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Key Technologies Regarding Distributed and/or Collaborating Satellite Systems

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Note Well

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- There is no free lunch.
- It is hard to develop simple, elegant solutions.
- Not much is completely new – it has probably been thought of before.
  - Technology may not have been capable of implementing the original concepts
- It is always easier to do things on the ground than in space
  - Power, processing, radiation, size, mass, vacuum, heat dissipation.
- Do not believe everything you read – particularly if there is a marketing aspect.

Outline

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- Network Centric Design
- Policy
- Satellite Communication Basics
- Orbital Mechanics
- Satellite Architectures
- Fractionated Spacecraft
- Cooperative Spacecraft
- Protocols
  - Transport Protocols
  - Store, Carry and Forward

Network Design Triangle

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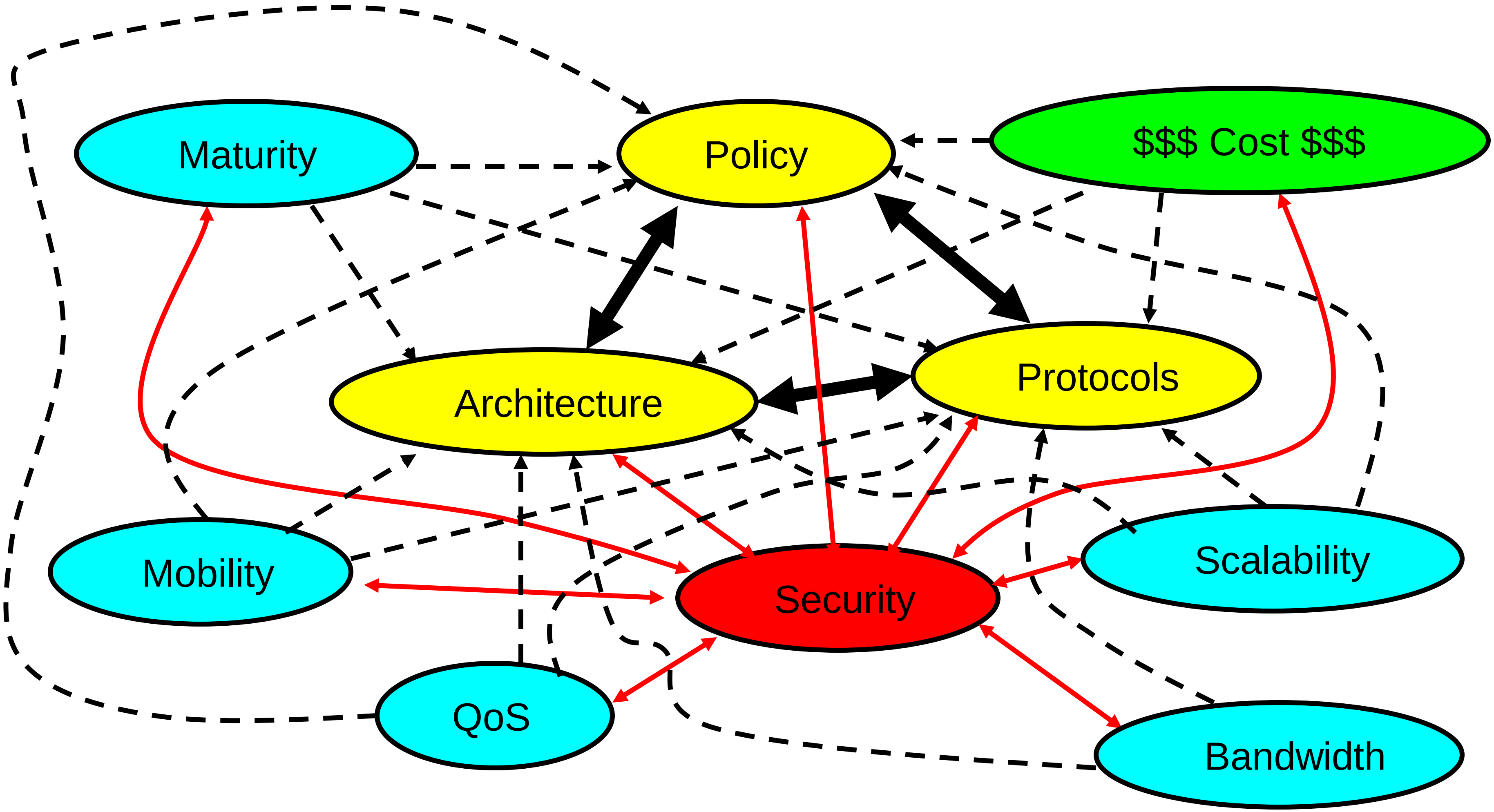

Policy

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- Understand Policy.
- It may be the most important thing you do.
- Policy may be the hardest thing to change.
- Security has numerous Policy Issues

Policy Example

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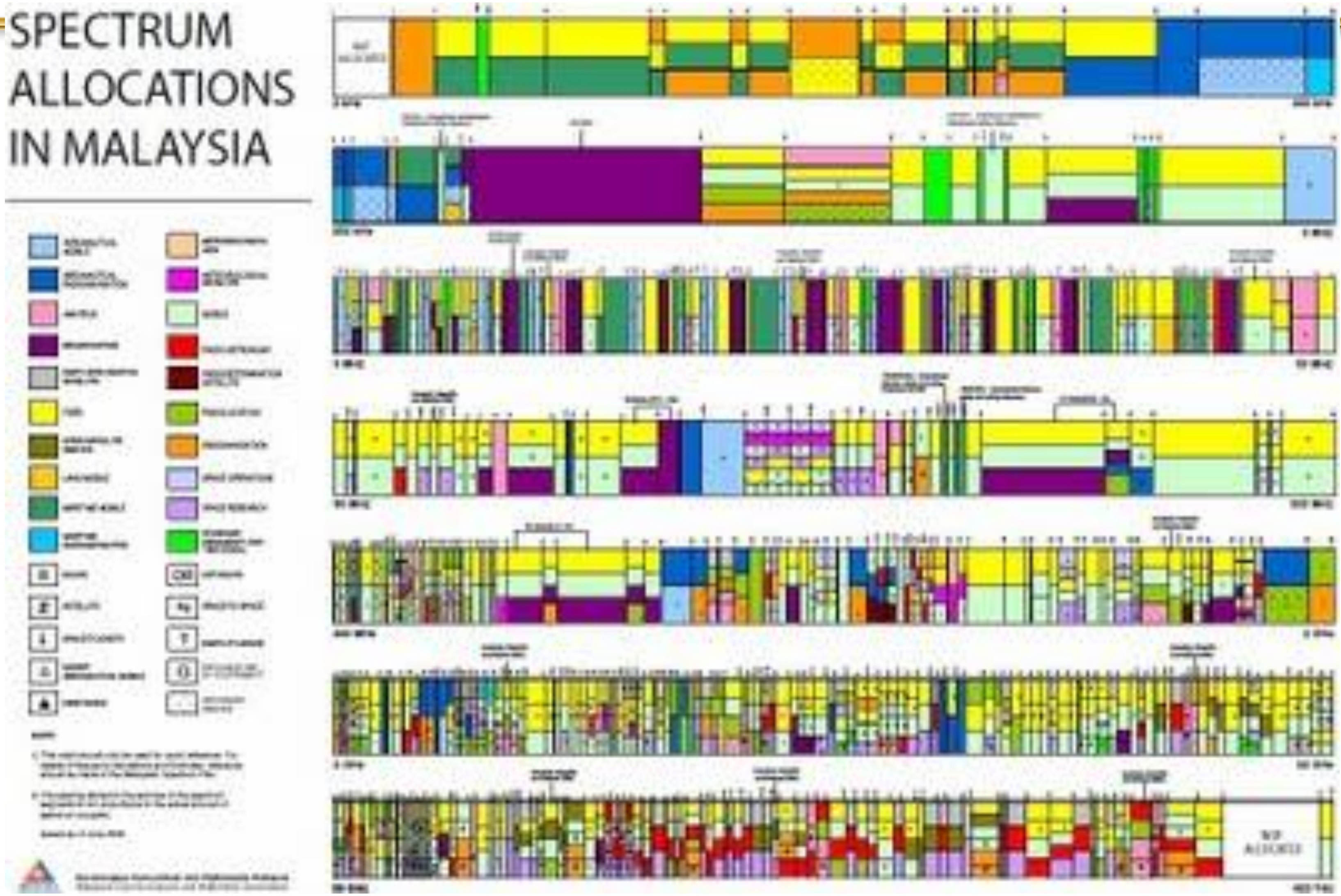

Spectrum

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- All transmitters have to register.
- Receivers do not have to register.
- A satellite provider must register the transmitters and should register as to what ground stations it will be transmitting to.
- A ground station should register which satellites it will be communicating with.
  - If the ground stations are in different countries, the transmitters are registered in that country.
- For CubeSats in the amateur band
  - The cubesat can transmit anywhere so long as it is within an acceptable power level
  - The ground station uplink is performed under and amateur radio license. Each ground station that transmits is responsible for that transmission under its license.
  - See GENSO - Global Educational Network for Satellite Operations

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Satellite Communications

95% of what you need to understand in two slides

Electromagnetic Communications

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$$G = \frac{4\pi A_{eff}}{\lambda^2} \qquad P_r = \frac{A_t A_r}{r^2 \lambda^2} P_t \qquad HPBW = \frac{k\lambda}{D}$$

$$c \approx 299\,792\,458 \text{ m / s}$$

- The larger the apertures (area) the higher the gain
- The gain increases as the square of the frequency, v where v=1/λ
  - This is why Optical is so attractive.
- Larger antenna Diameter (D) and higher frequency results in smaller angular beam widths (equation is for parabolic Antenna, but the generic concept applies)
  - This is why pointing becomes an issue with Optical (lasers)
- Power falls off as the square of the distance from the source and the square of the frequency
- One way trip time to GEO (35,786 km) is approximately 120 msec with a Round Trip Time of approximately 500 msec
- One way trip time to LEO (400 km) is 1.3 msec with a RTT of approximately 5.3 msec

Electromagnetic Communications

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$$C = B\log_2\left(1+\frac{S}{N}\right) \qquad \frac{E_b}{N_0} \propto \left(\frac{B}{f_b}\cdot\frac{S}{N}\right) \propto P_r$$

$$P_r(dbm) = P_t(dbm) + Gains(dbm) - Losses(dbm)$$

- Shannon–Hartley theorem: *C* is the maximum rate at which information can be transmitted over a communications channel of a specified bandwidth, B, in the presence of noise, N.
  - If I have more Bandwidth, B, I can transmit more information.
- The higher the energy per bit relative to noise, Eb/No, the lower the bit-error-rate BER.
  - Reducing the transmission data rate, f_b, improves (reduces) the BER
- Gains include antenna and amplifier gains

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Orbital Mechanics

The key to understanding space communication architectures

Projectile Motion – Throwing a ball

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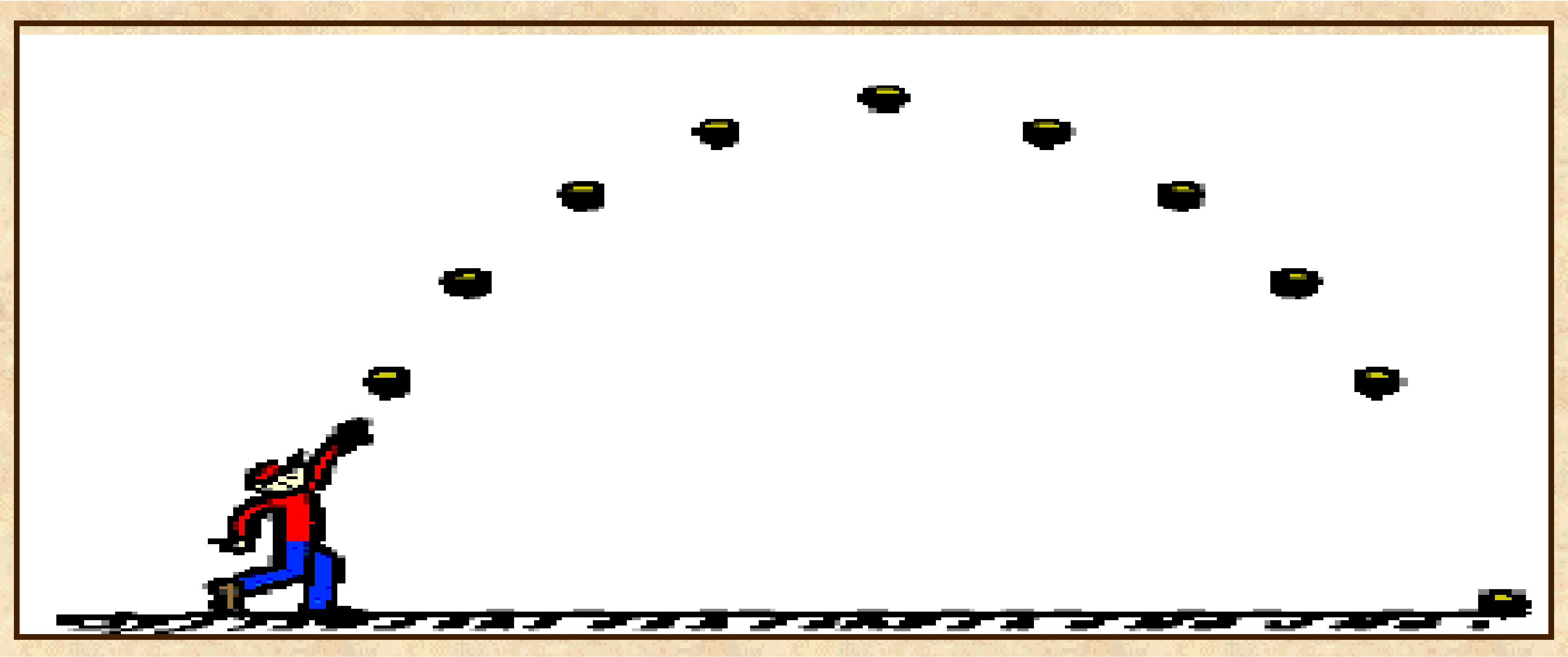

Projectile Motion – Fireworks #1

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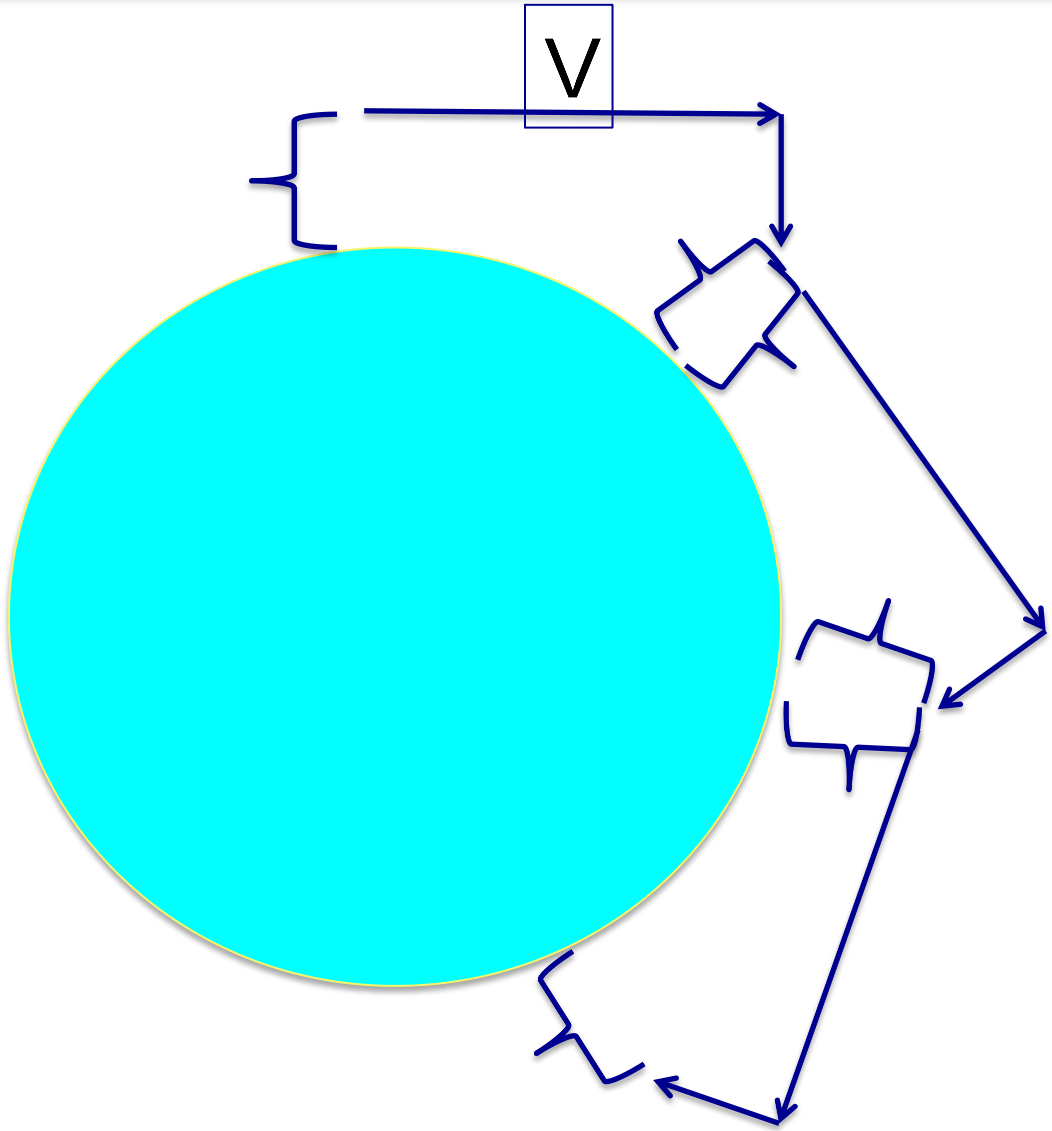
Orbital Velocity



Circular Orbital Equation

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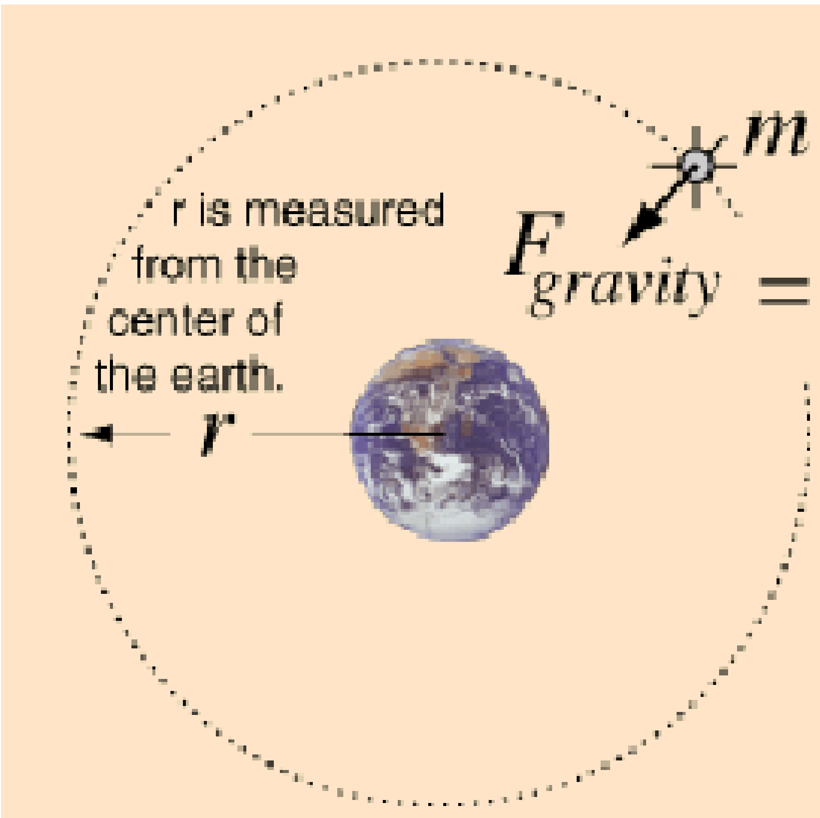

$$v = \sqrt{\frac{GM}{r}}$$

International Space Station travels at 27,744 kilometers per hour (over 6 times faster than the fastest bullet) resulting in an orbital period of ~ 90 minutes.

Introduction to Orbits
https://www.youtube.com/watch?v=IekLGgj_Wkk

Kepler's three laws

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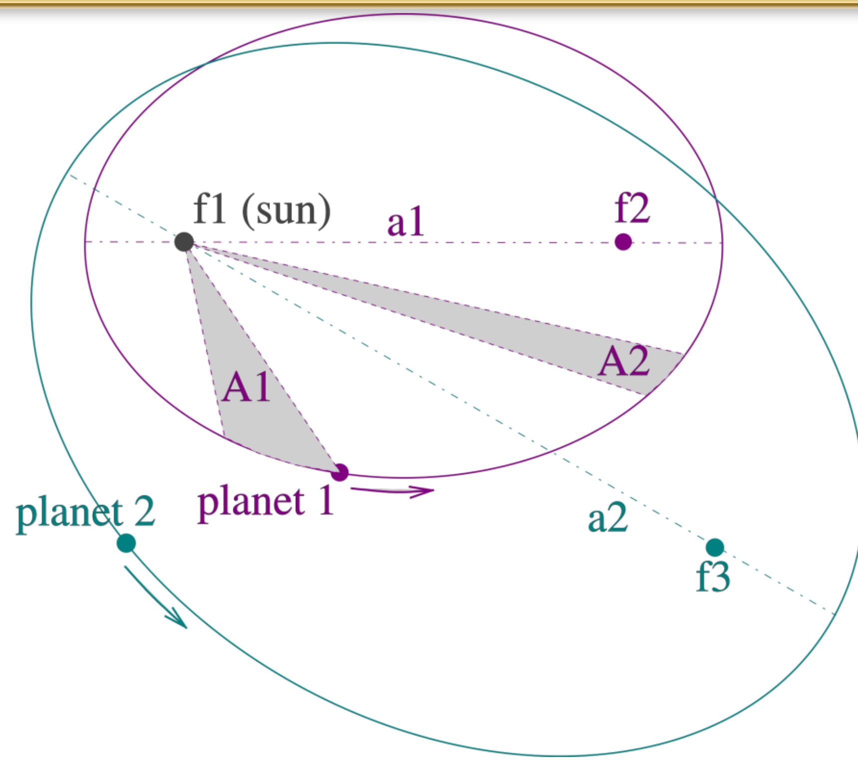
1. The orbits are ellipses, with focal points f_1 and f_2 for the first planet and f_1 and f_3 for the second planet.
2. The two shaded sectors A_1 and A_2 have the same surface area and the time for planet 1 to cover segment A_1 is equal to the time to cover segment A_2.
3. The total orbit times for planet 1 and planet 2 have a ratio $a_1^{3/2} : a_2^{3/2}$



Space is very predictable relative to orbital dynamics.

Source: http://en.wikipedia.org/wiki/Kepler%27s_laws_of_planetary_motion

Kepler's Second Law

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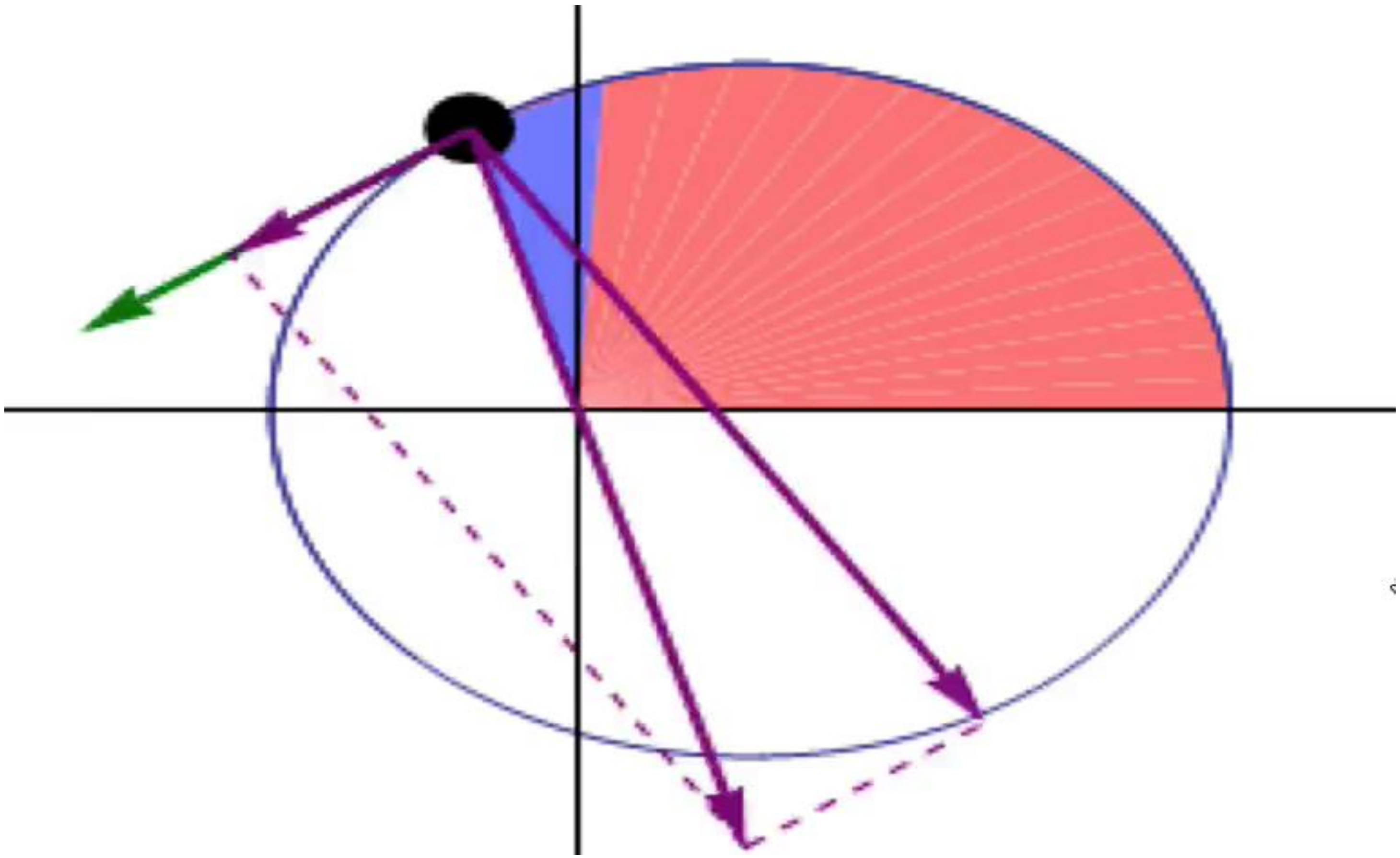

Source: Antonio González Fernández

Launch Cost to get 1 kg to GEO
is 5 to 10 times the cost to get 1 kg to LEO
And, at GEO, one needs
More power and larger antennas
to close the link (larger systems).

Basic Satellite Architectures

Often Highly Asymmetric Links

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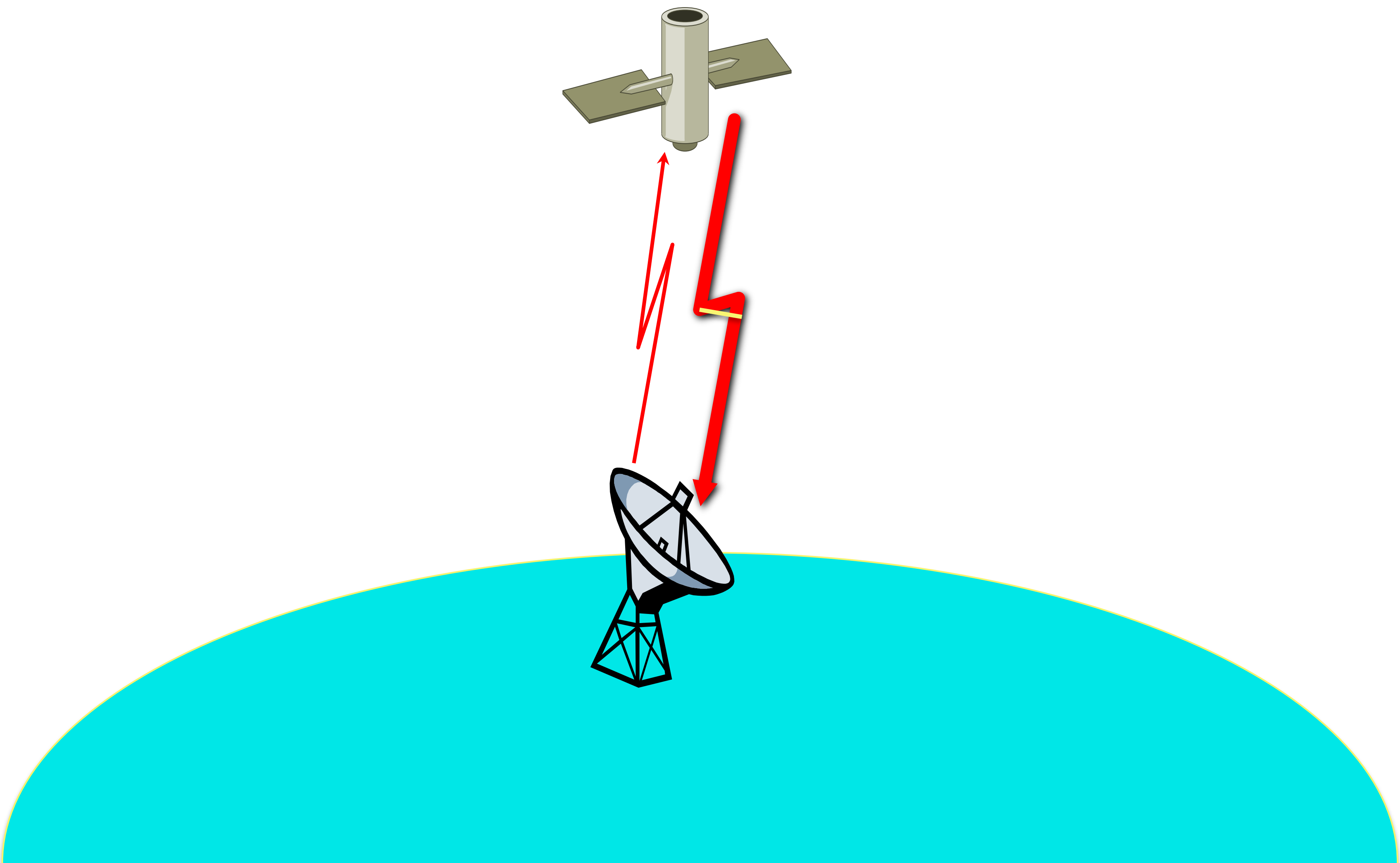

Low Earth Orbit (LEO) Only

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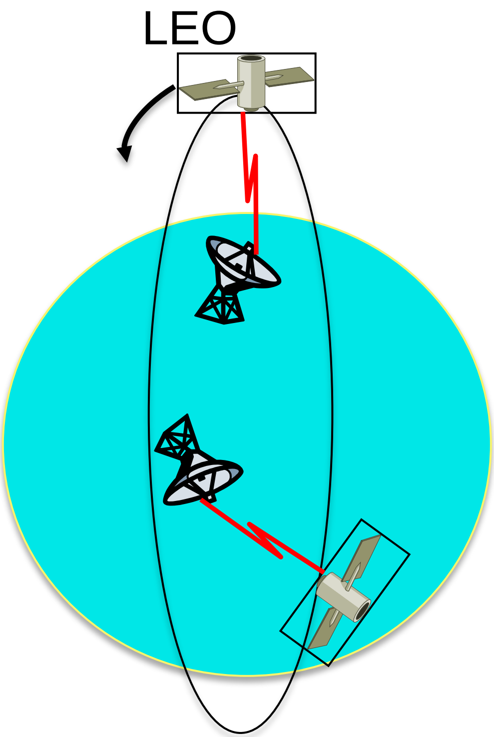
- LEO orbit are below the Earth's ***radiation belts***, which allows for use low-cost Commercial-Off-The-Shelf (COTS) components.
- Radiation still must be considered – depending on cost a duration of flight.



LEO via Geostationary Orbit (GEO)

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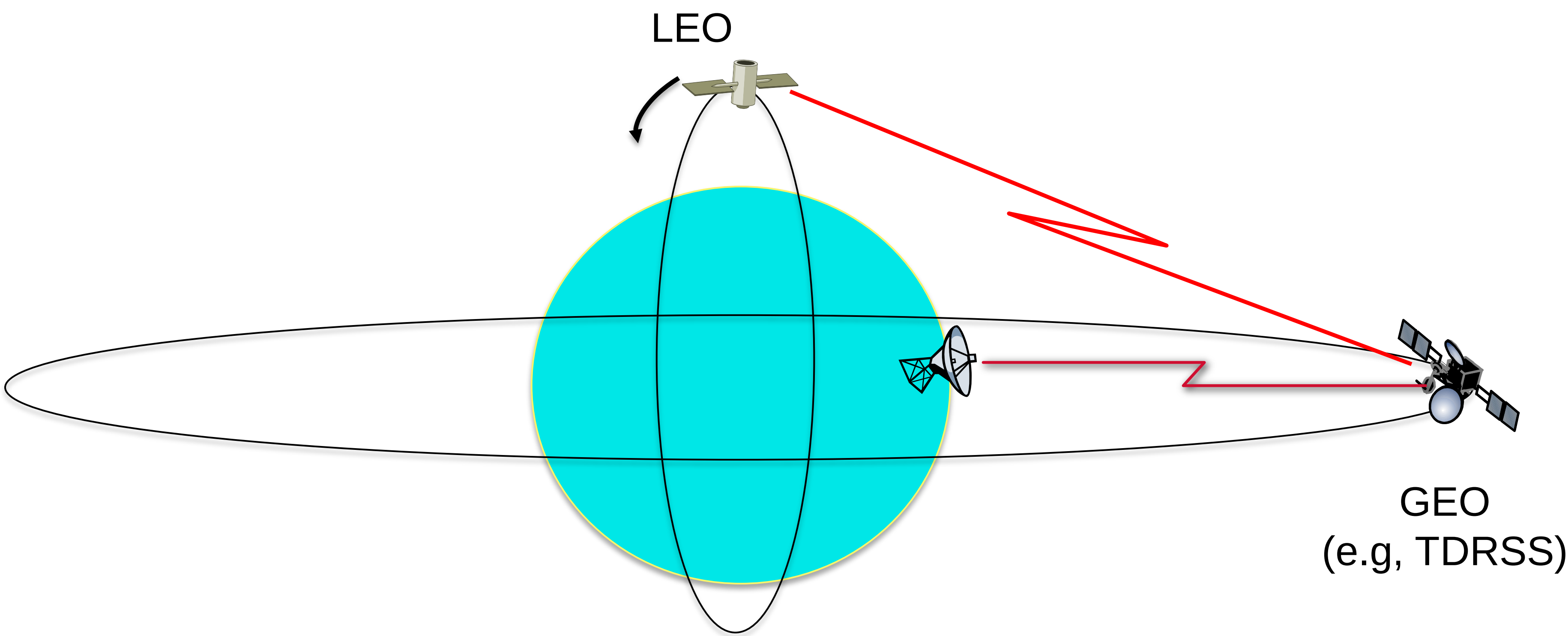

LEO and GEO

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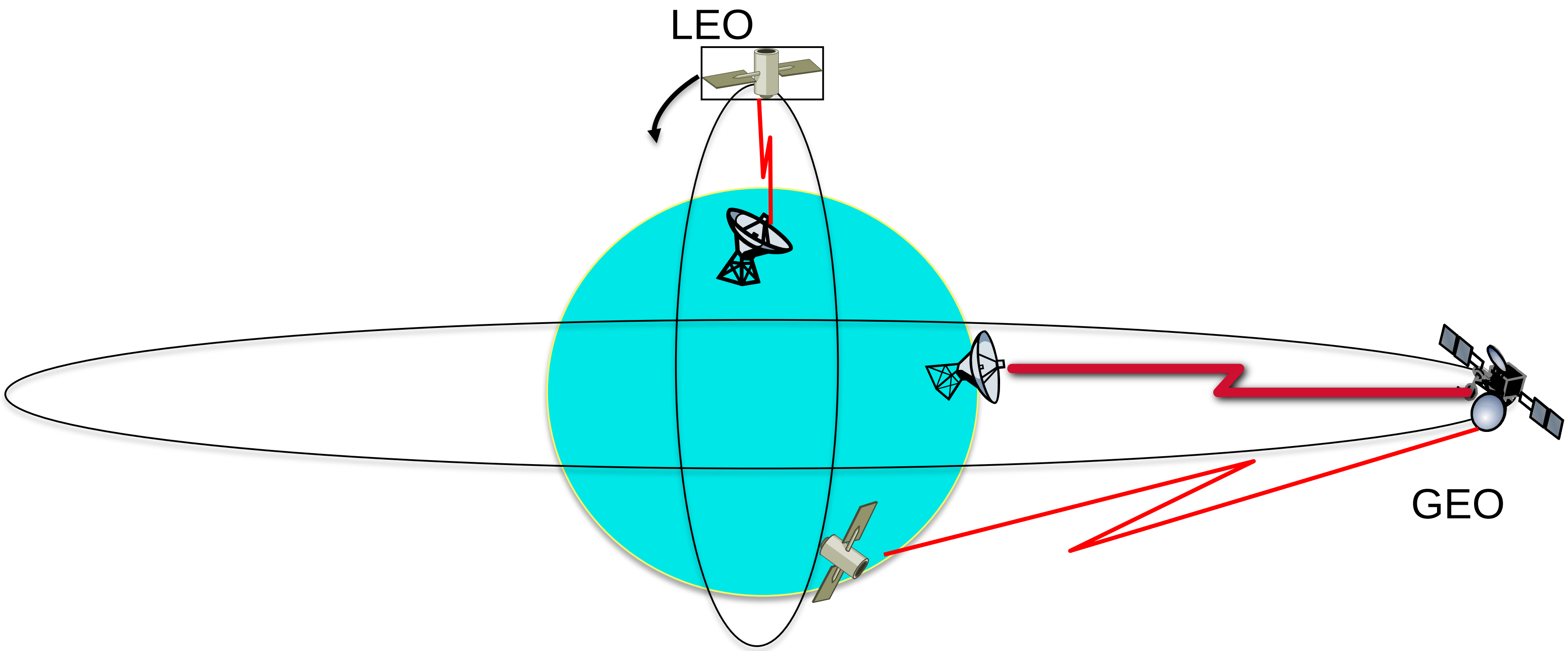

Polar Orbit

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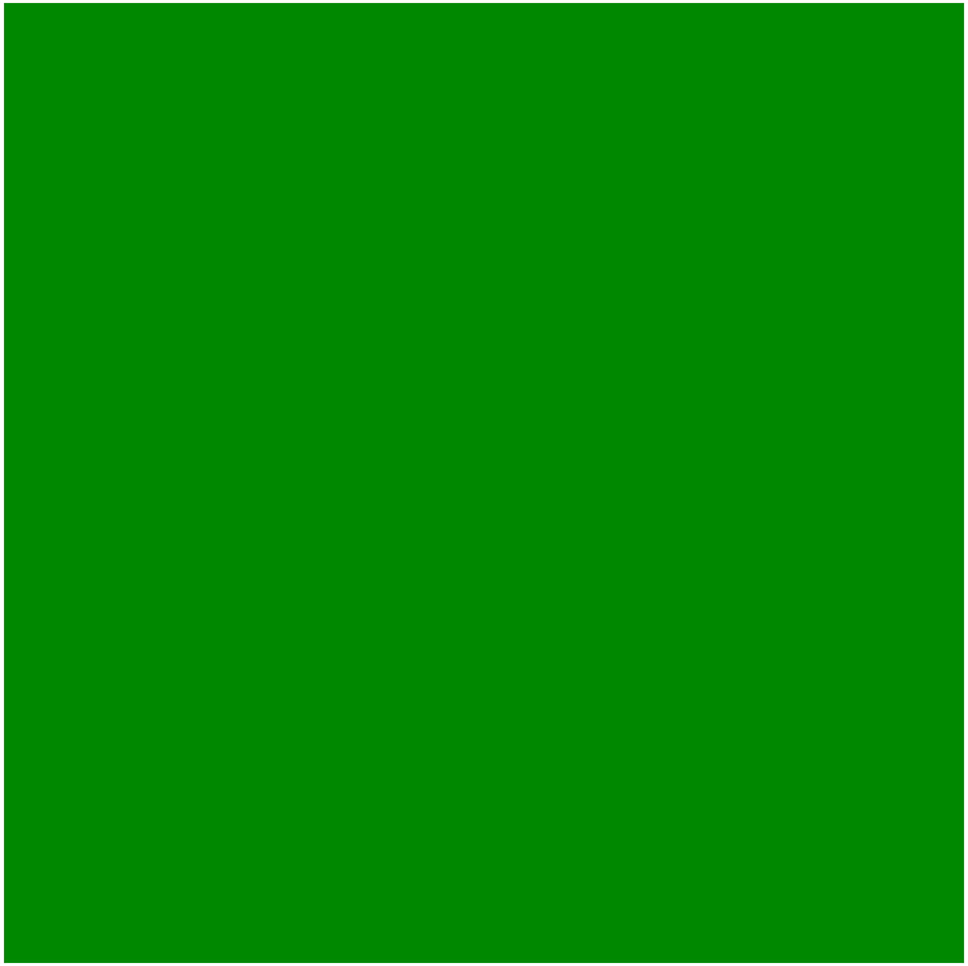

Source: http://commons.wikimedia.org/ via youtube

GEO Orbit

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Source: http://RKM.COM.AU Russell Knightley via youtube

Molniya Orbit

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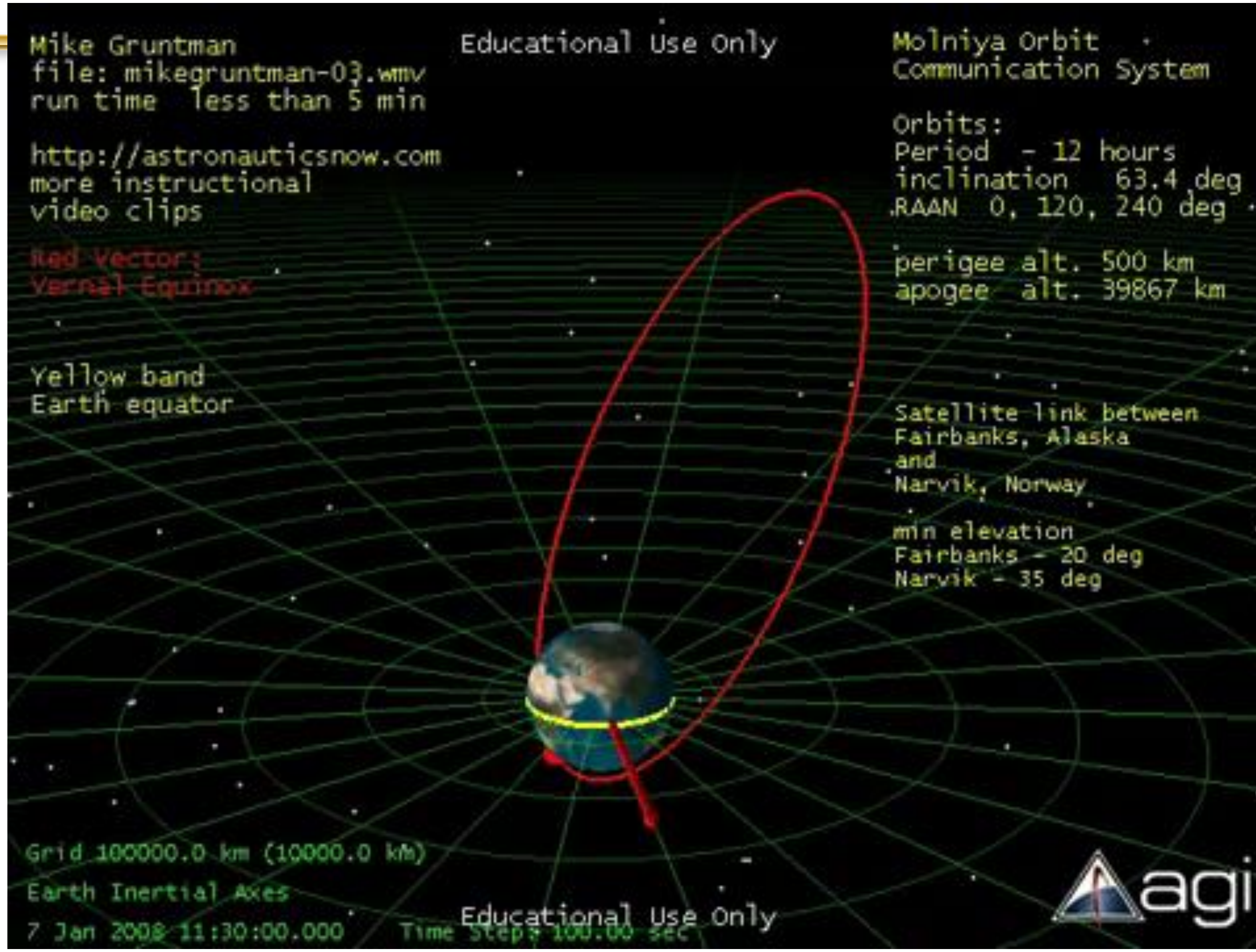

Source: http://www.astronauticsnow.com/vp/

Iridium – 66 Satellites in Polar Orbit

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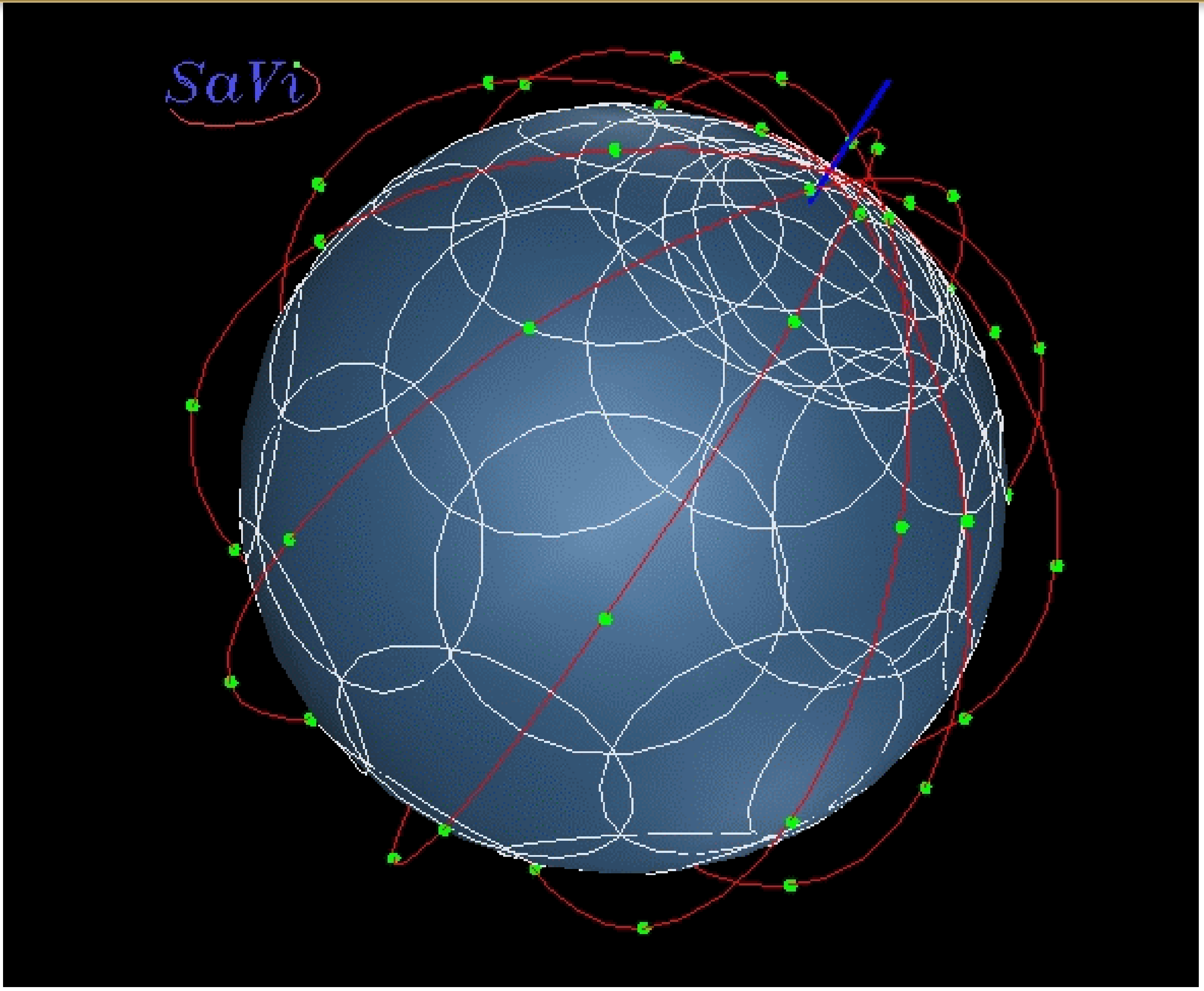

Globalstar – 48 Satellites

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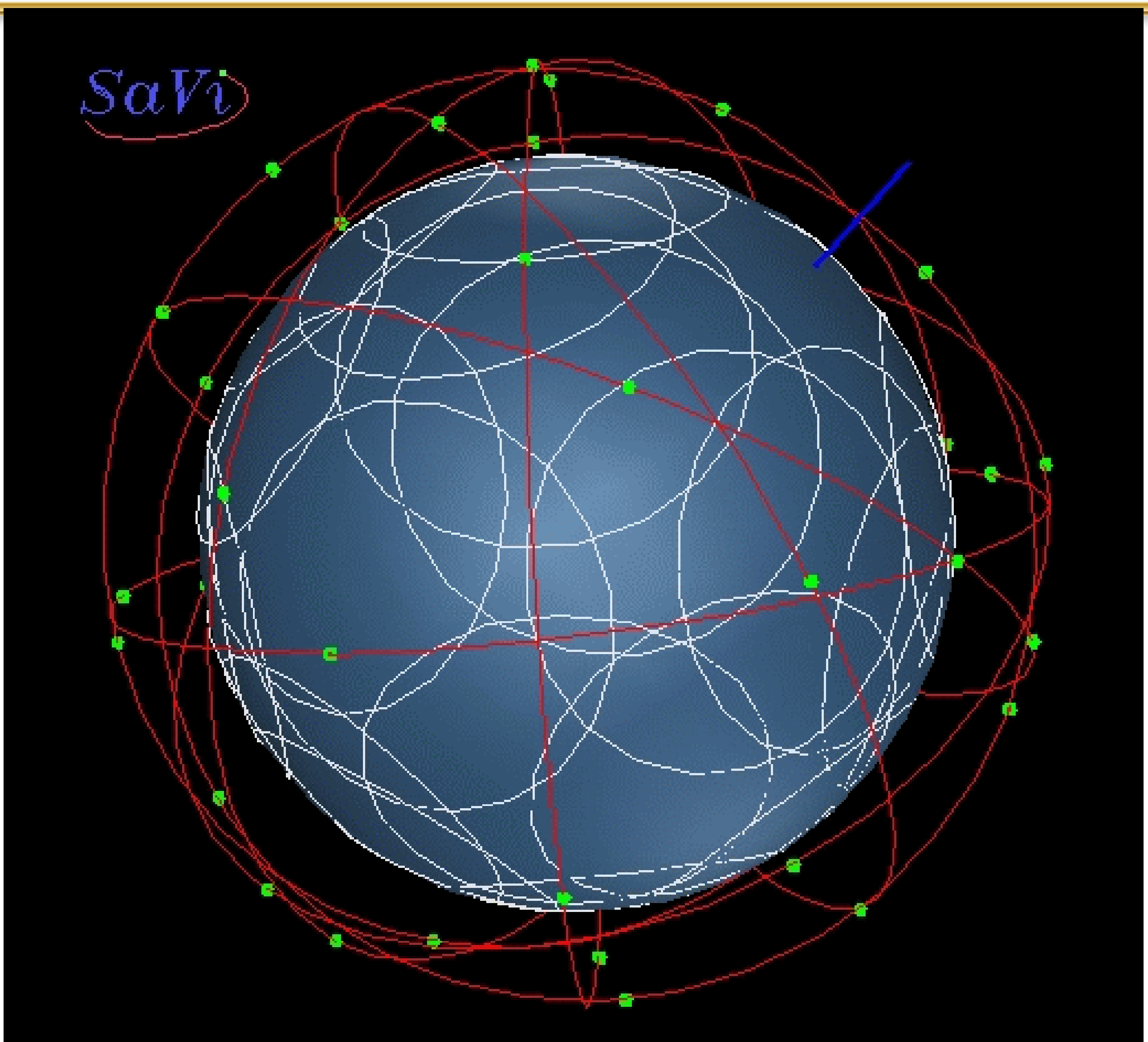

Teledesic – 840 Satellites in original plan

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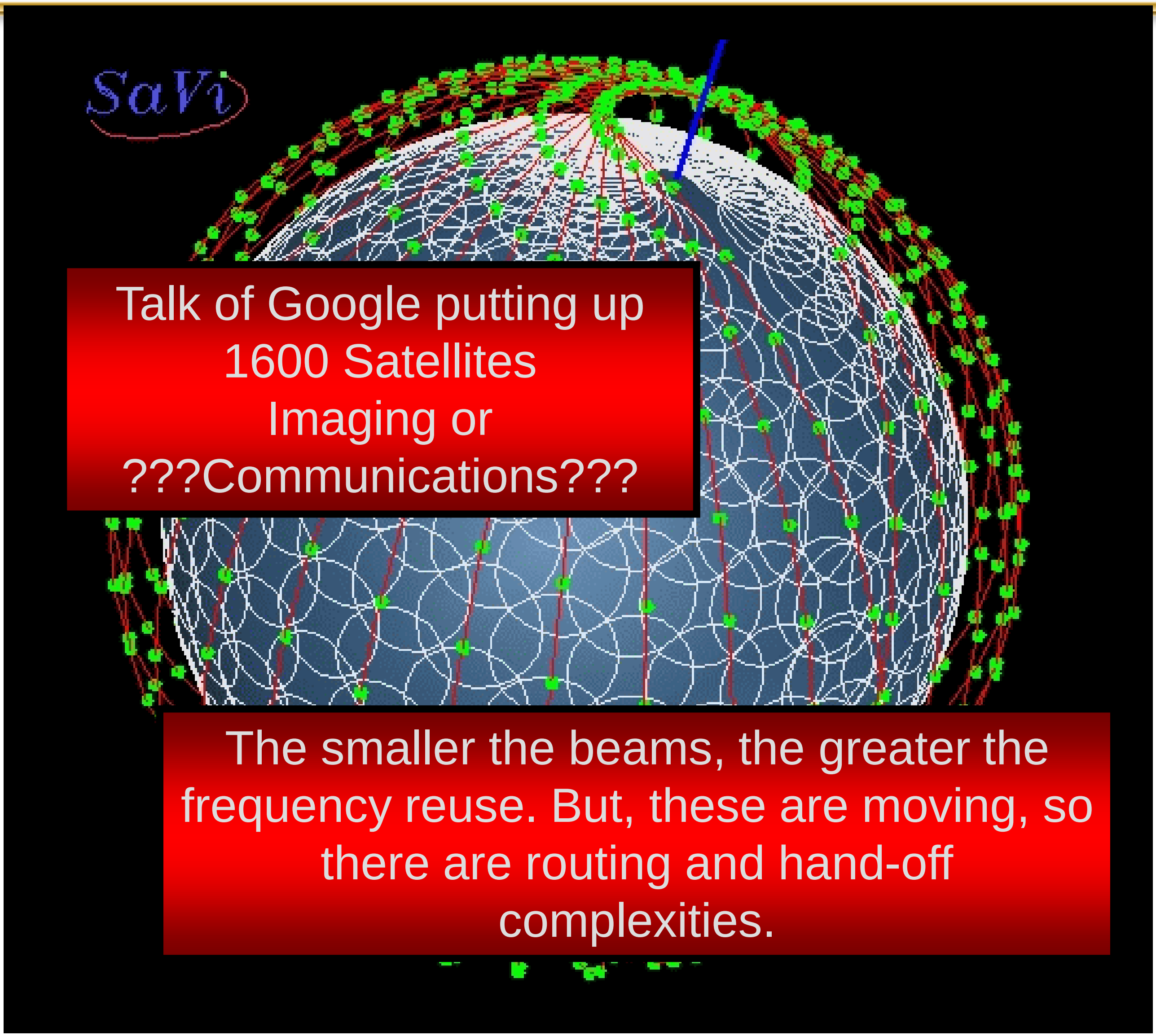

Talk of Google putting up 1600 Satellites
Imaging or
???Communications???

The smaller the beams, the greater the frequency reuse. But, these are moving, so there are routing and hand-off complexities.

Global Positioning System

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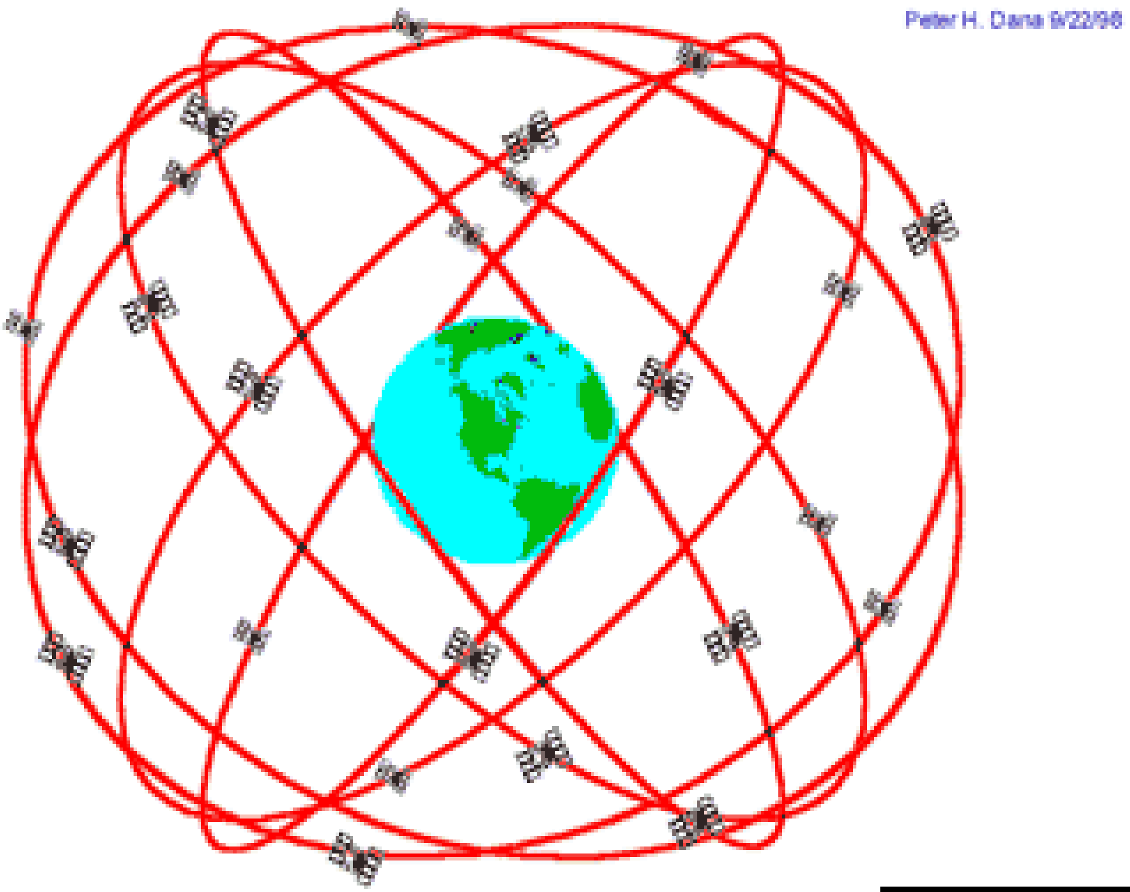

GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

GPS is in a much higher orbit than LEO.

Tracking and Data Relay Example

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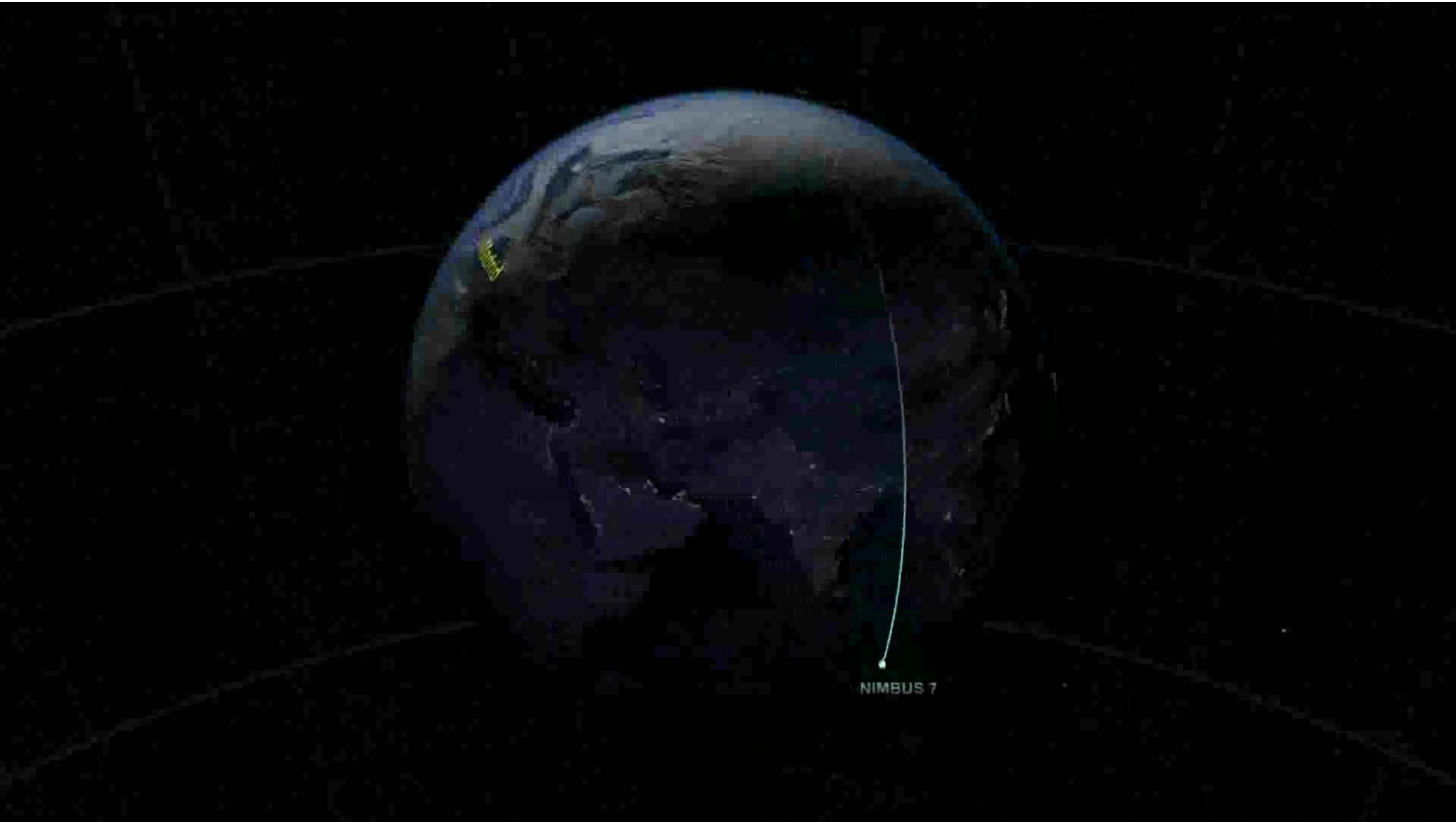
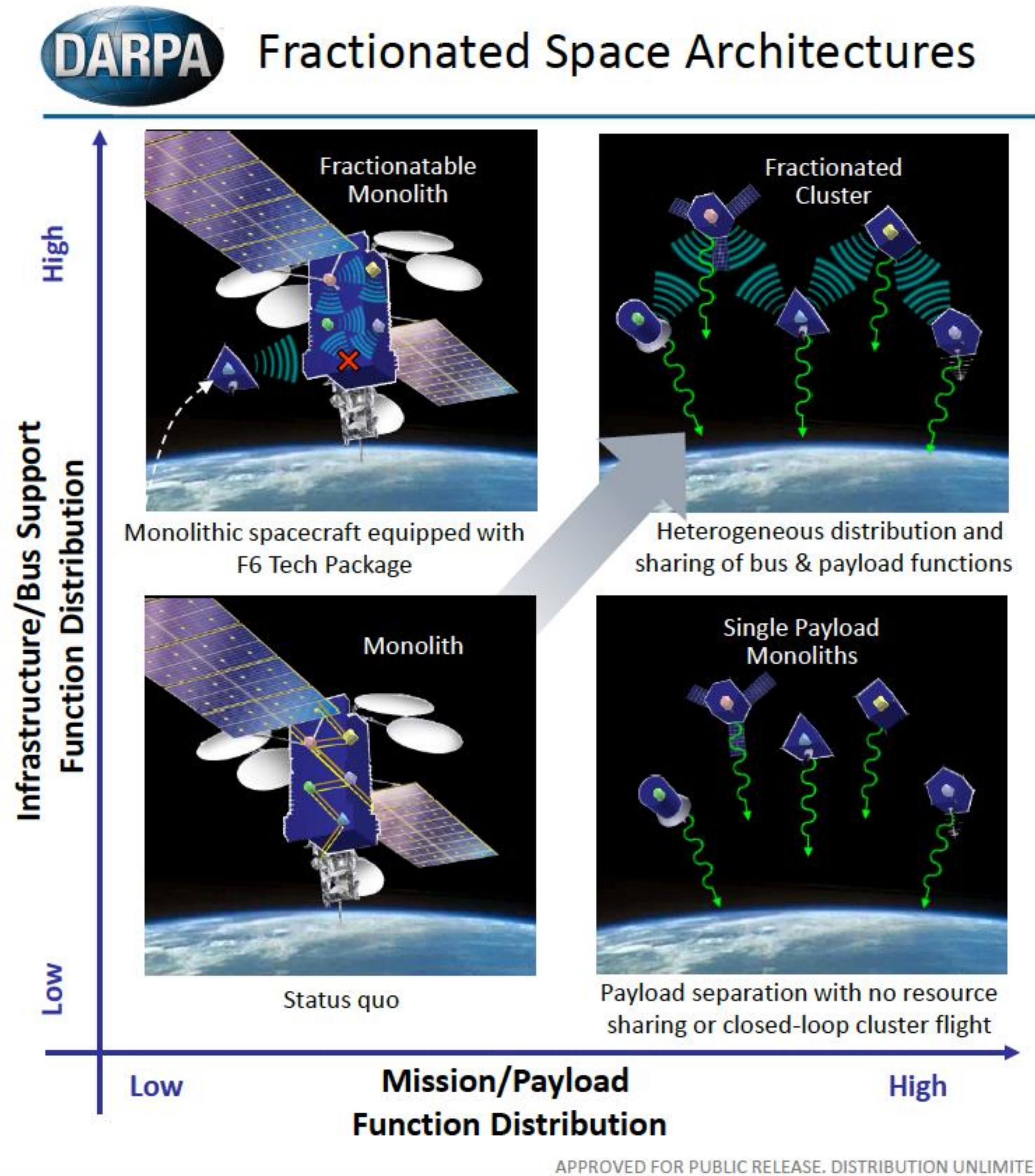


DARPA F6

Future, Fast, Flexible, Fractionated Free-flying Spacecraft United by Information Exchange, or System F6 was Cancelled in 2013

Fractionated Spacecraft



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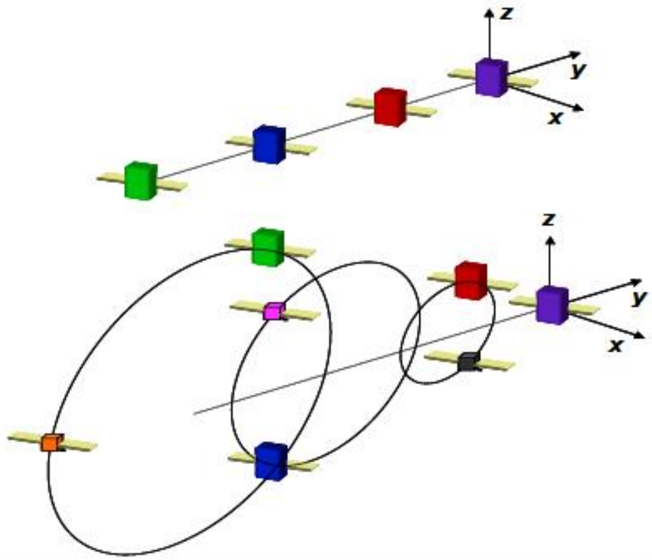
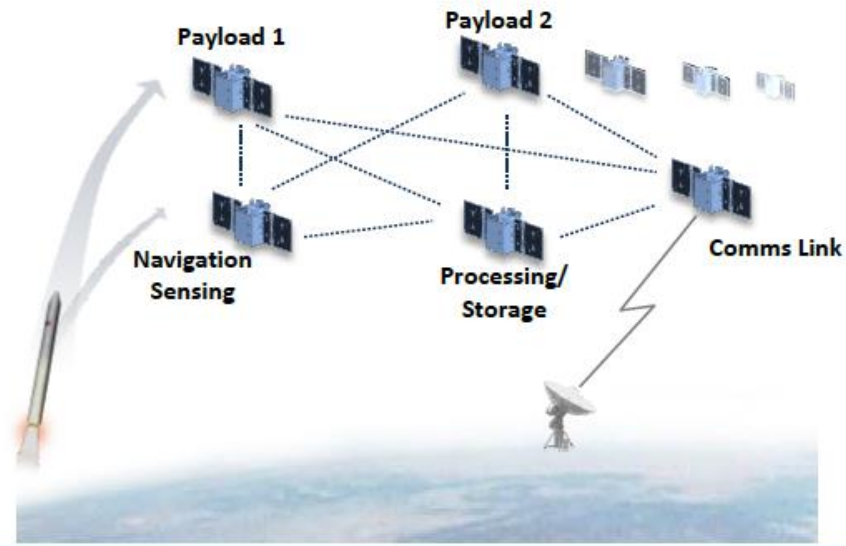
Enables

- Resource Sharing
  - Power
  - Telecommunication
  - Processing
- Redundancy
- Rapid cluster maneuvering
- Multiple Vendors
- Multi-level Security
- Security Isolation
- Build as you go
  - Everything does not have to be ready at the same time

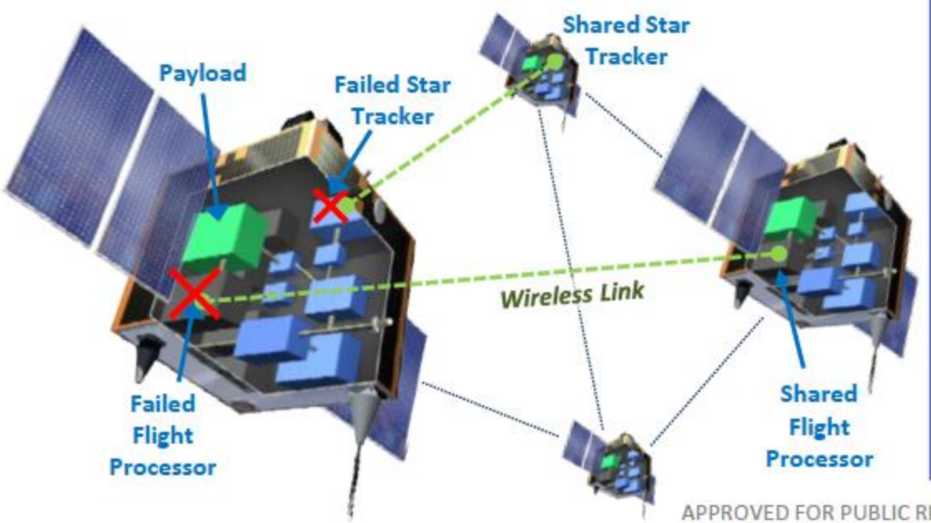
Key Capabilities for 2015 On-Orbit Demonstration



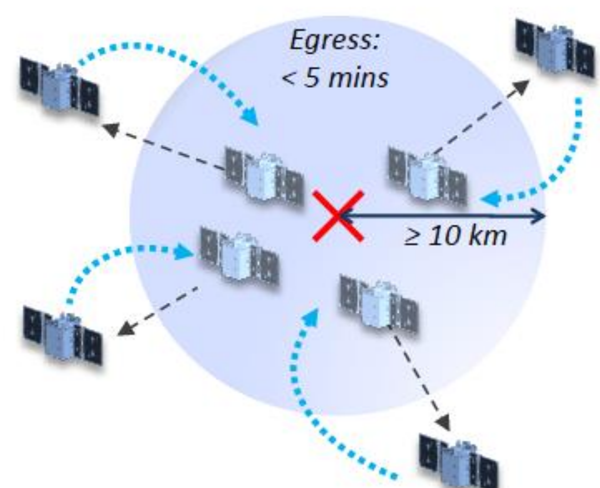
Demo 2: Resource Sharing at Multiple Security Levels



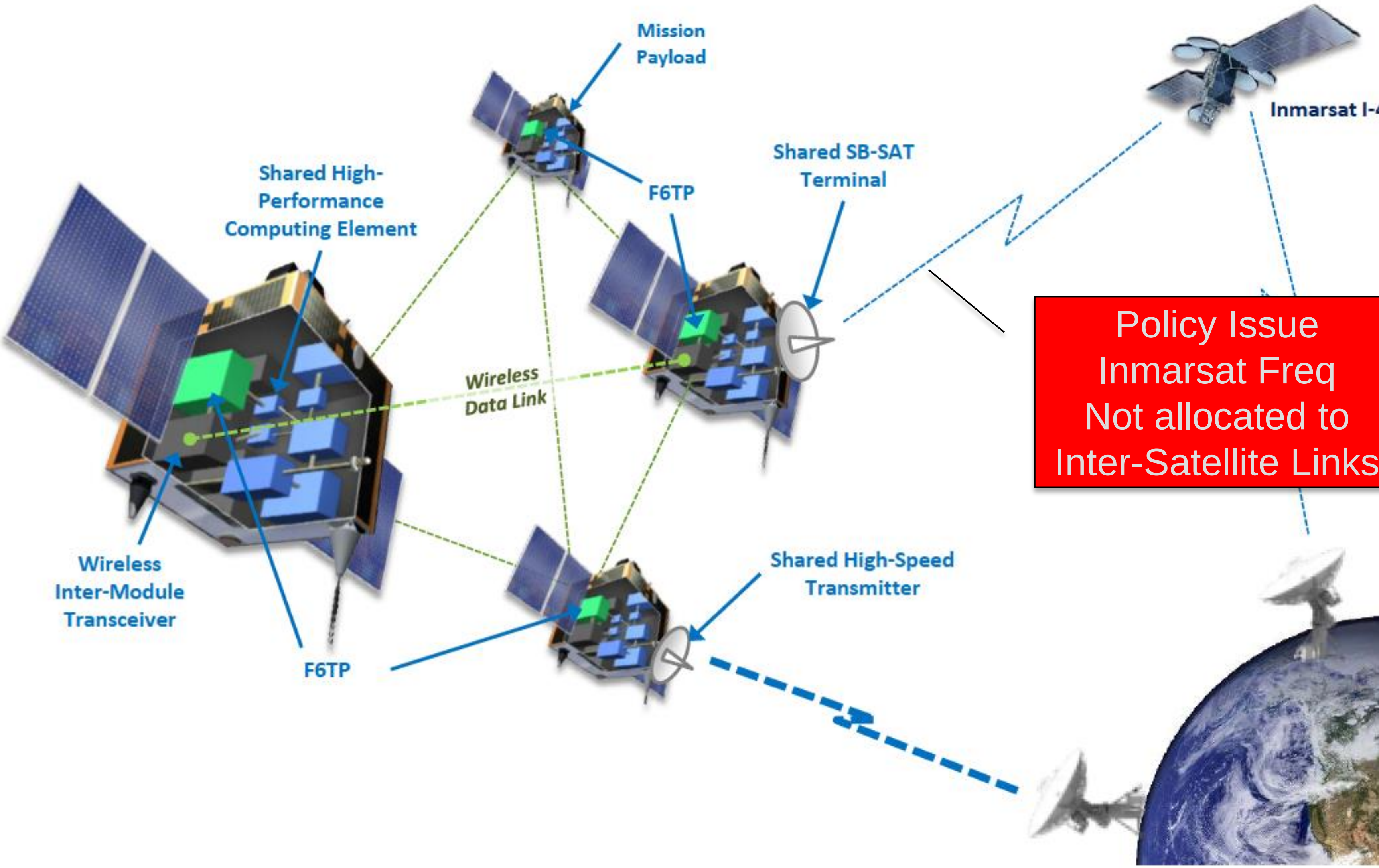
Demo 3: Cluster-Level Fault Tolerance



Demo 4: Defensive Scatter and Re-Gather

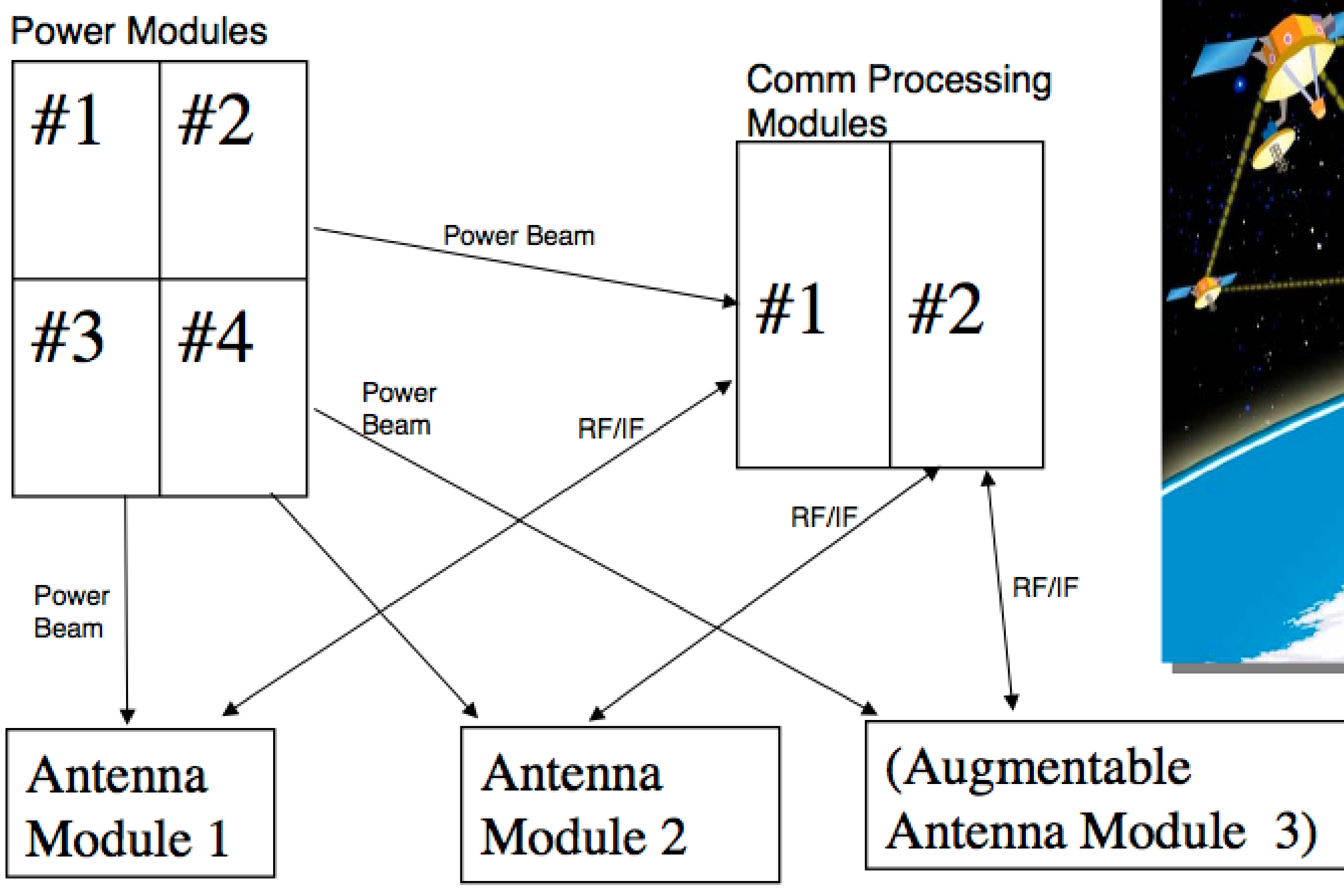


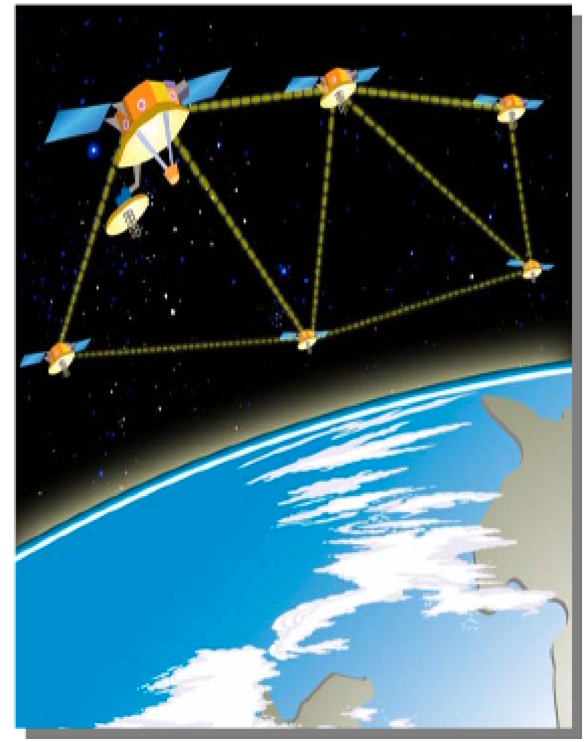
Notional System F6 On-Orbit Demo



Policy Issue
Inmarsat Freq
Not allocated to
Inter-Satellite Links

Resultant Fractionation Diagram





Source: An Exercise in Spacecraft Mission Fractionation - Kevin Rooney August 2006

Key Issues and Technologies

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- Formation flying metrology and control
- Power beaming (potential to be highly efficient i.e. 95%)
- Precision navigation and time distribution
- Low-power, high capacity communications (depending on mission)
- Have at least two shared-capacity modules of each type, to accommodate robustness paradigm while avoiding multiple internal redundancies
- Launch vehicle limitations artificially increase the number of modules, with inefficient duplication of housekeeping functions
- Equalize the mass of each module: Accomplishes synergy in design with max use of common building blocks; permits maximized advantage to be taken of learning curve and launch-vehicle bulk-buy economy

Source: An Exercise in Spacecraft Mission Fractionation - Kevin Rooney August 2006

Space Interferometer
(Conceptual – Fractionated Instrument)

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- Higher angular resolution in astronomical images requires increasing apertures of telescopes or increasing baselines of interferometers.
- For monolithic units, the mass of the support structure, and propellant for launch is about to exceed technical and financial boundaries.
- Solution to overcome the mass constraint is to combine satellites in autonomous formation flight to behave just like a rigid body.
- Requires precise navigation, control and timing (to correlate data)

Cooperative Spacecraft

NASA's A-Train

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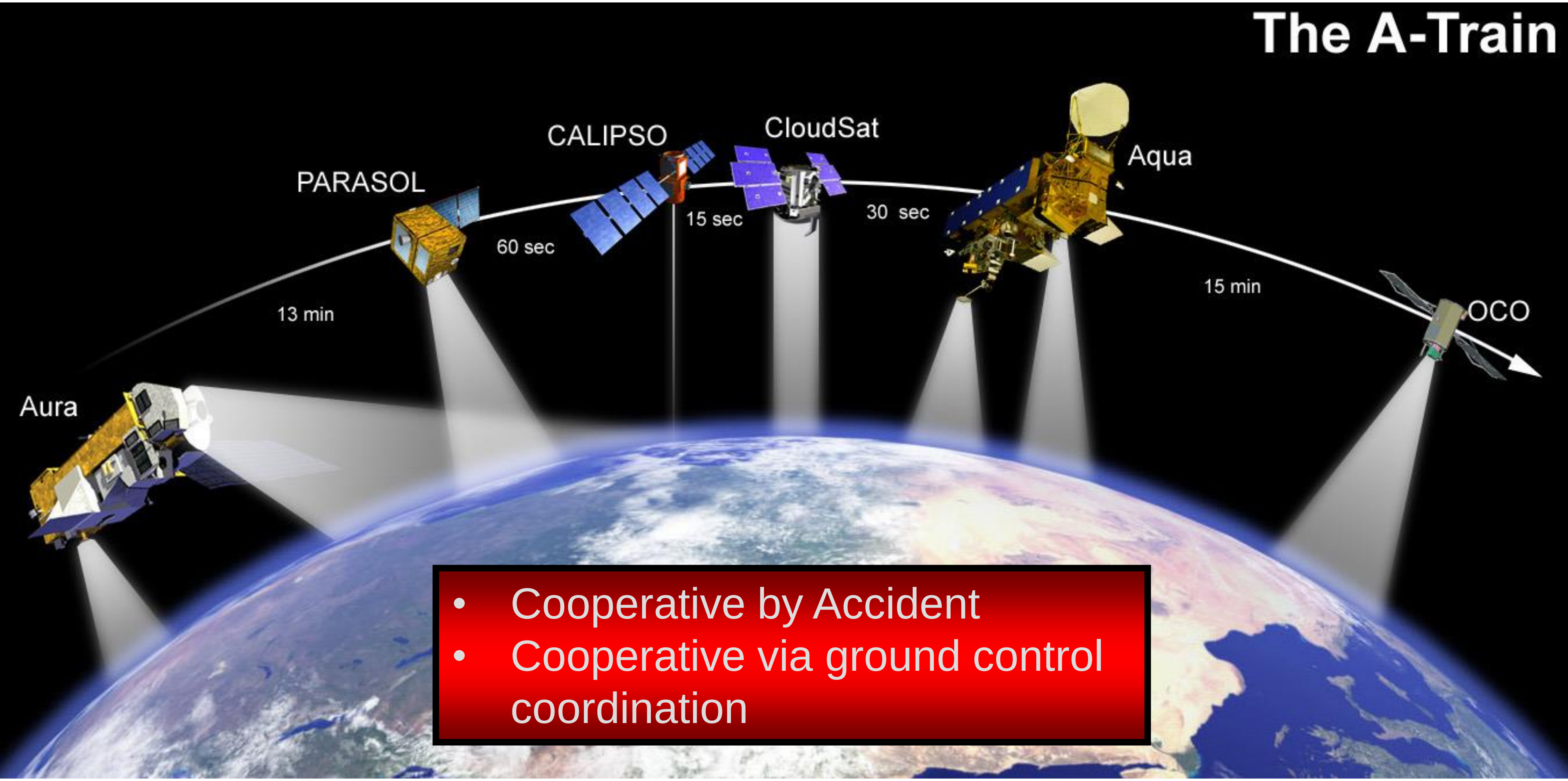
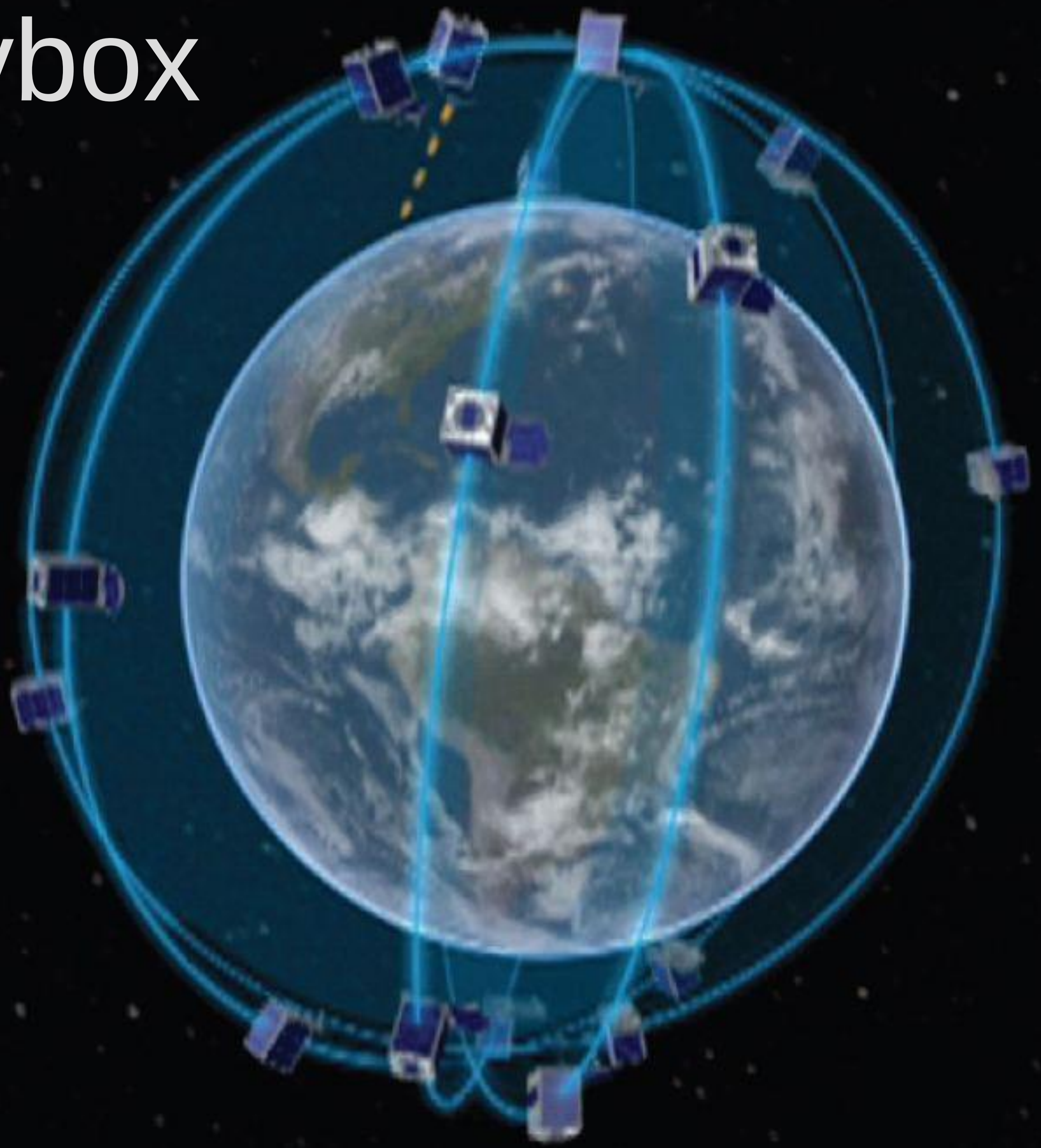


- Cooperative by Accident
- Cooperative via ground control coordination

Skybox



Skybox

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- 24-satellite constellation at a 500-kilometer orbit
- Skybox treats each satellite as just another server in a server farm.
- 4 different orbital planes
- Downlink Feed X-band, 8025-8400 MHz
  - Critical to applications such as change detection
- Uplink Feed S-band, 2025-2110 MHz
- Satellite revisit rates of five to 10 times per day
- High-resolution imagery (1 meter or better) and full-motion video for commercial sale.
  - Business case is data-mining and analytics

Skybox

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Skybox Frequency Plan

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Frequency Bands

Band	Use	Service	Table
2080.89 - 2081.11 MHz	Skybox Imaging telemetry uplink	Earth Exploration-satellite (Earth-to-space)	N
2082.89 - 2083.11 MHz	Skybox Imaging telemetry uplink	Earth Exploration-satellite (Earth-to-space)	N
8045 - 8105 MHz	Skybox Imaging data downlink	Earth Exploration-satellite (space-to-Earth)	N
8170 - 8230 MHz	Skybox Imaging data downlink	Earth Exploration-satellite (space-to-Earth)	N
8295 - 8355 MHz	Skybox Imaging data downlink	Earth Exploration-satellite (space-to-Earth)	N
8374.744 - 8375.256 MHz	Skybox Imaging telemetry downlink	Earth Exploration-satellite (space-to-Earth)	N
8379.744 - 8380.256 MHz	Skybox Imaging telemetry downlink	Earth Exploration-satellite (space-to-Earth)	N

Planet Lab "Dove" CubeSat

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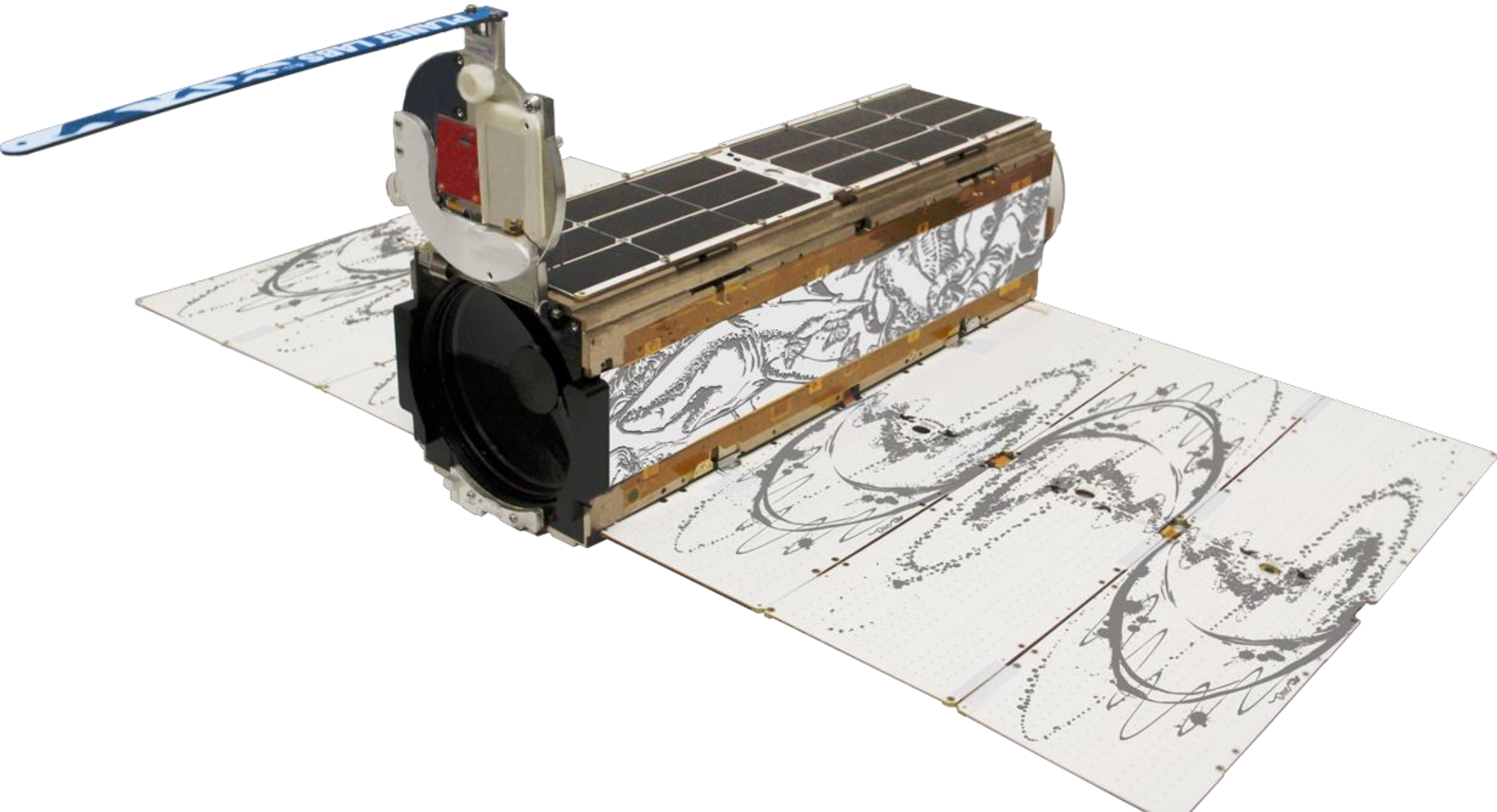

Planet Lab

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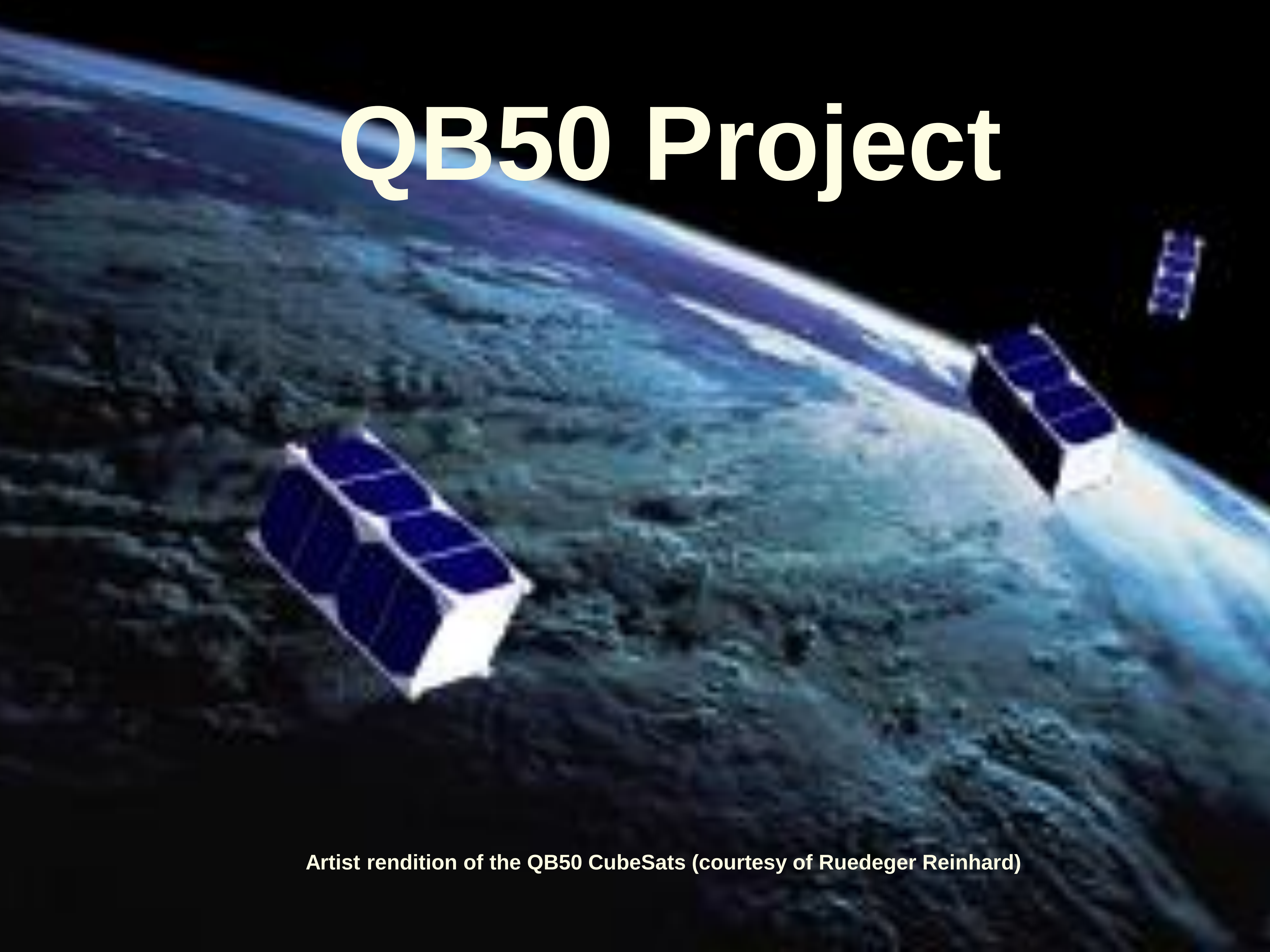
- Earth-imaging satellite constellation
- 28 Doves currently
- 100 planned
- Orbit at 400 miles (640 km) and provide imagery with 3-5 m resolution
- Currently launches from the International Space Station
- Fresh data from any place on Earth
- Business Case: Global sensing and analytics

QB50 Project



Artist rendition of the QB50 CubeSats (courtesy of Ruedeger Reinhard)

QB50

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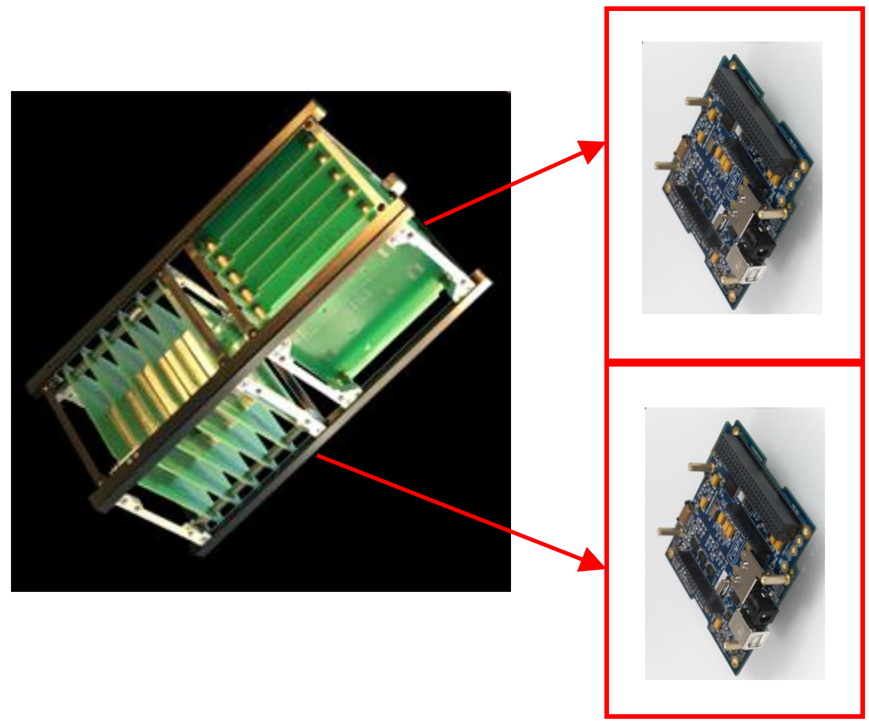
- An international network of 50 CubeSats sequentially deployed – String of Pearls
- Multi-point in-situ long-duration measurements and in-orbit demonstrations in the lower thermosphere
- Initial altitude: 350 km (circular orbit, high inclination)
- Downlink using the QB50 Network of Ground Stations
- On all other missions CubeSats are a secondary payload, on QB50 the CubeSats are the primary payload.

Science Unit



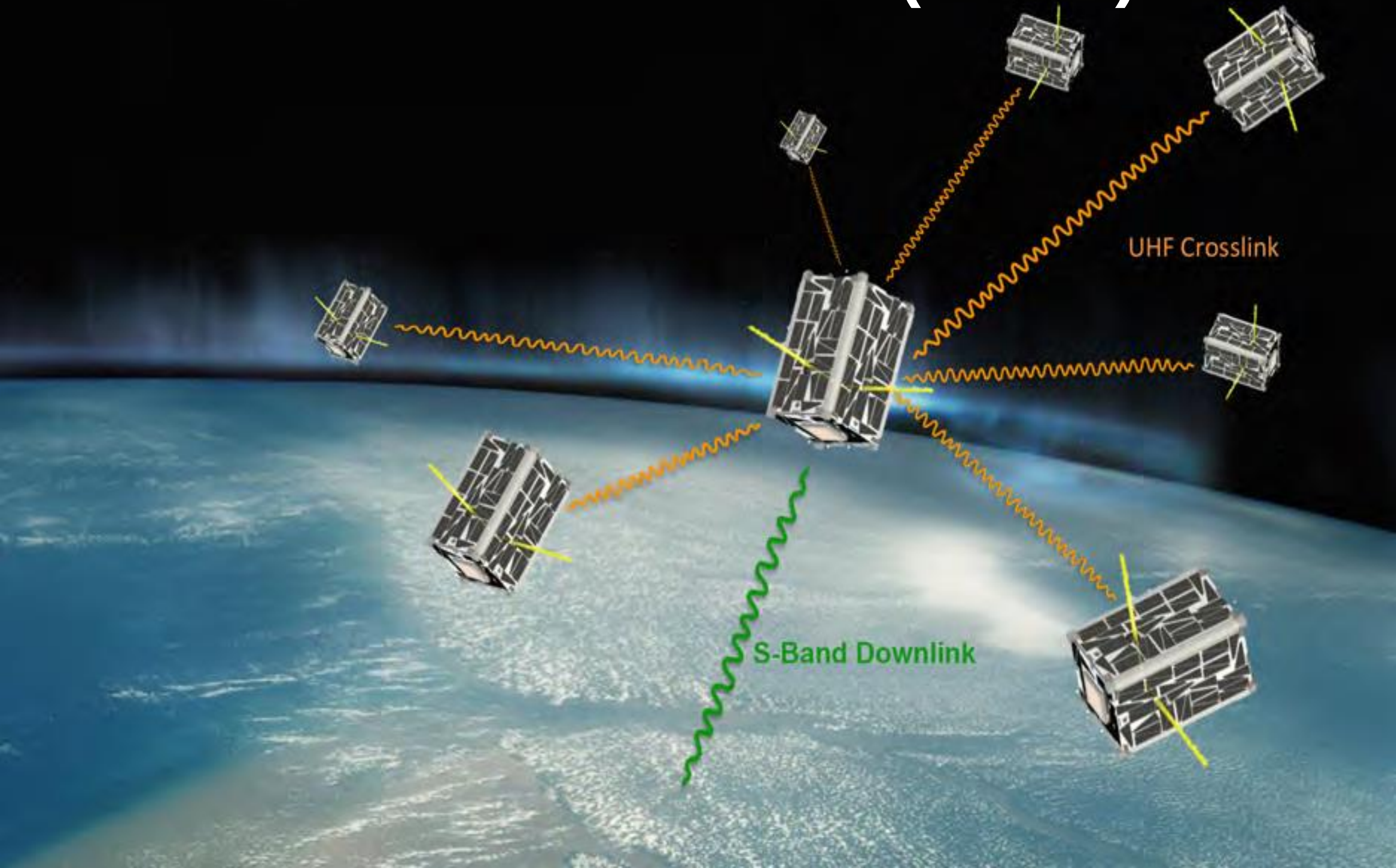
Functional Unit

Power

Telecommunications

Tech Demostrations

NASA's Edison Demonstration of Smallsat Networks (EDSN)



EDSN

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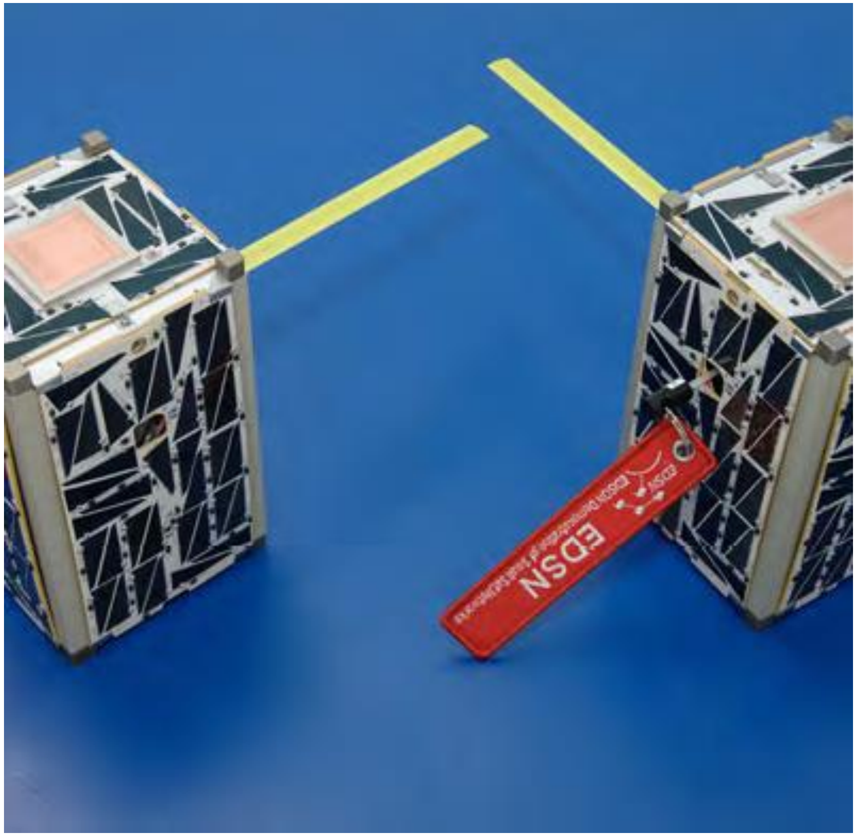
Enable Cross-Link Communication and Multipoint Physics

- **8 cubesats into a loose formation**
- **Approximately 500 km above Earth**
- **1.5 cubesat unit**
  - **about the size of a tissue box**
  - **weighs approximately 4 pounds(2 kg)**
- **60-day operational period in orbit.**
- **Make distributed, multipoint space radiation measurements.**
- **Demonstrate advanced communications, including a network that allows for data to be sent between satellites as needed.**

Completed EDSN Spacecraft



RapidEye
(by BlackBridge)

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- **The largest sub-meter constellation of satellites**
  - **IKONOS can collect panchromatic and multispectral imagery which can be merged to create 0.82-meter color pan-sharpened imagery.**
  - **QuickBird is a 60 cm, 4-band color satellite, and is capable of collecting multispectral and panchromatic imagery.**
  - **WorldView-1 is a 50 cm TRUE*, panchromatic satellite and is also capable of collecting in-track stereo imagery.**
  - **GeoEye-1 acquires 50 cm TRUE* panchromatic and 2.0 meter multispectral imagery.**
  - **WorldView-2 is a 50 cm TRUE*, 8-band color satellite capable of collecting 2.0 meter multispectral, panchromatic, and in-track stereo imagery.**

Disaster Monitoring Constellation

Surrey Satellite Technology LTD

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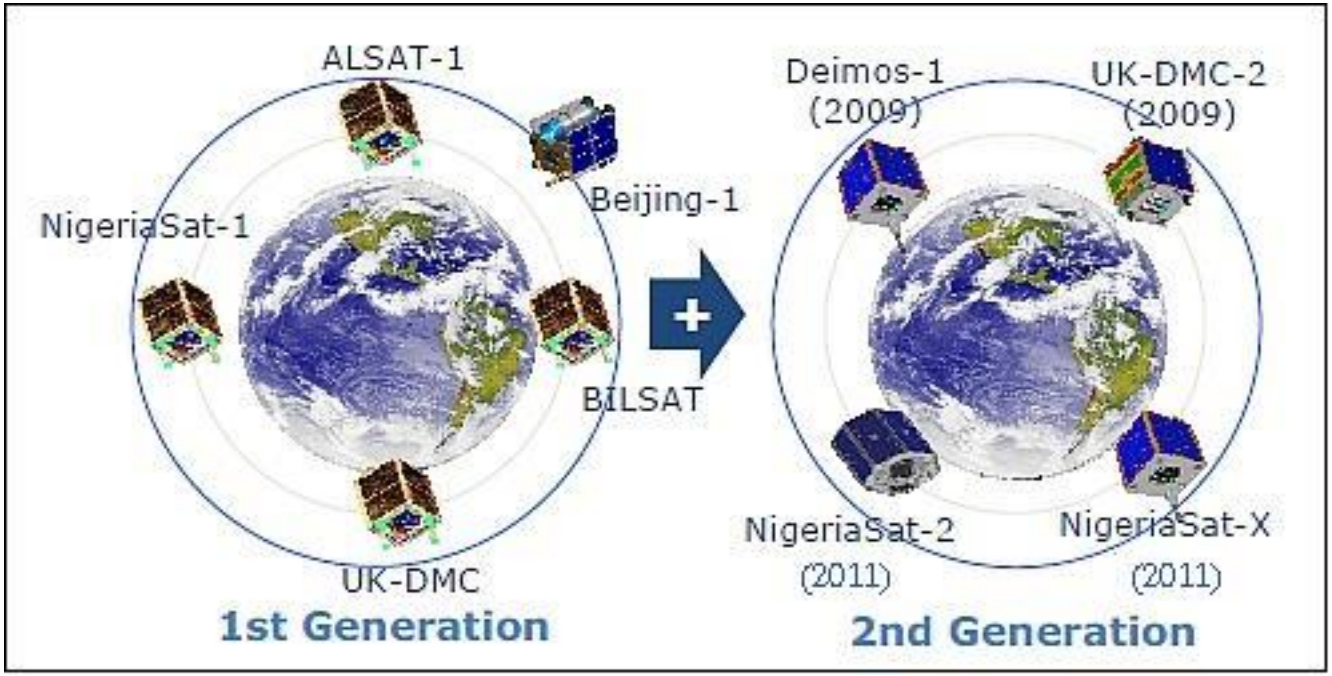

The sun-synchronous orbits of these satellites are coordinated so that the satellites follow each other around an orbital plane, ascending north over the Equator at 10:15 am local time (and 10:30 am local time for Beijing-1).

Virtual Mission Operations Center

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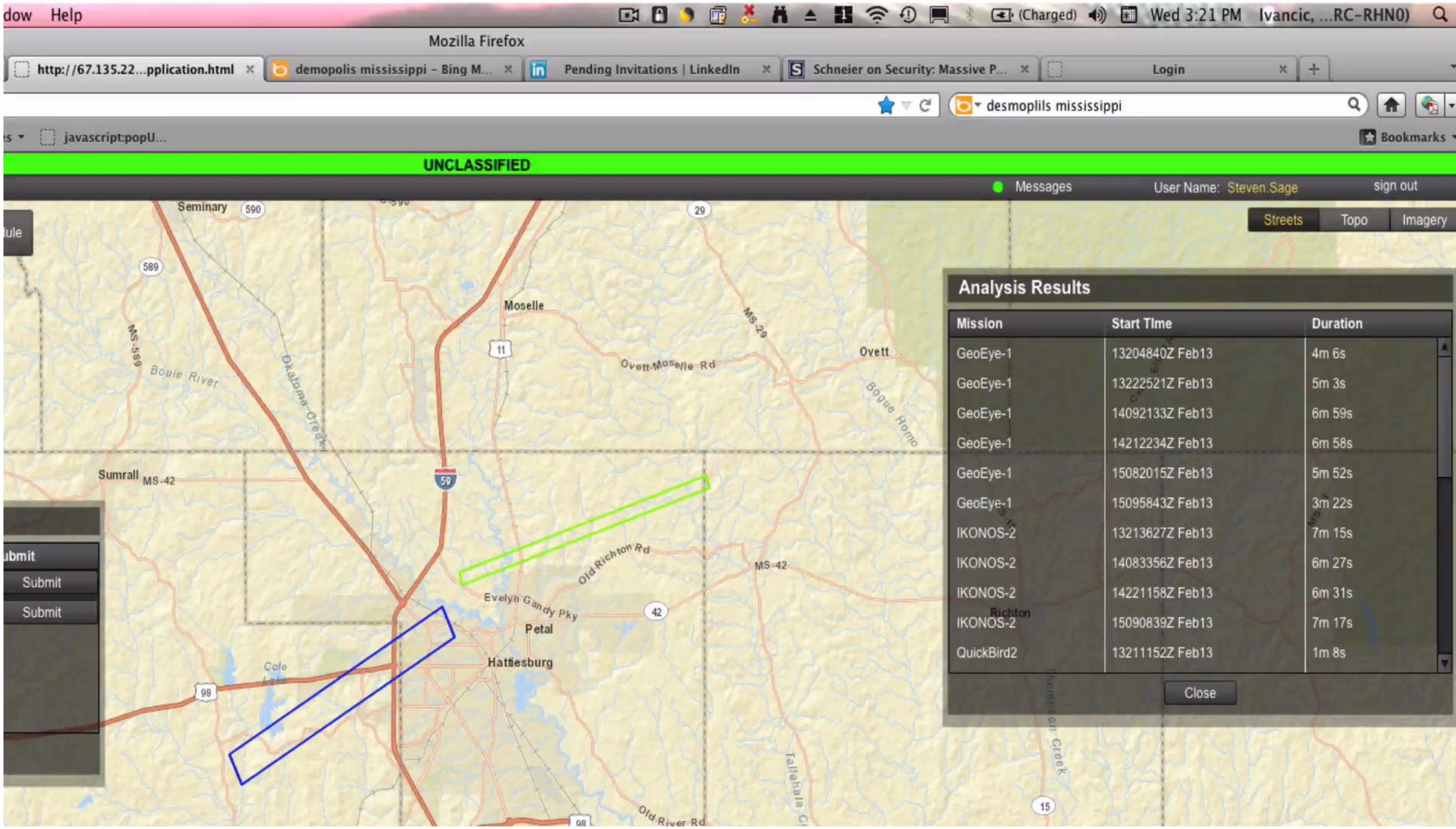

Population Growth

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Blackout of August 14, 2003

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