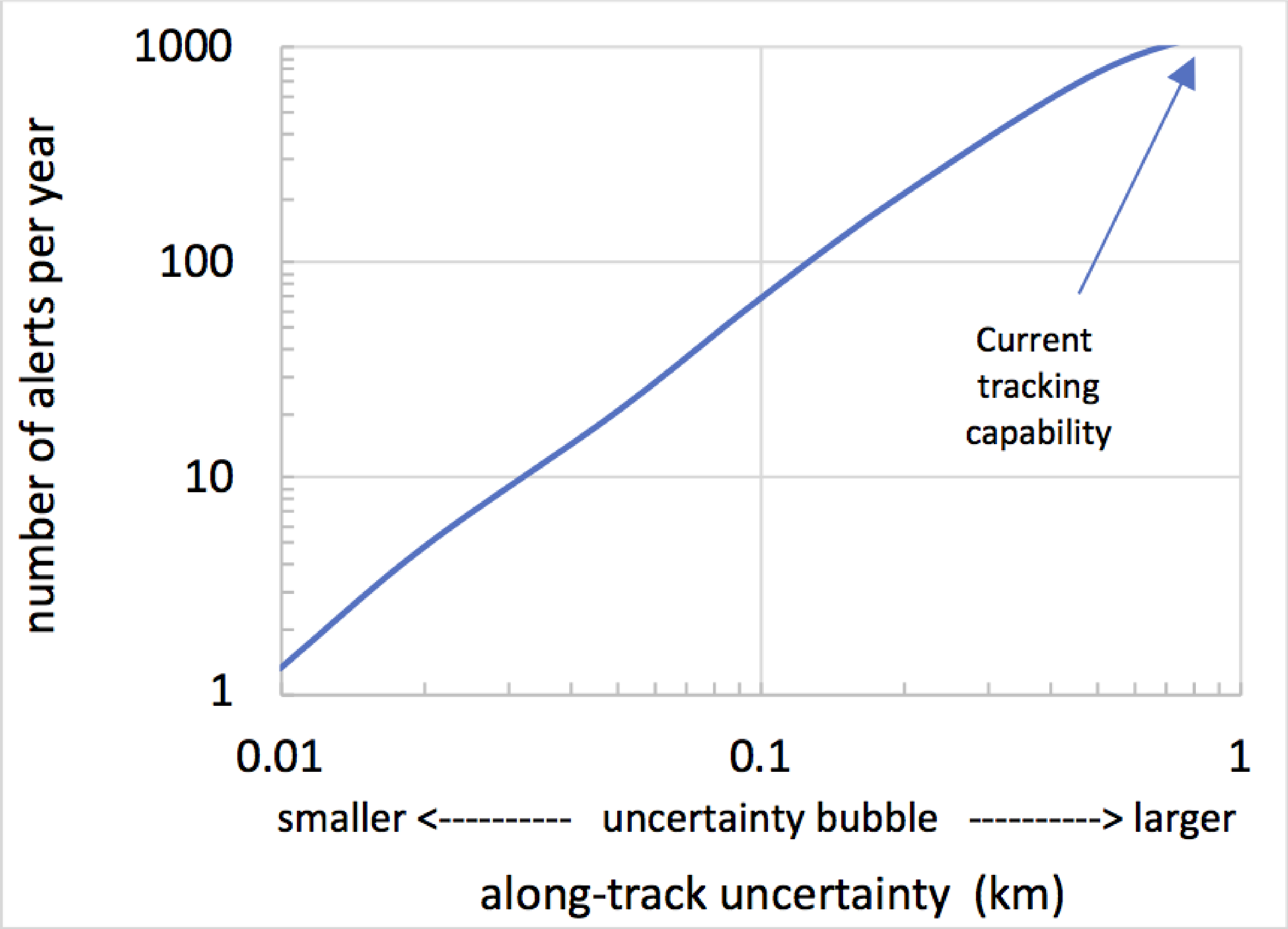


Iridium constellation conjunction probabilities during week of Feb 7, 2009. Under current tracking accuracies, the actual collision between Iridium-33 and Cosmos 2251 did not stand out from other conjunctions that week as being noticeably dangerous.

Reference: Peterson, Sorge, and Ailor, "Space Traffic Management in the Age of New Space," CSPS Policy Paper, The Aerospace Corp, April 2018.

The Problem

The Solution is to Reduce Your Covariance!

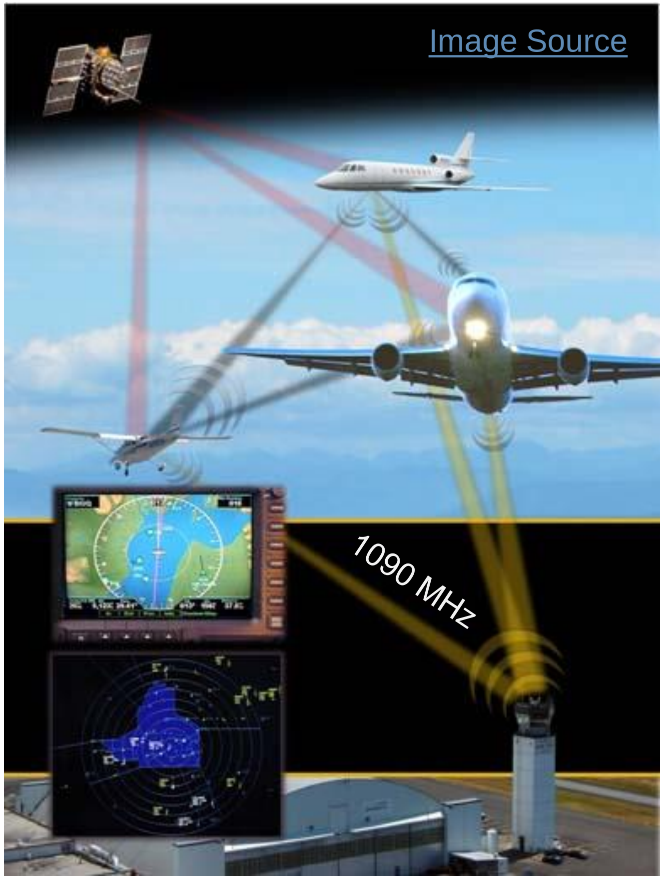


Annual number of expected alerts for Iridium constellation using a threshold probability of 1 in 100,000 (using a present-day catalog)

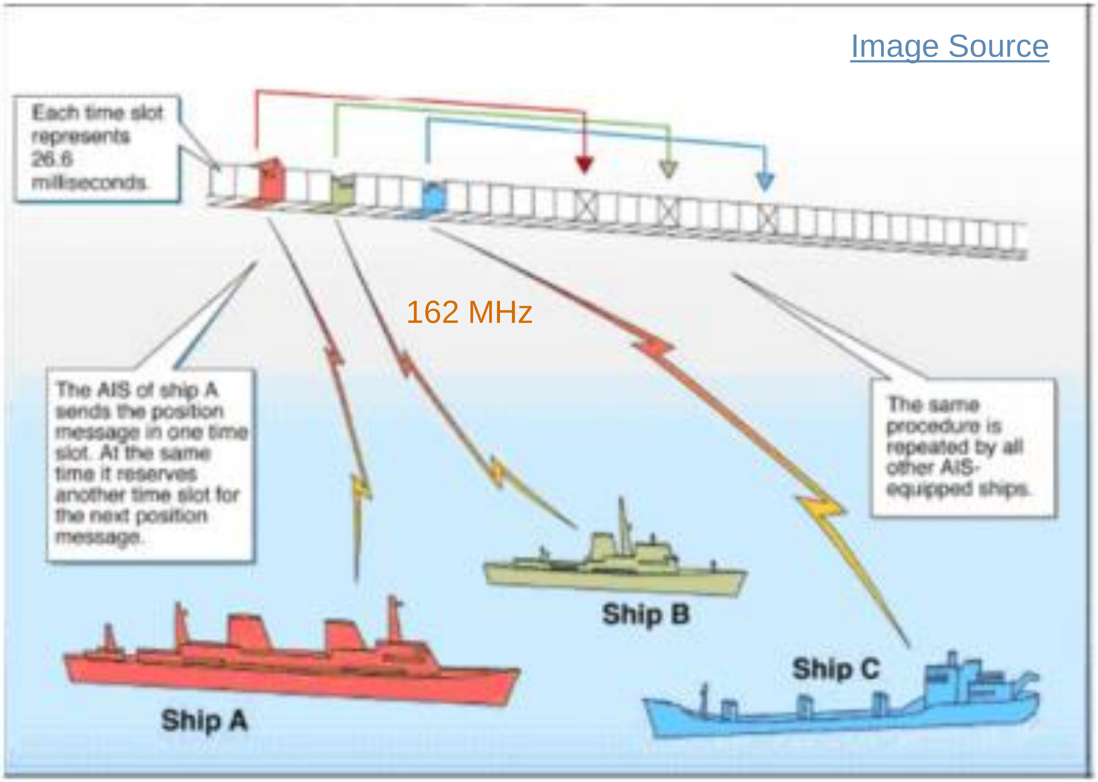
Reference: Peterson, Sorge, and Ailor, "Space Traffic Management in the Age of New Space," CSPS Policy Paper, The Aerospace Corp, April 2018.

Inspiration from Other Domains

ADS-B (Air Traffic) and AIS (Marine Traffic)



Automatic Dependent Surveillance-Broadcast (ADS-B)



Automatic Identification System (AIS)

The Solution

Value and Objectives of a STM Transponder

An ideal Space Traffic Management transponder will address three primary issues:

1) ***Exquisite Covariance**: minimize the uncertainty in the position of a space object in order to enhance flight safety for all space operators (i.e. avoiding collisions).*

2) ***Satellite ID**: how can one quickly, easily, and without ambiguity distinguish one space object from another? (Trust & confidence building measure.)*

3) ***Tracking while Thrusting**: Non-cooperative tracking networks operate via a track-and-predict methodology. This breaks down for thrusting objects (especially low-thrust).*

The goal is to design an inexpensive, small, and self-sufficient hosted payload package that will report data at regular intervals to enhance space situational awareness and better enable space traffic management activities. ***This should be accomplished even if the host spacecraft is dead, inactive, or otherwise uncontrolled****. It will be used on all intentionally deployed space objects that are able to accommodate a transponder.*

Many Potential Solutions (All Very Experimental)

Significant Trades Between Valuable Data and Size, Weight & Power

Name	Inventor	Mass	Size (cm)	Sponsor	Sat ID	Improved Covariance	Custody During Thrust	*a priori* Orbit Required	Description
GPS Transponder	The Aerospace Corporation	100 - 150 g	9x6x1.5		Yes	Yes	Yes	No	Using GPS recivers, a radio, solar cells, and a battery
CUBEIT	SRI	100 g		DARPA	Yes	Not Currently	Not Currently	Yes	RFID using Allen Telescope Array
ELROI	Los Alamos National Lab		2x2x0.5		Yes	Not Currently	Not Currently	Yes	LED transmits data to ground telescope (at night) No RFI risk
Spacecraft ID Device	Steller Exploration			DARPA	Yes	Not Currently	Not Currently		
M2M Self Reporting*	Owner/ Operator				Yes	Unknown	Likely		

- All methods have pros and cons (usually $SWaP vs. capability/reliability)
- No clear “winner” or dominant approach
- All methods have significant value and should be further developed

Disclaimer: Data in this table may be incomplete or outdated; references at end of document

Orbit Determination Comparison of Data Products

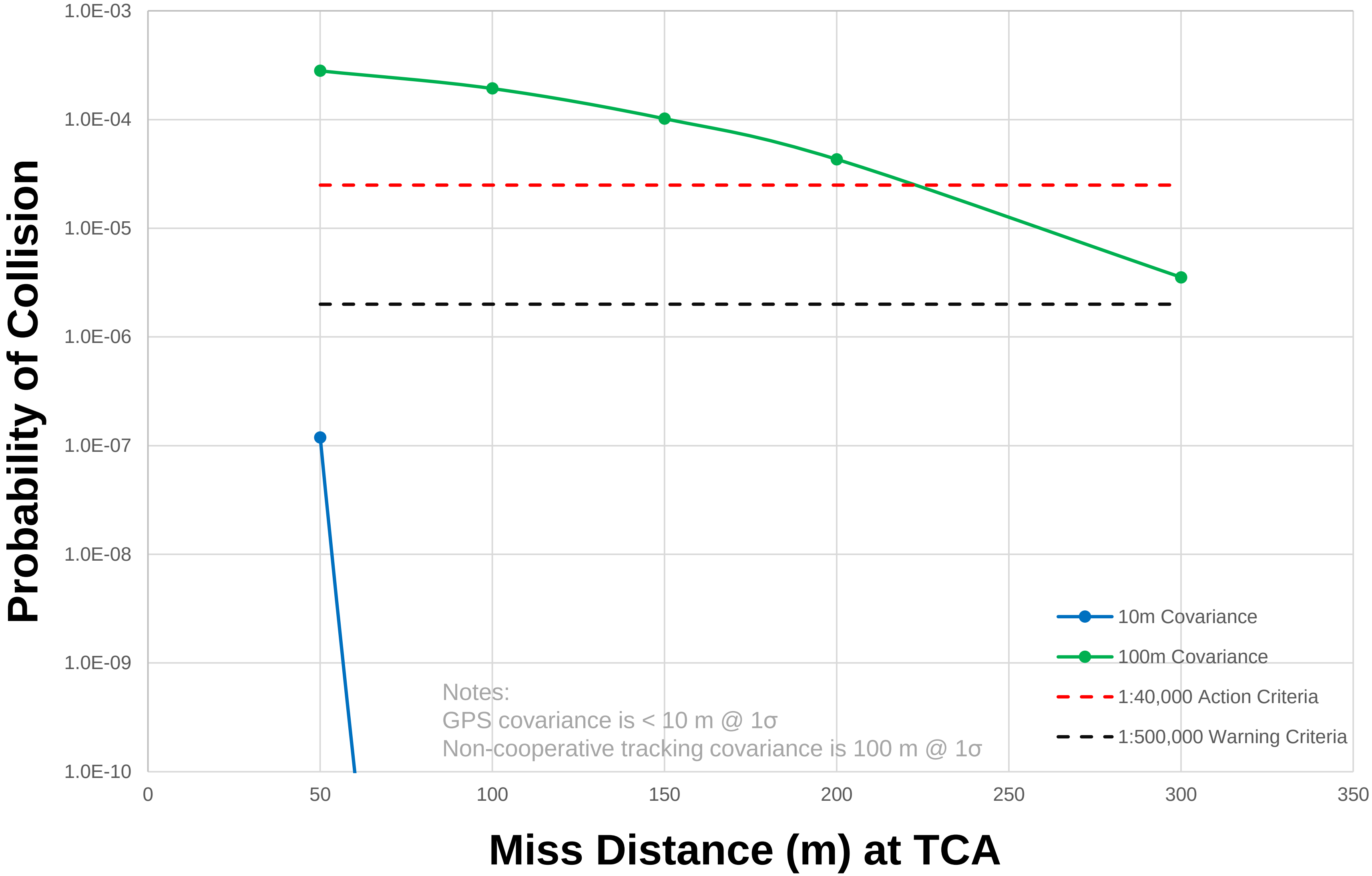
Accuracy of Competing Data Products

Data Source	Covariance Accuracy
Space-Track.org	Kilometers?
Non-Cooperative Tracking Network	Hundred(s) of meters
M2M Self-Reporting*	10 m using GPS
GPS Transponder	10 m

*Machine-to-Machine Self Reporting: System must be independently verified and validated and have a mature "debris mode" fail-safe to qualify; a.k.a. "virtual transponder"

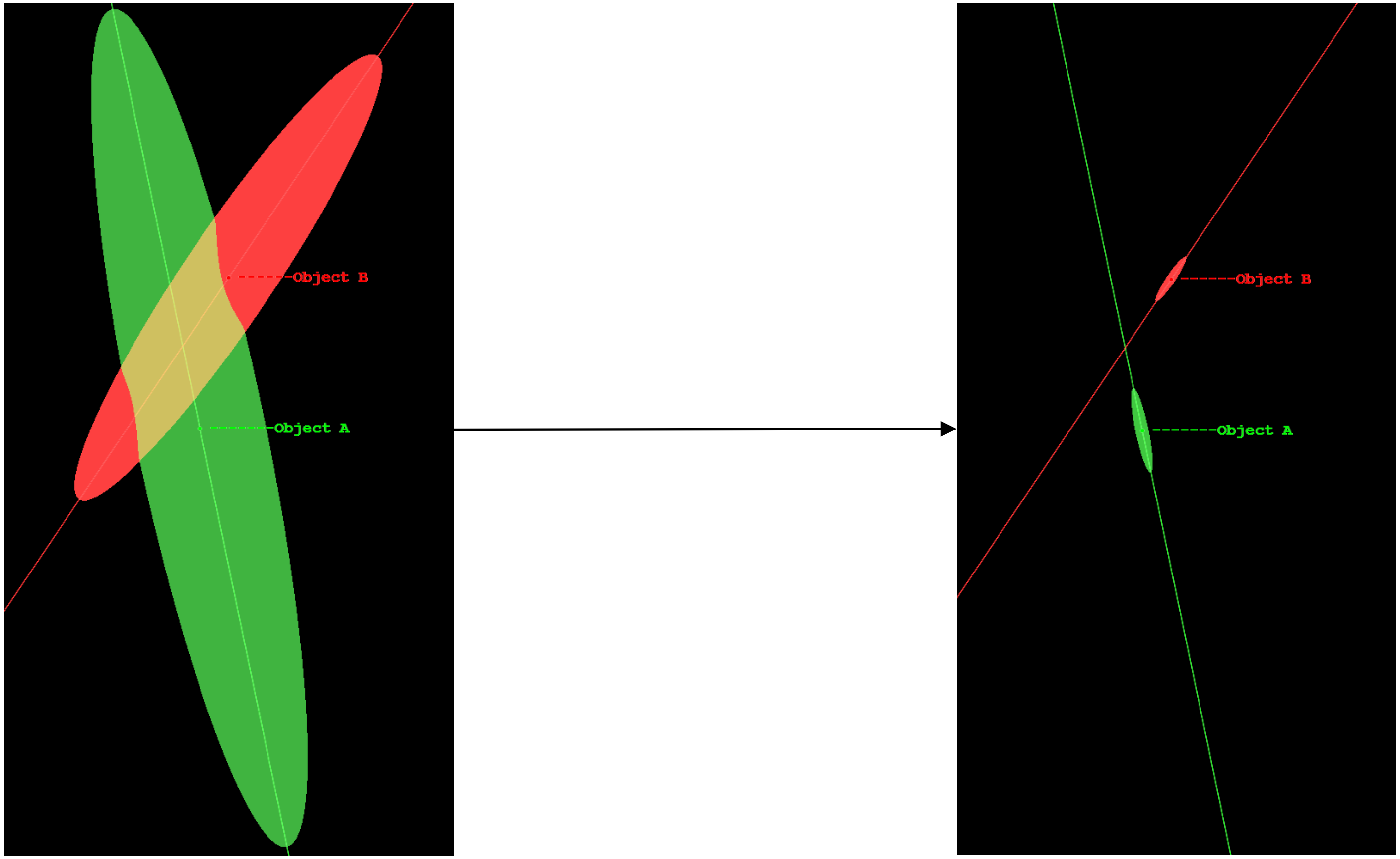
How Covariance Influences Collision Probability

Covariance Size and Miss Distance vs. Collison Probability



Visualization of Covariance Reduction

The two scenarios are identical except for the covariance size



Non-Cooperative Tracking Network Covariance
(Shown at Time of Closest Approach)

GPS Transponder Covariance
(Shown at Time of Closest Approach)

Example of Satellite Identification Value

ISRO Deployment of 104 CubeSats on 15 February 2017

Initial Deployment…

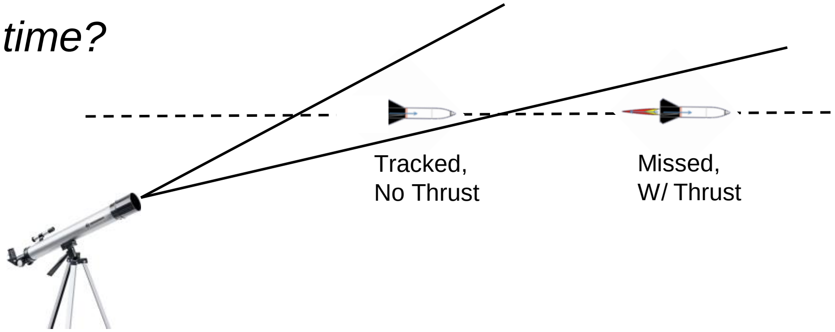
…150 Seconds Later

Reference: Steven Clark, "Don't Miss This Spectacular Video of 104 Satellites Deployed in Space," Spaceflightnow, 16 February 2017.

Overcoming Track-and-Predict Limitations

Thrusting Issues

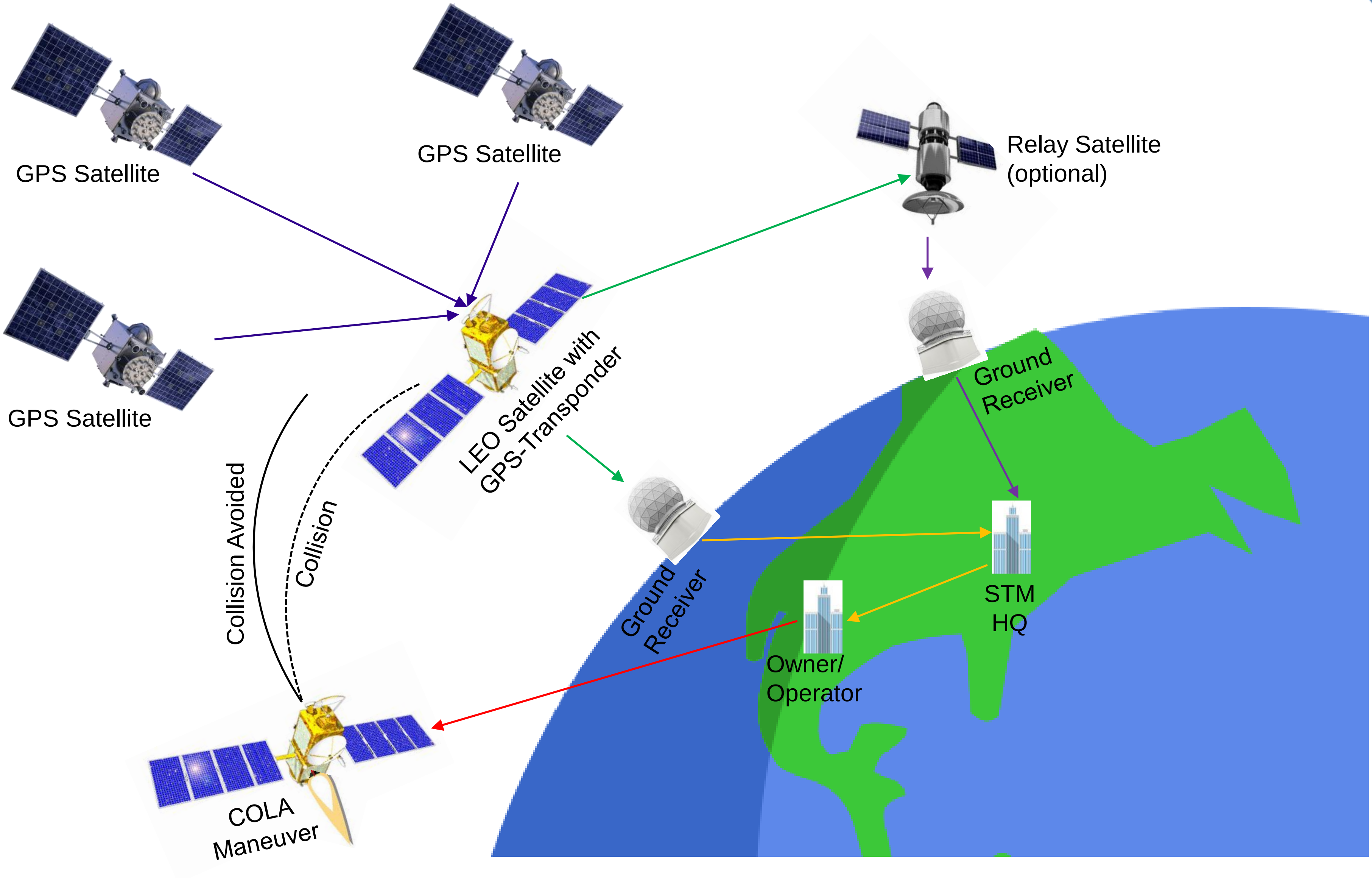
- A non-cooperative tracking network has a limited ability to track thrusting objects
  - *The network consists of "surveillance" (fence) assets as well as "tracking" assets*
  - *Track-and-predict system: not enough assets to maintain continuous custody of an object*
  - *Thrusting objects often lie outside of tracking box; they must be re-acquired and re-ID*
- There are many unknowns when attempting to model thrusting objects
  - *What is the intended & actual thrust-profile over time?*
  - *What direction is the thrust being applied in?*
    - Spacecraft attitude?
    - Configuration of solar panels?
    - Sets of thrusters & their on-times?



- Low-thrust objects are particularly difficult
  - *They are usually thrusting and not behaving according to modeled orbit perturbations*
  - *Thrust controls are often difficult to predict*
  - *This can be solved by transmitting frequent updates on position and optionally velocity, pointing, acceleration, etc.*

Background

OV-1: GPS-Transponder



Further Reading: A. Abraham, "GPS Transponders for Space Traffic Management," CSPS Policy Paper, The Aerospace Corp, April 2018.

GPS Transponder Use Cases

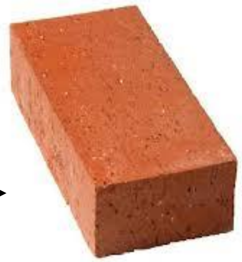
Three Modes of Operation

1. **Normal Mode**: This mode is active while the host spacecraft is controlled and providing power to the GPS Transponder. The transponder will transmit updates around <u>once per minute</u>

2. **Thrust Mode**: This mode is activated by the host sending a trigger signal to the GPS Transponder (host will also provide power). The transponder will transmit updates around <u>once per second</u>. Acceleration and attitude data will be the most useful in this mode.

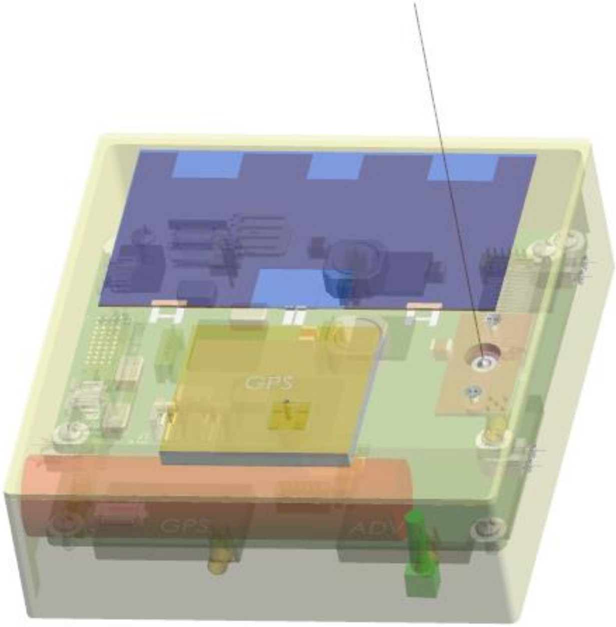
3. **Debris Mode**: This mode is active while the host spacecraft is not providing power and is not controlling its attitude. Assume the host is a brick.

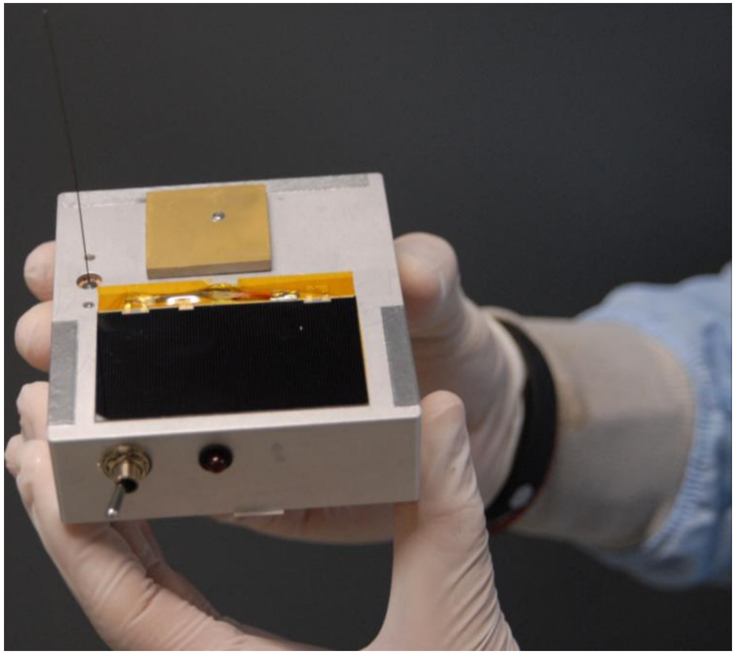
If a launch vehicle deploys a brick this system should operate without incident for years if not decades →



First Prototype

CAD Drawing and Photograph





- First Aerospace Corporation prototype
- 9.4 x 8.6 x 3.2 cm and 285 grams
- Final Prototype will be much smaller (deck of playing cards, 100 grams)

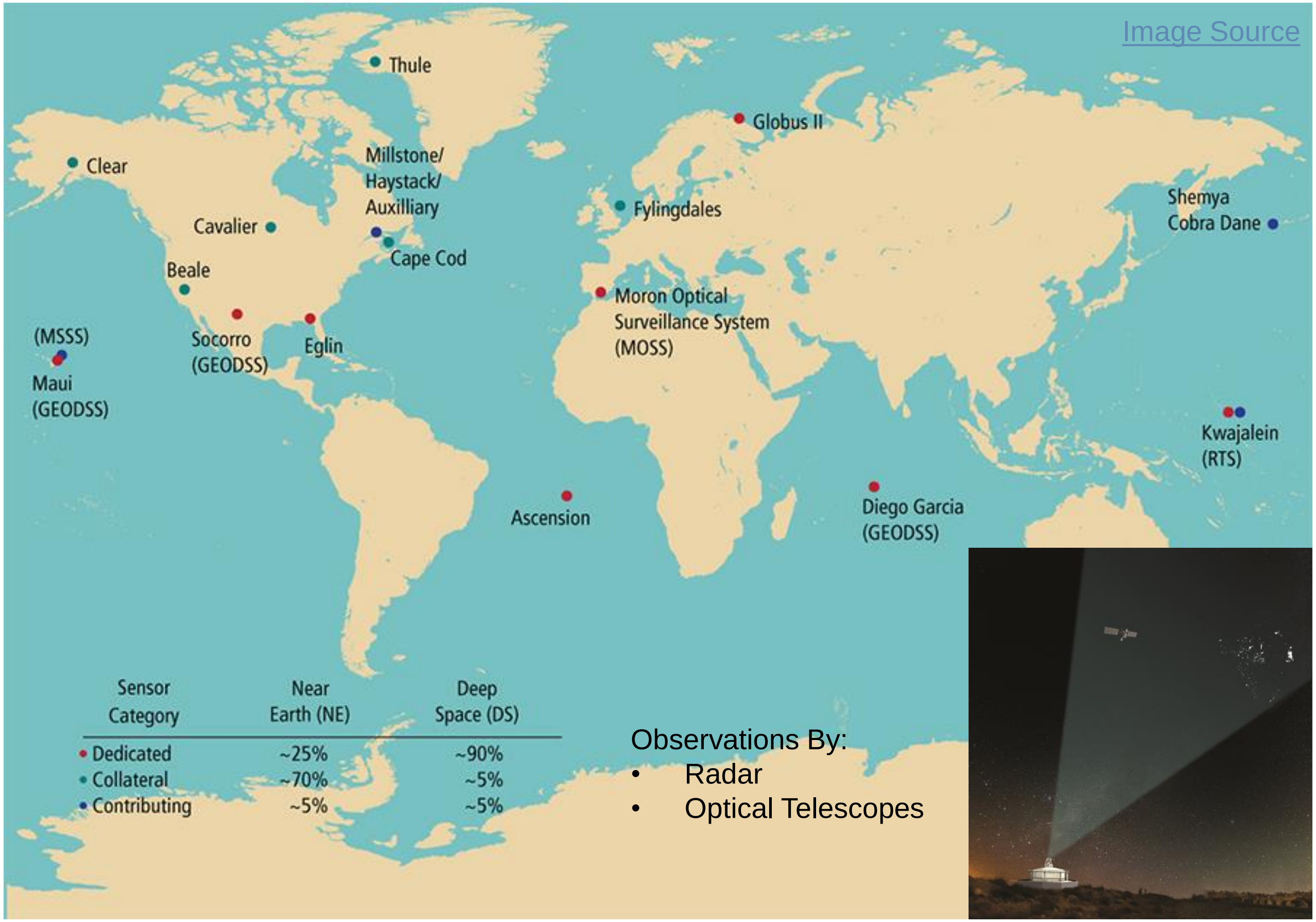
GPS Transponder Video

Questions?

Backup Slides

Background

USSTRATCOM's Space Surveillance Network



Observations By:

- Radar
- Optical Telescopes

Could Add-On Devices Help?

Optional Transponder Sensors

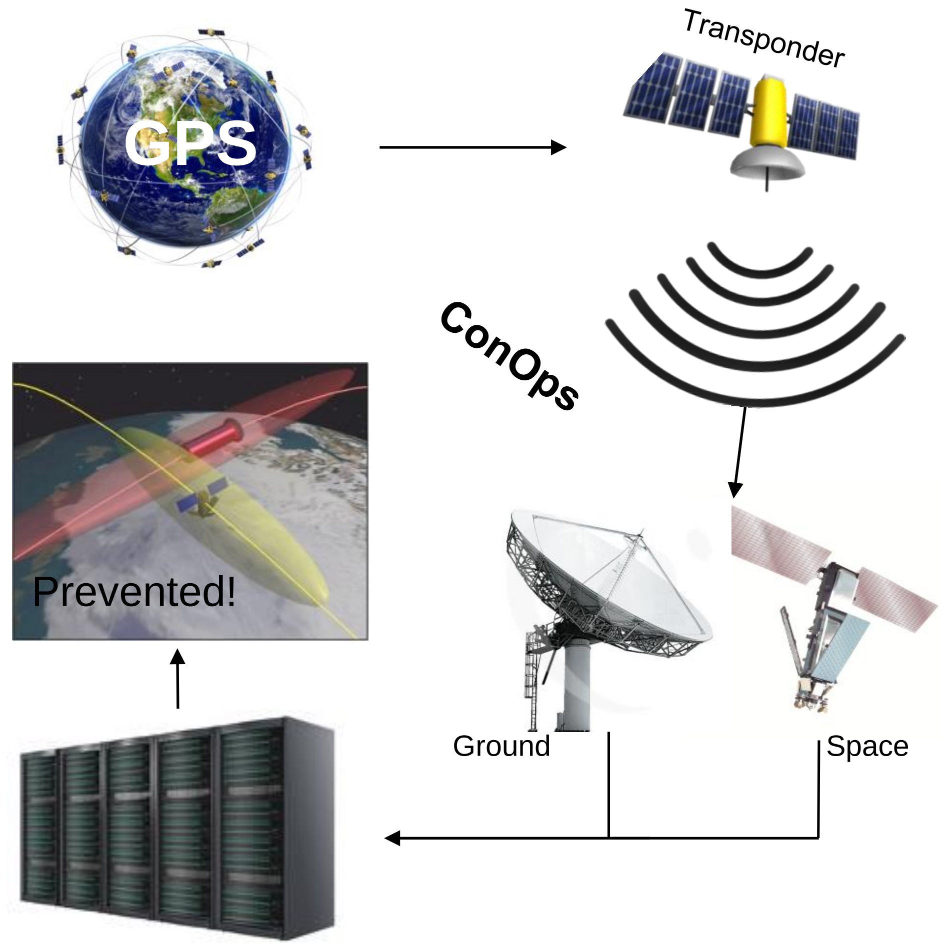
Other sensors can be added if power, volume, mass, and cost permits…

- ***MEMS Gyroscope**: will give a rough idea of tumble rate which is useful for drag calculations as well as Rendezvous and Proximity Operations (RPO)*
- ***Accelerometer**: will record high-thrust, may record low-thrust if sensitive enough*
- ***Magnetometer**: will give a rough indication of spacecraft pointing relative to Earth's magnetic field*
- ***Photodiode:** will provide a rough sun-sensor; may be useful for attitude/tumble info*
- ***Dosimeter:** will provide a measurement of ionizing radiation over time*
- ***Temperature**: will give an indication of transponder health as well as condition of host*
- ***Others?***

Concept of Operations

Broad Overview

The GPS Transponder receives a GPS signal and periodically transmits its location to either the ground or a satellite communications network. The data is then processed on the ground and used to enhance Space Situational Awareness.



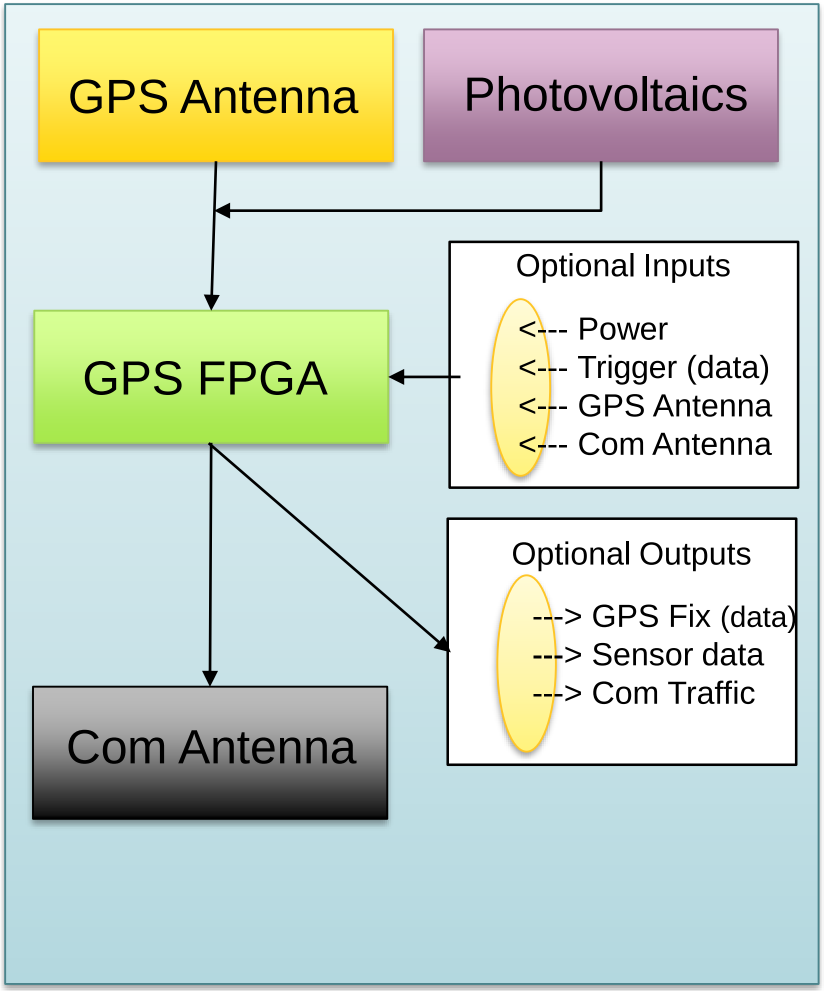
What can be Offered to the Host Satellite?

Box Level Design

The GPS Transponder will be designed primarily for use in LEO because:

- A low power transmitter is suitable for this short distance
- Satellites are within the main lobe of the GPS signal
- LEO is the most congested region of near-Earth space

A later effort can extend the GPS Transponder concept to MEO & GEO

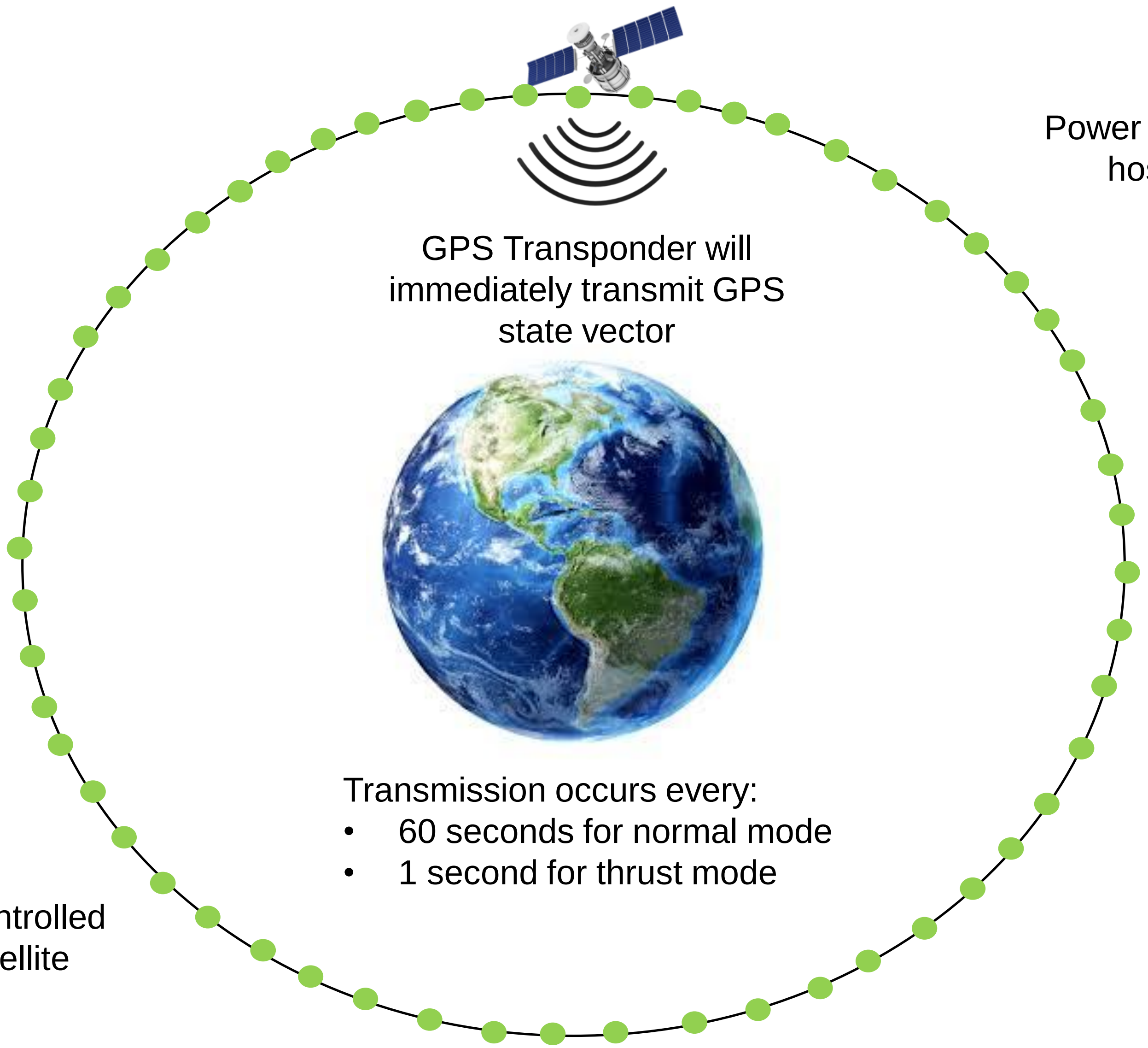


GPS Transponder Block Diagram

Concept of Operations

Normal & Thrust Modes

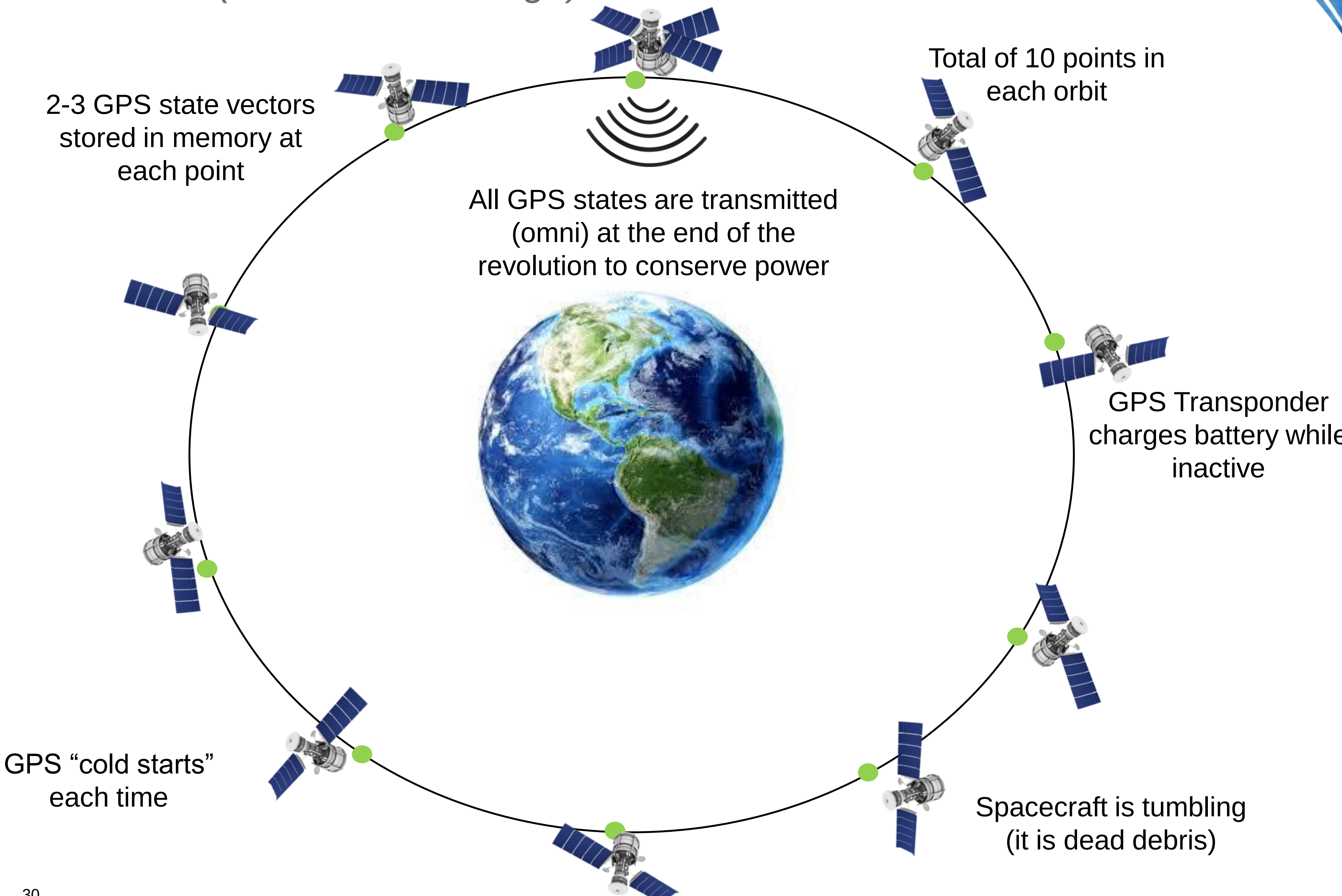
Power is provided by host satellite



Attitude is controlled by host satellite

Concept of Operations

Debris Mode (AeroCube Heritage)



The Mathematics of Collision Probability

- Two objects with known positional uncertainties are passing by each other
- Assuming the uncertainties are a 3-dimensional Gaussian distribution
  - *Probability is a measure of the interaction of the uncertainties and is given by the volume integral*

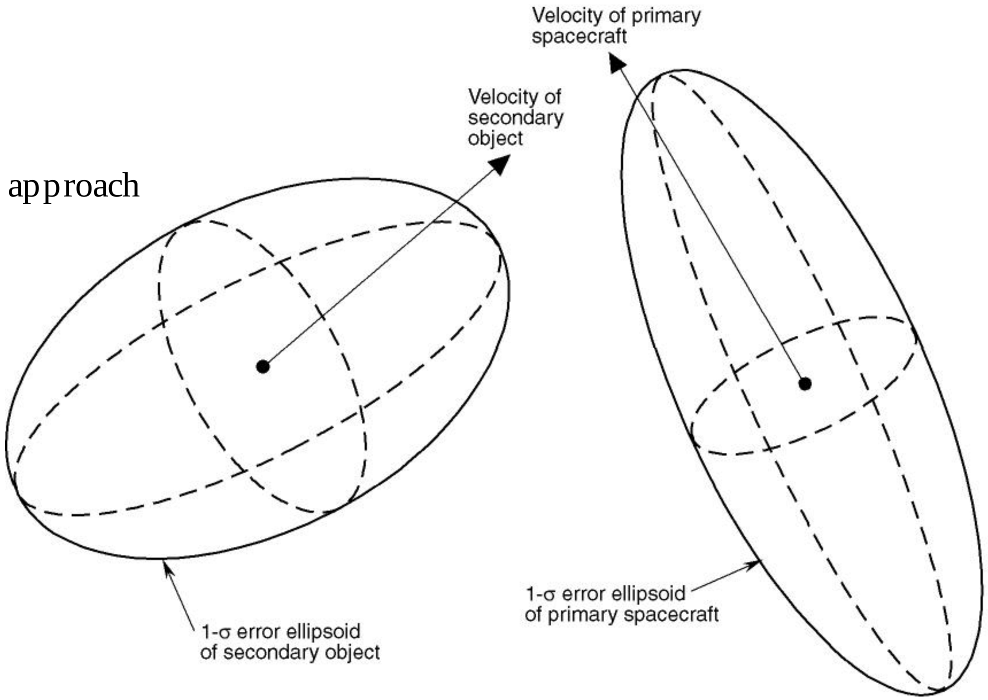
$$P_c = \iiint_V \frac{1}{\sqrt{(2\pi)^3 |C_p|}} \exp\left[-\frac{1}{2}\left(\bar{r}^T C_p^{-1} \bar{r}\right)\right] dxdydz$$

P_c = probability

C_p = covarinace

$\bar{r}$ = relative position vector at closest approach

Pc Driving Factors:
- Object Sizes
- Miss Distance
- Covariance Sizes



Ref: Chan, K., “Improved Analytical Expressions for Computing Spacecraft Collision Probabilities”

GPS Transponder for LEO Space Traffic Management

May need to consider add-ons depending on host

- The host could be any space object that was originally intended to act as a “free flyer”
  - *Payloads (from large satellites down to 1U Cubesats…)*
  - *Rocket Bodies (anything that survives more than 1 full rev)*
  - *Deployables that are larger than 1U*
- The “debris mode” will be a driving factor
  - *May require different power/antenna harness depending on the space object*
  - *Small satellites may do well with a single antenna and solar cell on device’s surface*
  - *Rocket bodies may need a circular band of solar-cells/antenna to:*
    - 1) radiate communications in a truly omnidirectional manner
    - 2) generate enough power for the GPS Transponder – especially when tumbling
  - *A second transponder located on the opposite side of the rocket body is a viable alternative*
- Radiation may be an issue
  - *Low LEO may not need too much radiation shielding; High LEO is more of a problem*
- Reliability is paramount
  - *Transponder must be designed, tested, and certified for resilience and longevity*

GPS Transponder for LEO Space Traffic Management

May need to consider add-ons depending on host

- Extremely Low Resource Optical Identifier (ELROI)
  - *David M. Palmer and Rebecca M. Holmes, "Extremely Low Resource Optical Identifier: A License Plate for Your Satellite," Journal of Spacecraft and Rockets, April 30, 2018, https://doi.org/10.2514/1.A34106.*
- CubeSat Identification Tag (CUBIT)
  - *Roberta Ewart, "Enhanced Space Object Identification: Taking the Guesswork out of LEO CubeSats," SPACE Conference and Exposition, September 2016, Long Beach, CA.*
- GPS-Transponders for Space Traffic Management
  - *Andrew Abraham, "GPS Transponders for Space Traffic Management," Center for Space Policy & Strategy, The Aerospace Corporation, April 2018.*