SYZYGY Engineering

Key Technologies Regarding Distributed and/or Collaborating Satellite Systems

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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

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.

Network Design Triangle

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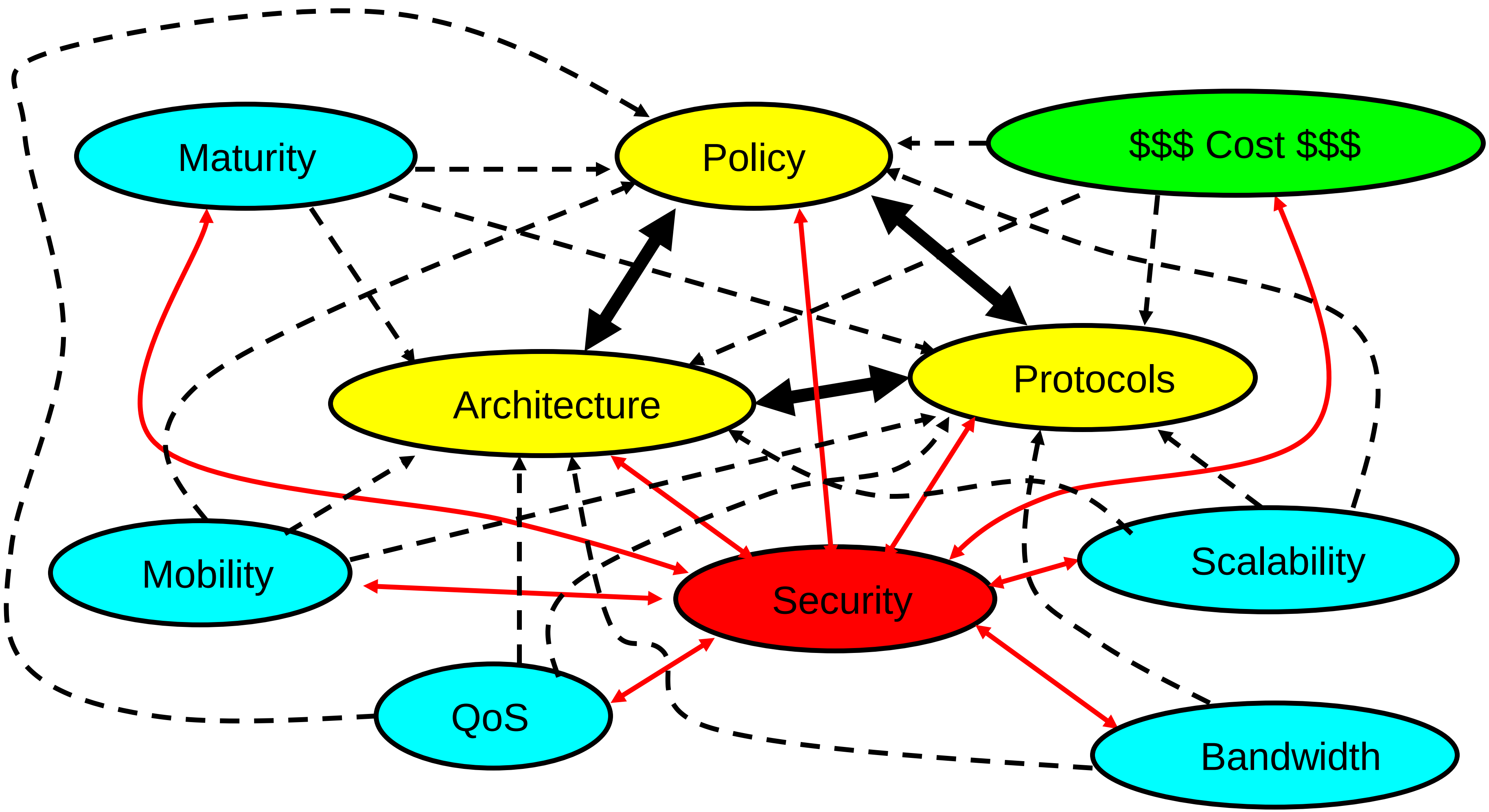

Policy

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- Understand Policy (rules of engagement and legal issues).
    - It may be the most important thing you do.
    - Policy may be the hardest thing to change.
- Security has numerous Policy Issues
- Spectrum has numerous policy issues

Policy Example

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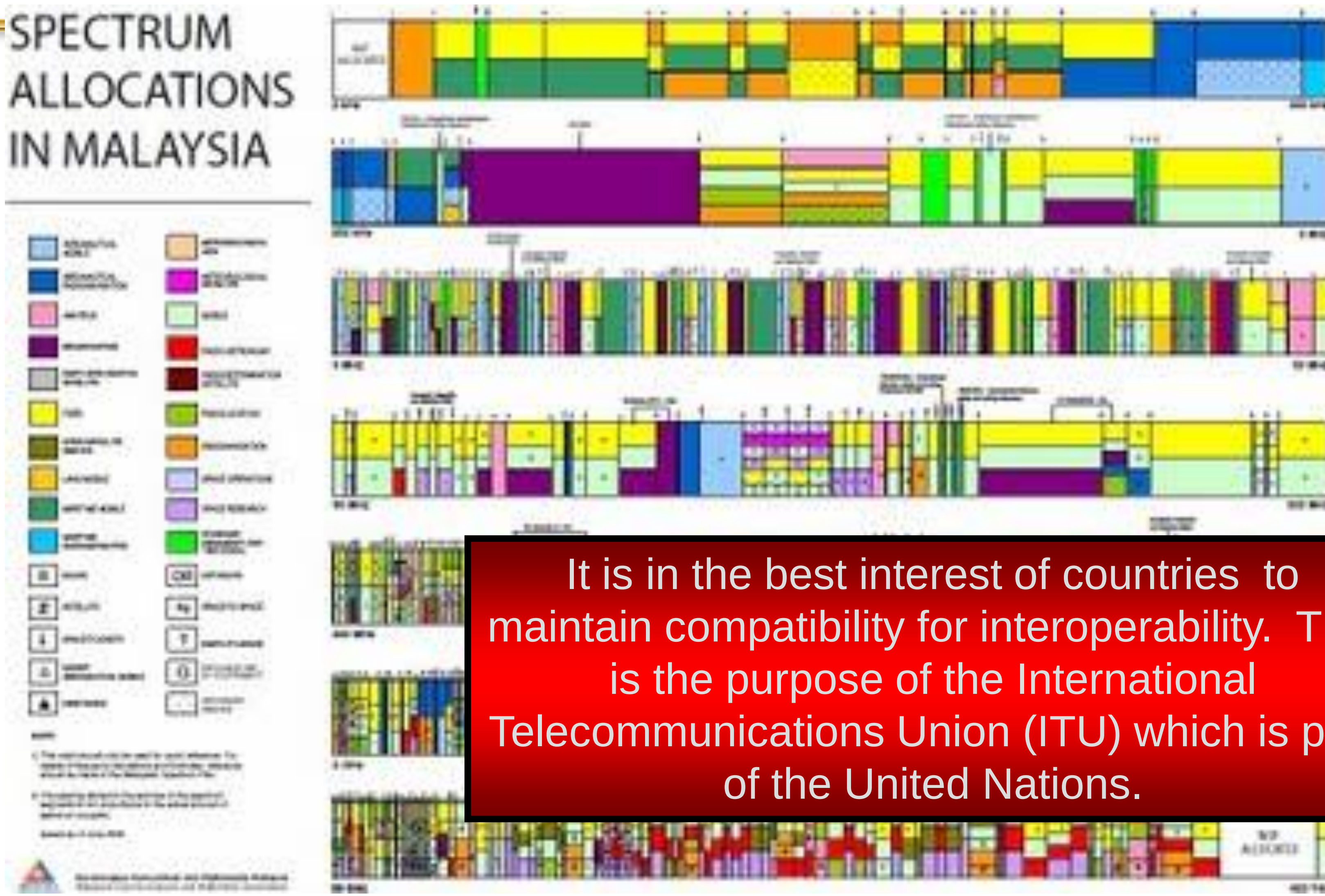

It is in the best interest of countries to maintain compatibility for interoperability. This is the purpose of the International Telecommunications Union (ITU) which is part of the United Nations.

Spectrum

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- All transmitters have to be registered.
- Receivers do not have to be registered.
- 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 according to the country's regulations that is transmitting over 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

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

Orbital Mechanics and Rocket Science

The keys to understanding space communication architectures

Circular Orbital Equation

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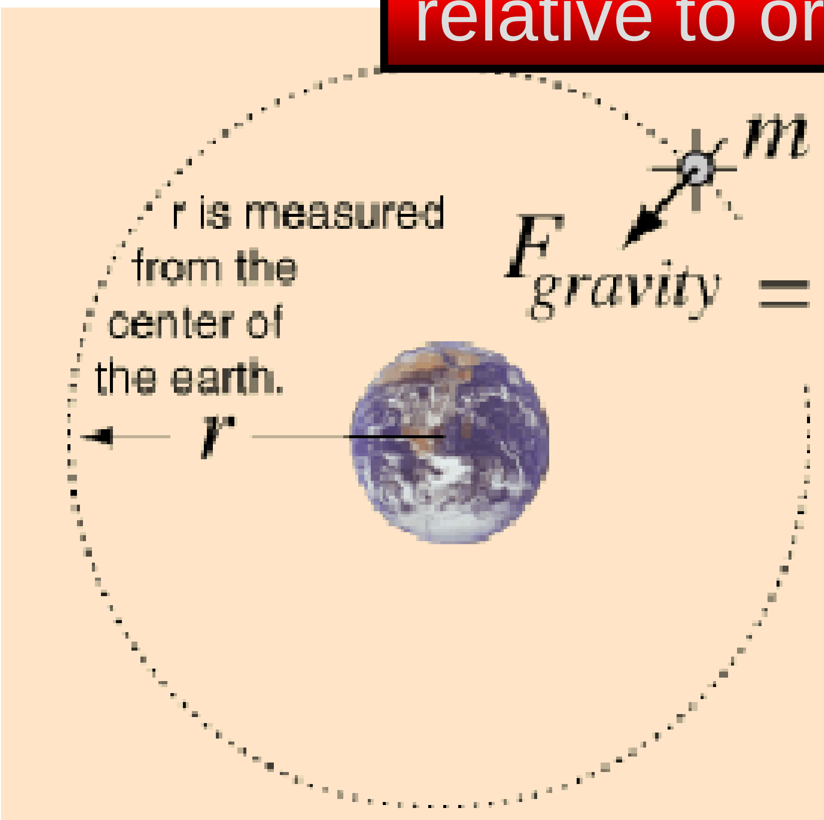
Space is very predictable relative to orbital dynamics.



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

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

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 transmitter power and larger antennas
to close the link (larger systems).

Basic Satellite Architectures

Often Highly Asymmetric Links

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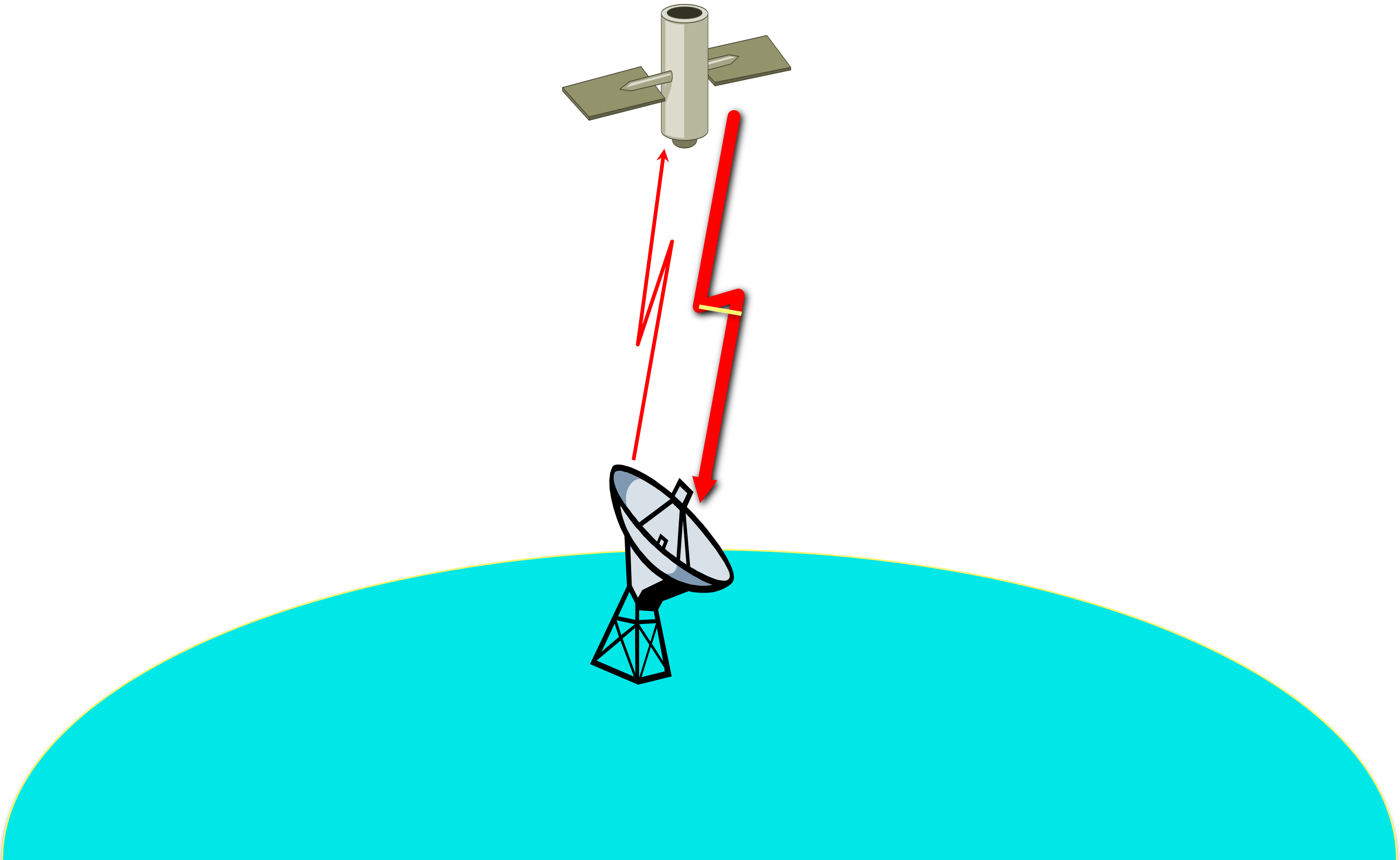

Polar Orbit

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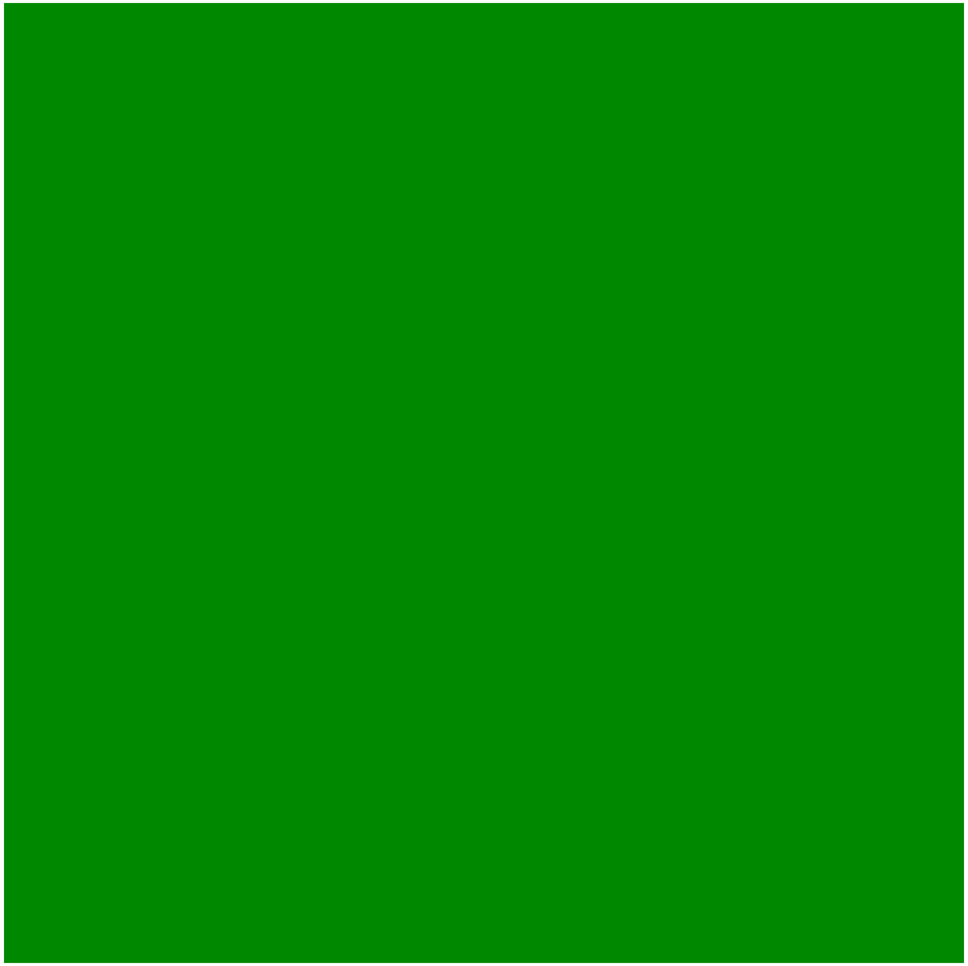

Source: http://commons.wikimedia.org/ via youtube

Low Earth Orbit (LEO) Only

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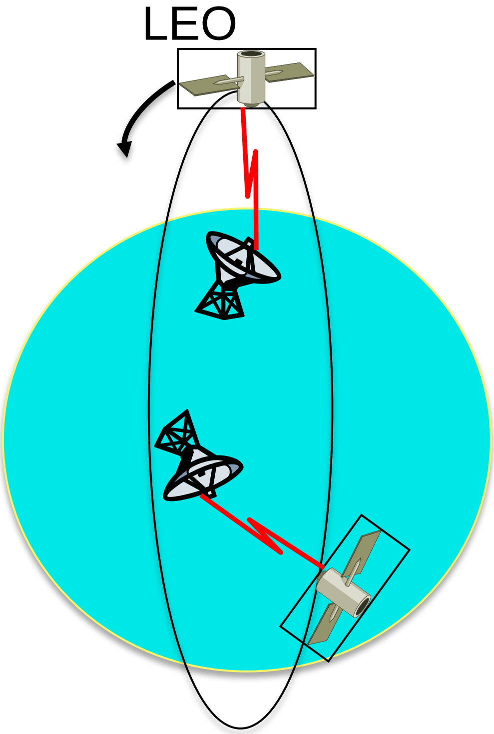
- LEO orbit are below the Earth's ***radiation belts***, which allows for use low-cost Commercial-Off-The-Shelf (COTS) components.
- Radiation still must be considered – depending on the duration of flight.



LEO via Geostationary Orbit (GEO)

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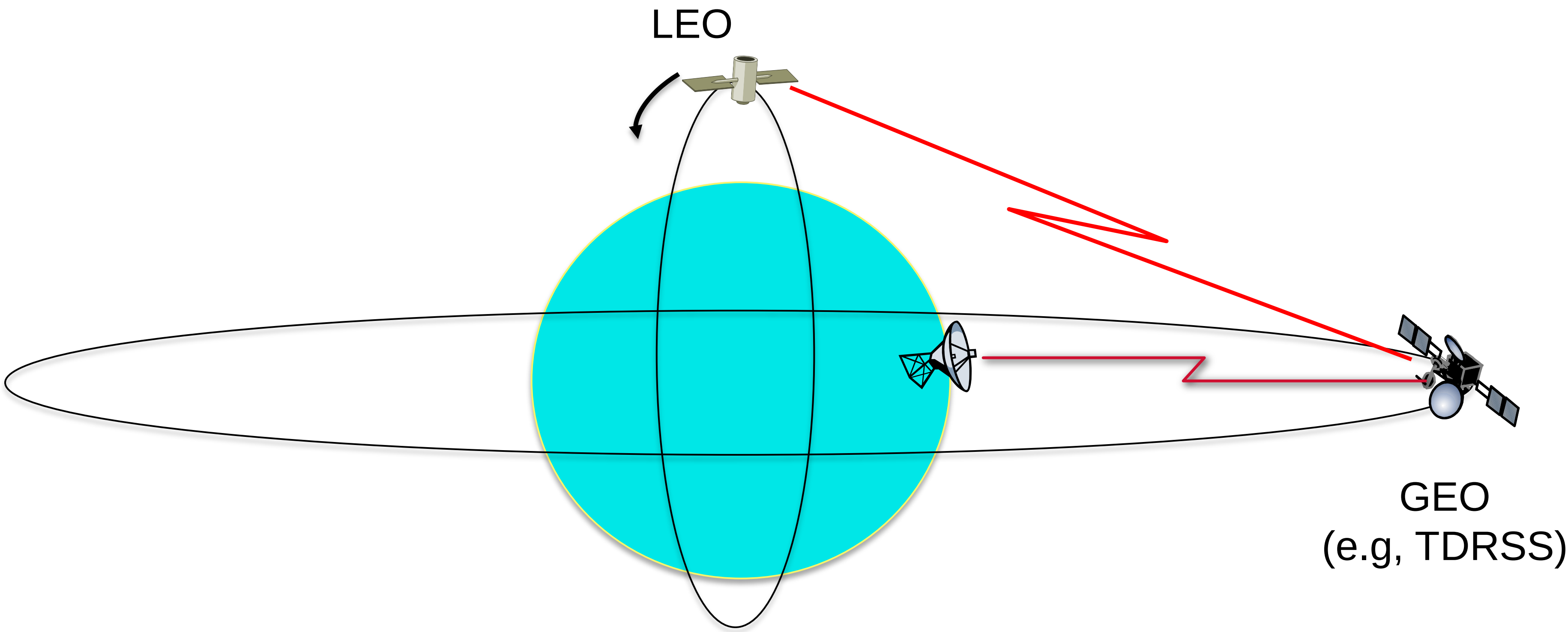

LEO and GEO

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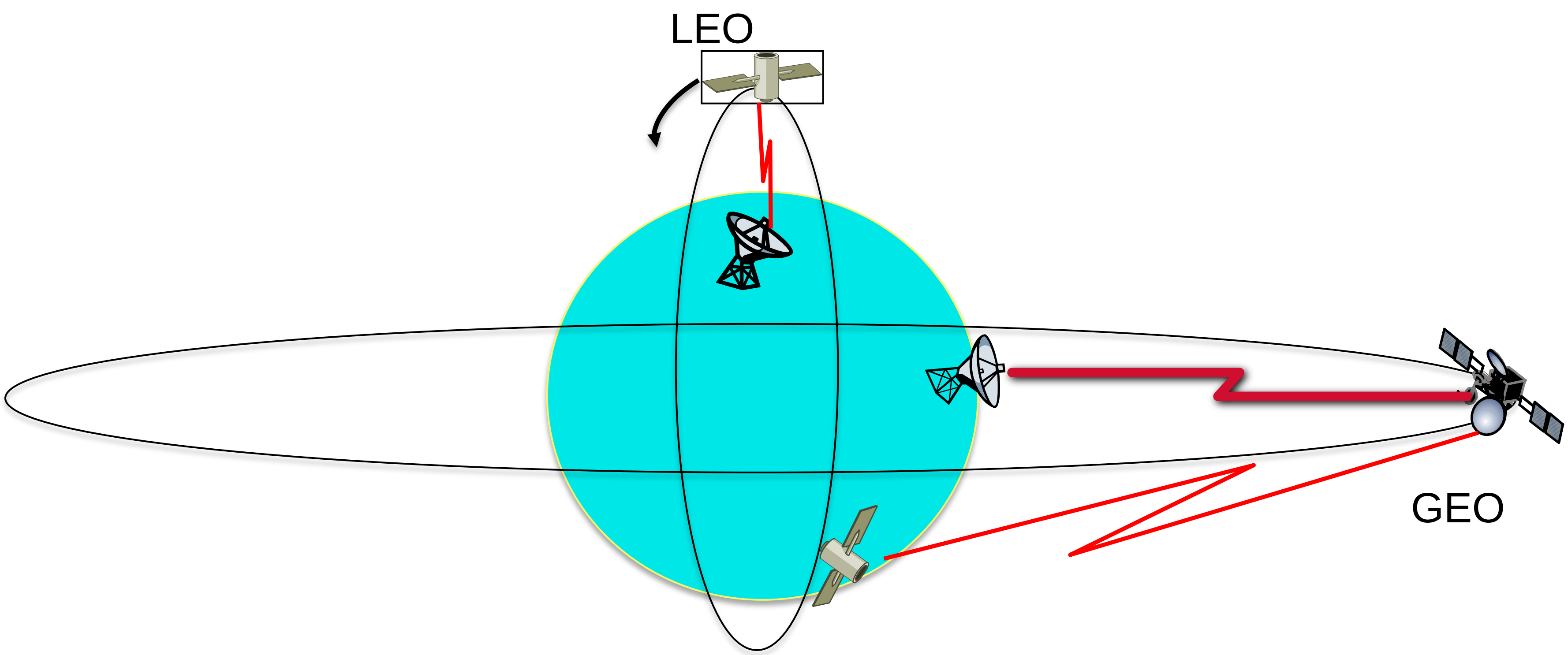

Teledesic – 840 Communication Satellites in original plan

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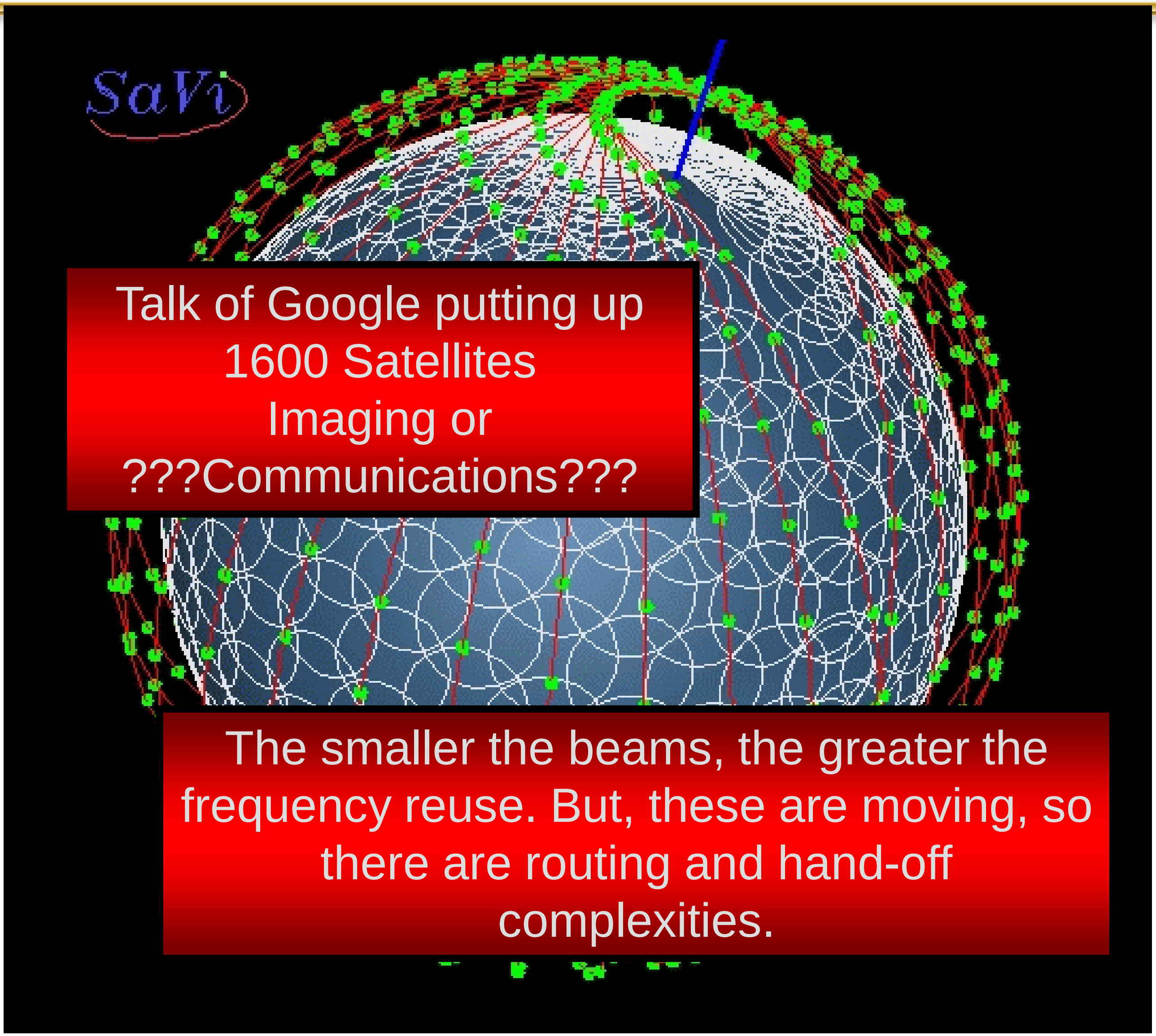

Talk of Google putting up 1600 Satellites
Imaging or
???Communications???

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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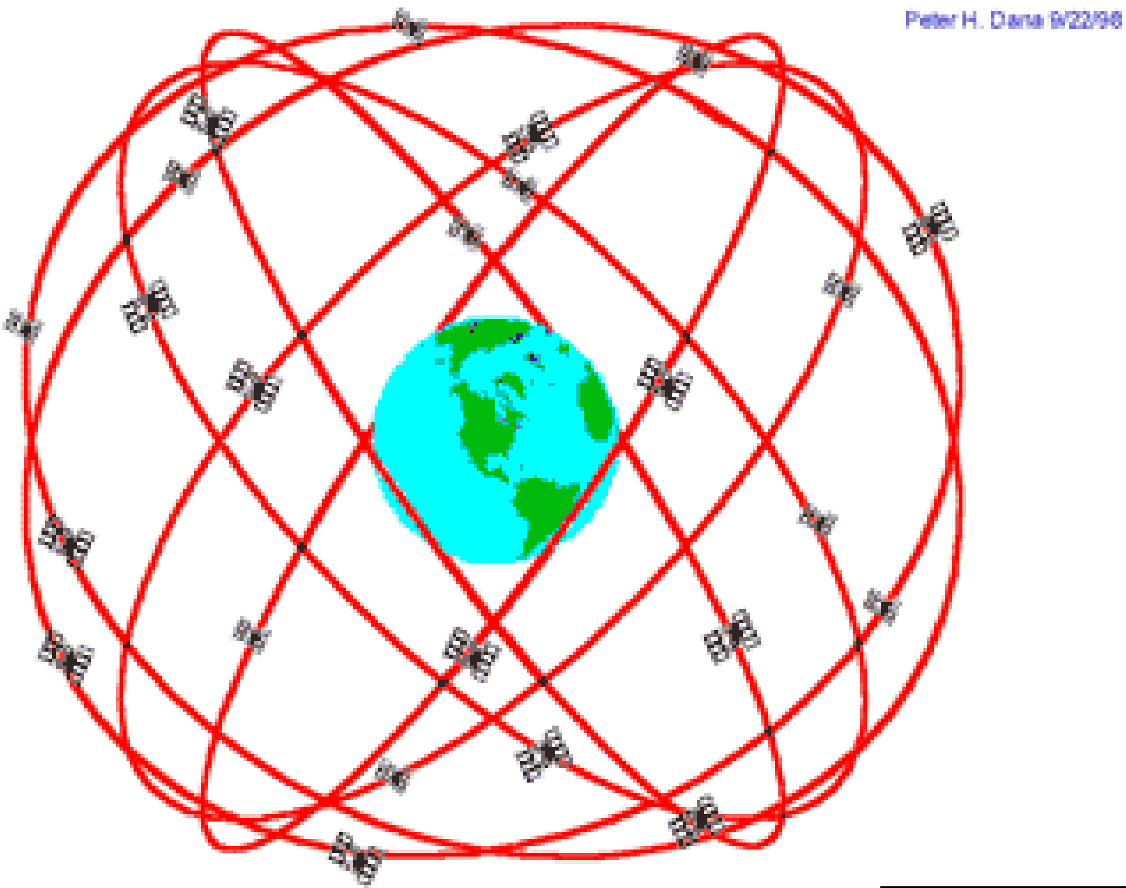

GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

GPS is in a much higher orbit than LEO.

Stationary LEO!

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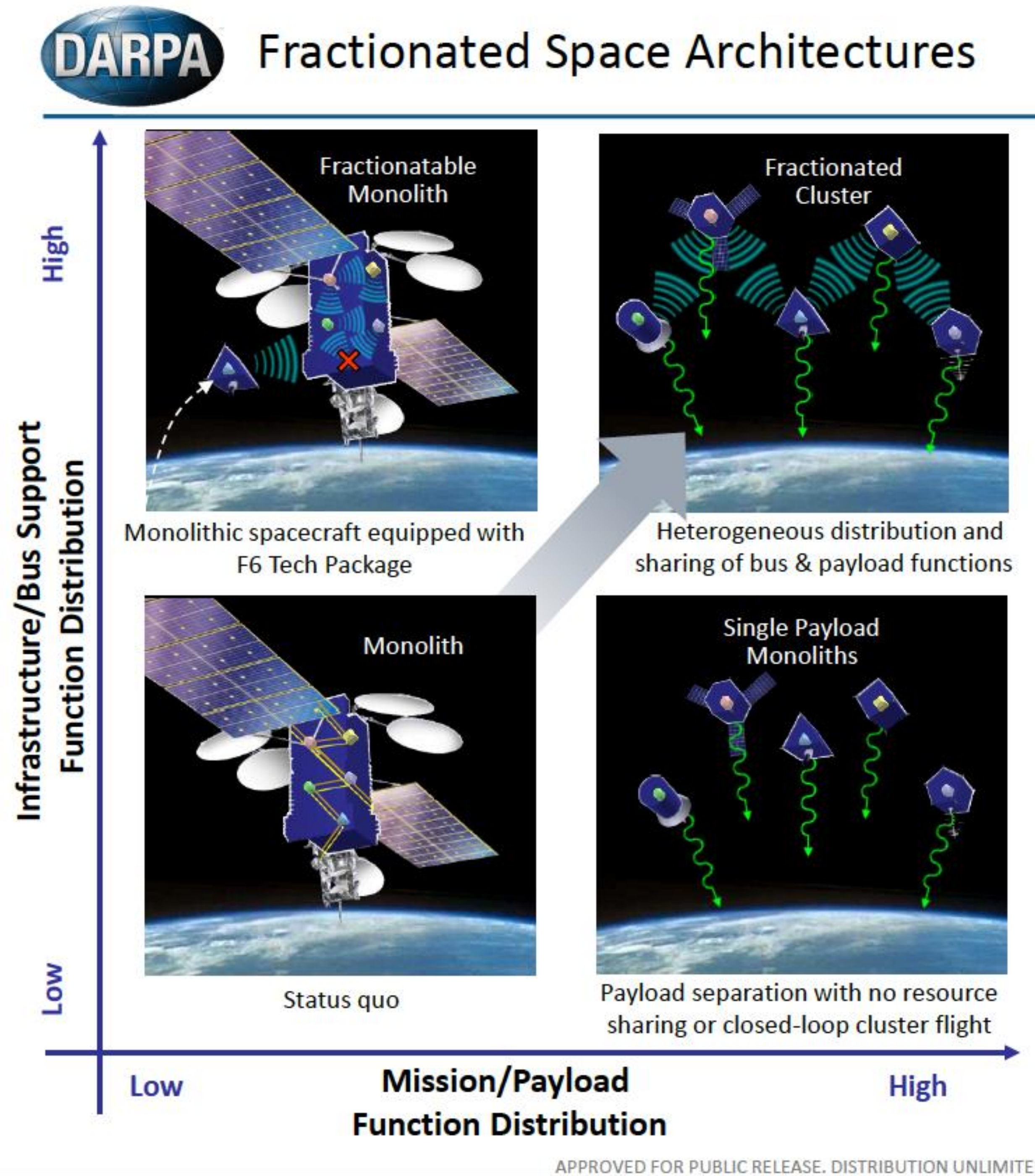
DARPA F6

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

Fractionated Spacecraft



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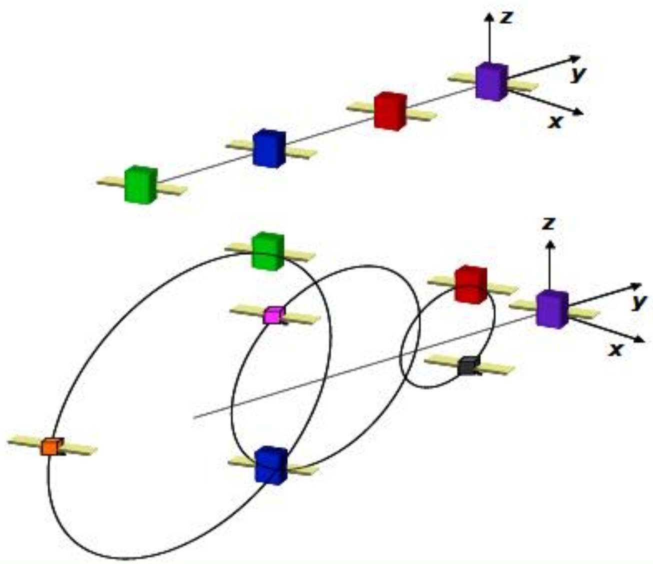
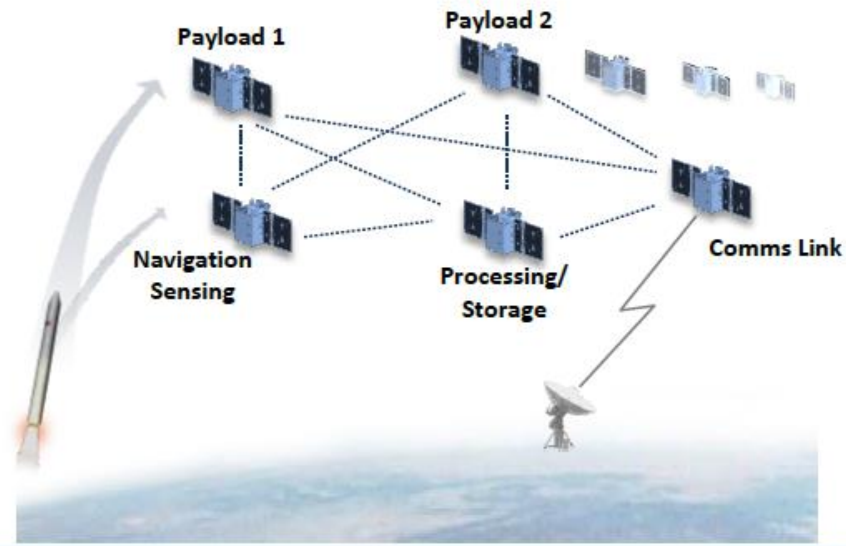
Enables

- Resource Sharing
    - Power
    - Telecommunication
    - Processing
- Redundancy
- Rapid cluster maneuvering
- Multiple Vendors
- Multi-level Security
- Security Isolation
- Stabilization Isolation (i.e., telescope)
- Build as you go
    - Everything does not have to be ready at the same time

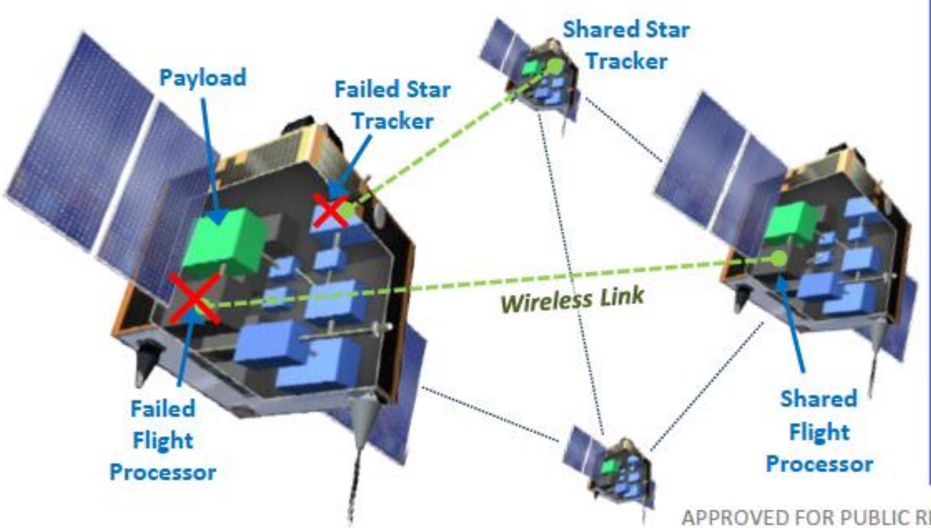
Key Capabilities for 2015 On-Orbit Demonstration



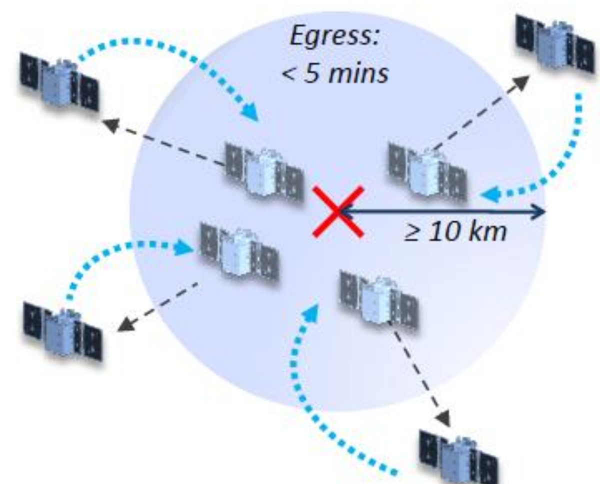
Demo 2: Resource Sharing at Multiple Security Levels



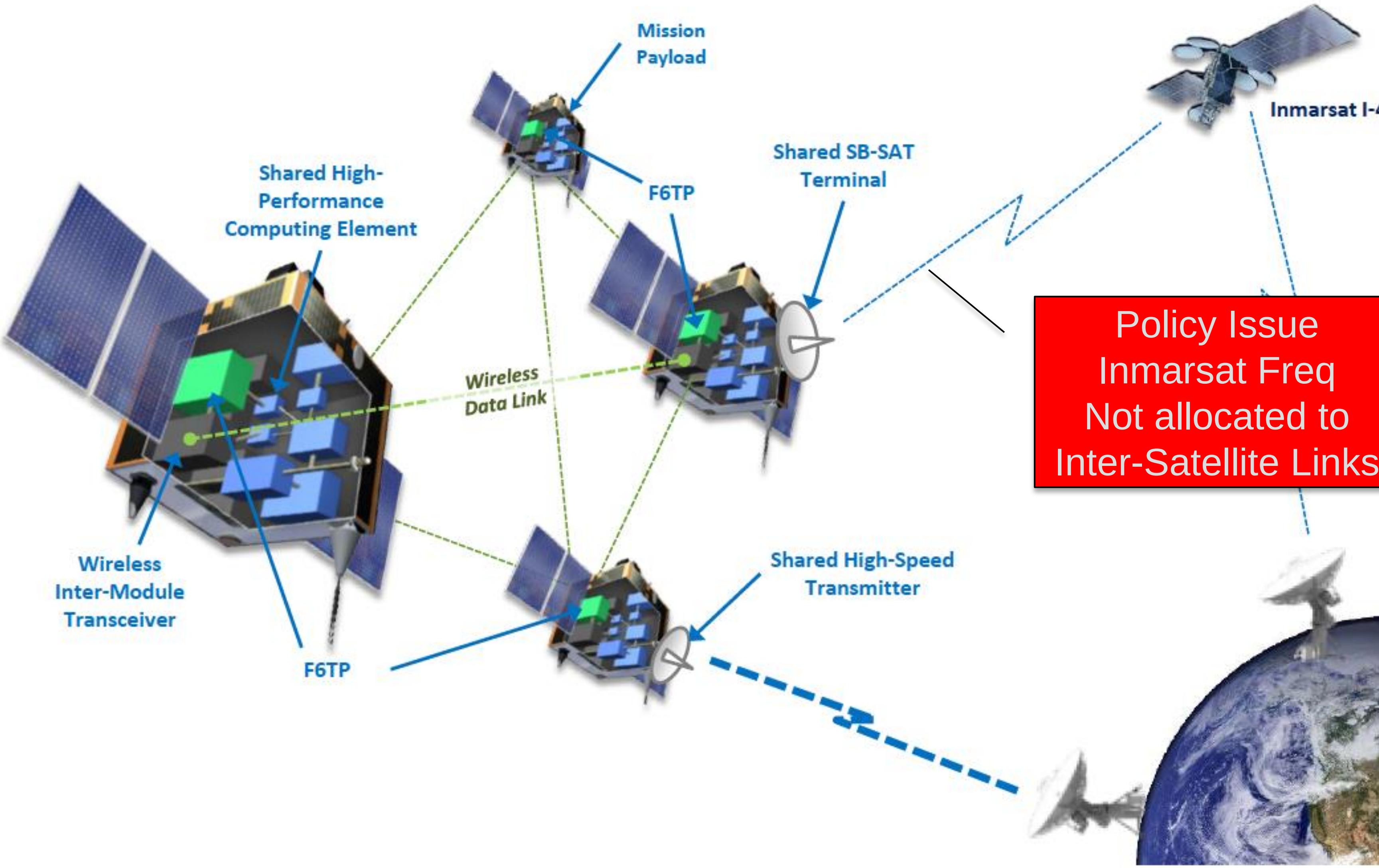
Demo 3: Cluster-Level Fault Tolerance



Demo 4: Defensive Scatter and Re-Gather



Notional System F6 On-Orbit Demo



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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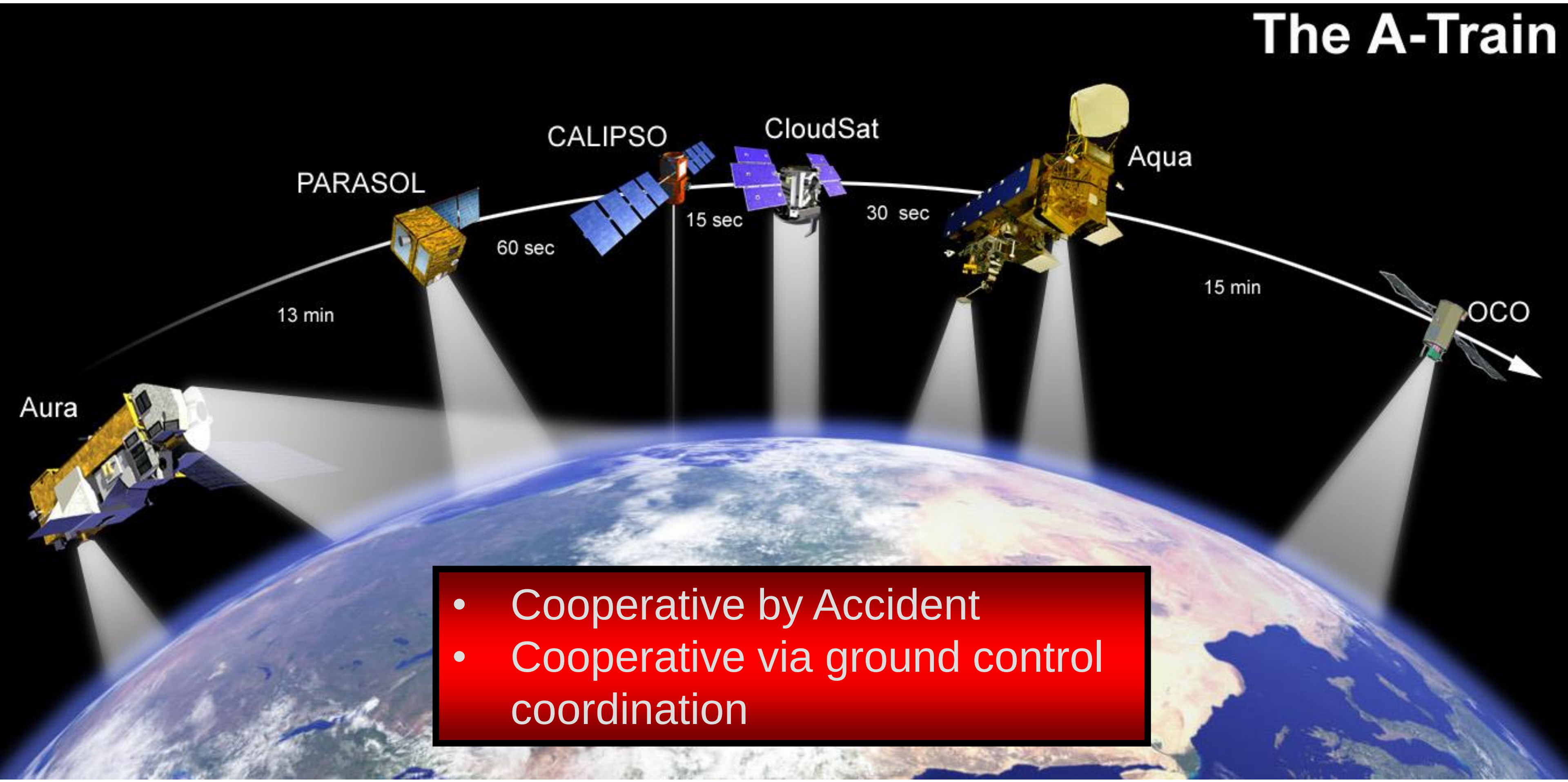
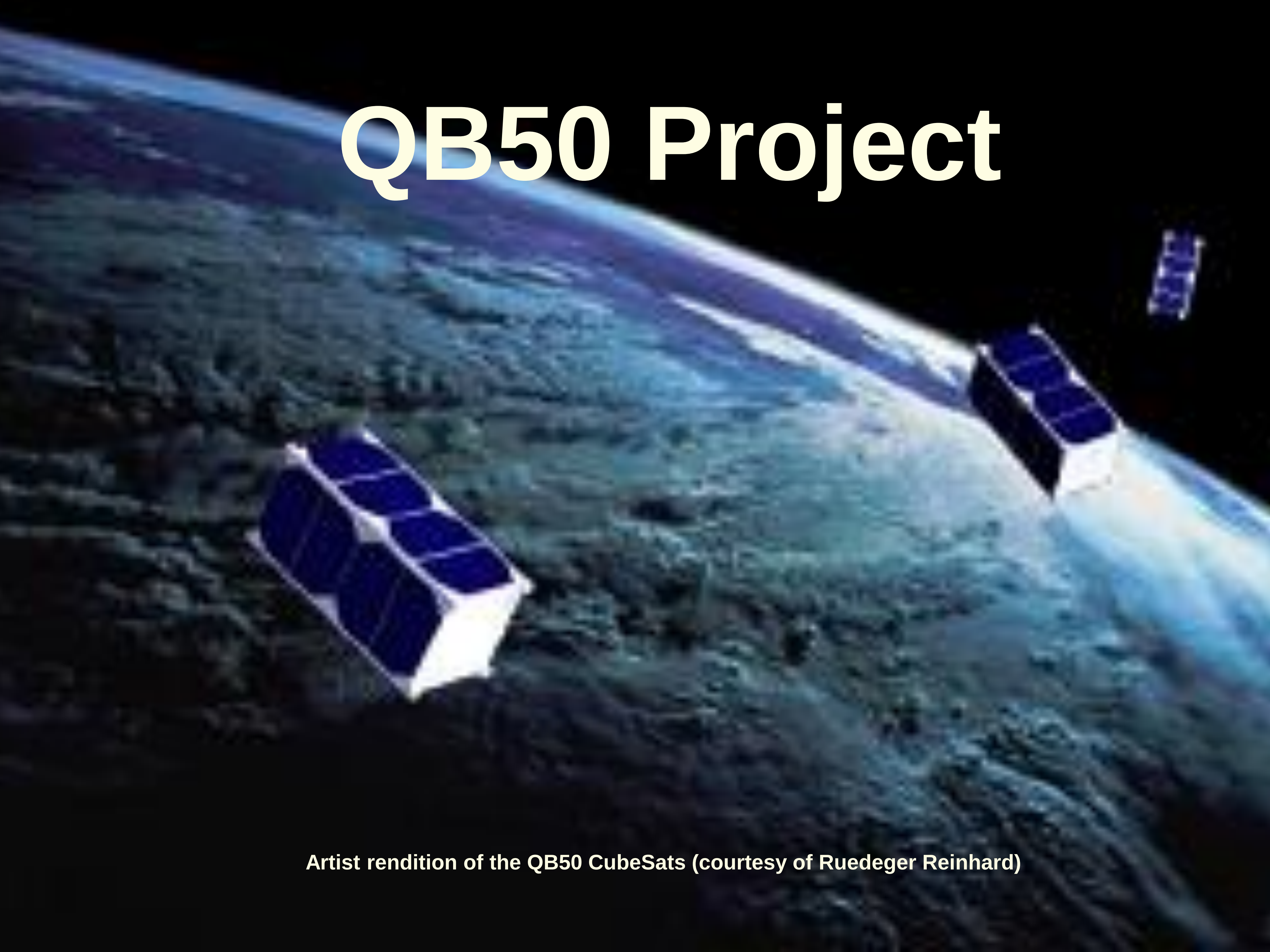


- Cooperative by Accident
- Cooperative via ground control coordination

QB50 Project



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

QB50

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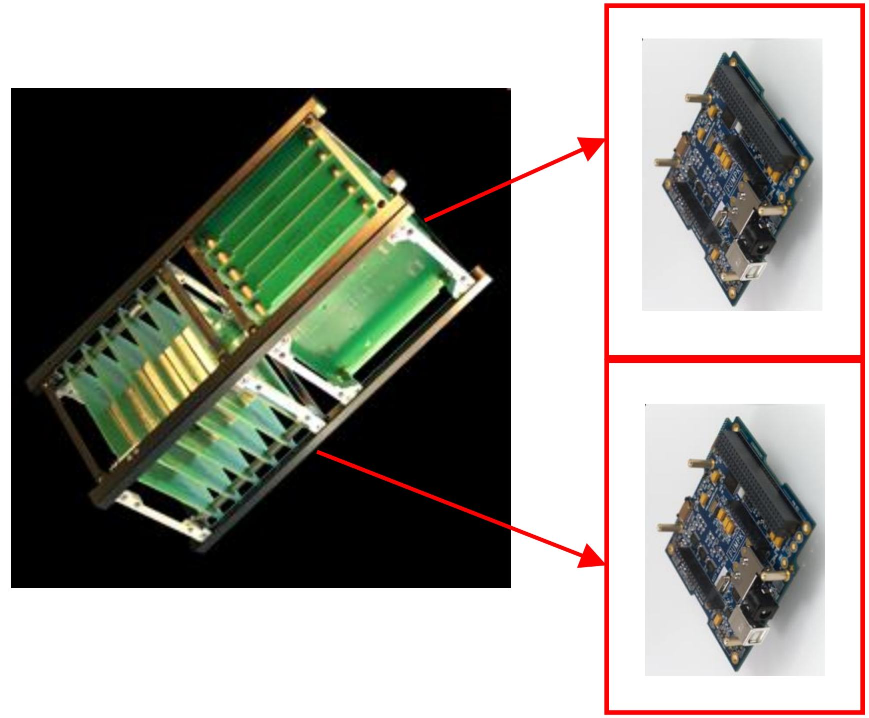
- An international network of 50 CubeSats sequentially deployed – String of Pearls
- Science: Multi-point in-situ long-duration measurements and in-orbit demonstrations in the lower thermosphere
- Initial altitude: 350 km (circular orbit, high inclination)
- Downlink using the QB50 Network of Ground Stations
- On QB50, the CubeSats are the primary payload. On all other missions CubeSats have been secondary payloads.
- Launch scheduled for January 2016

Science Unit



Functional Unit

Power

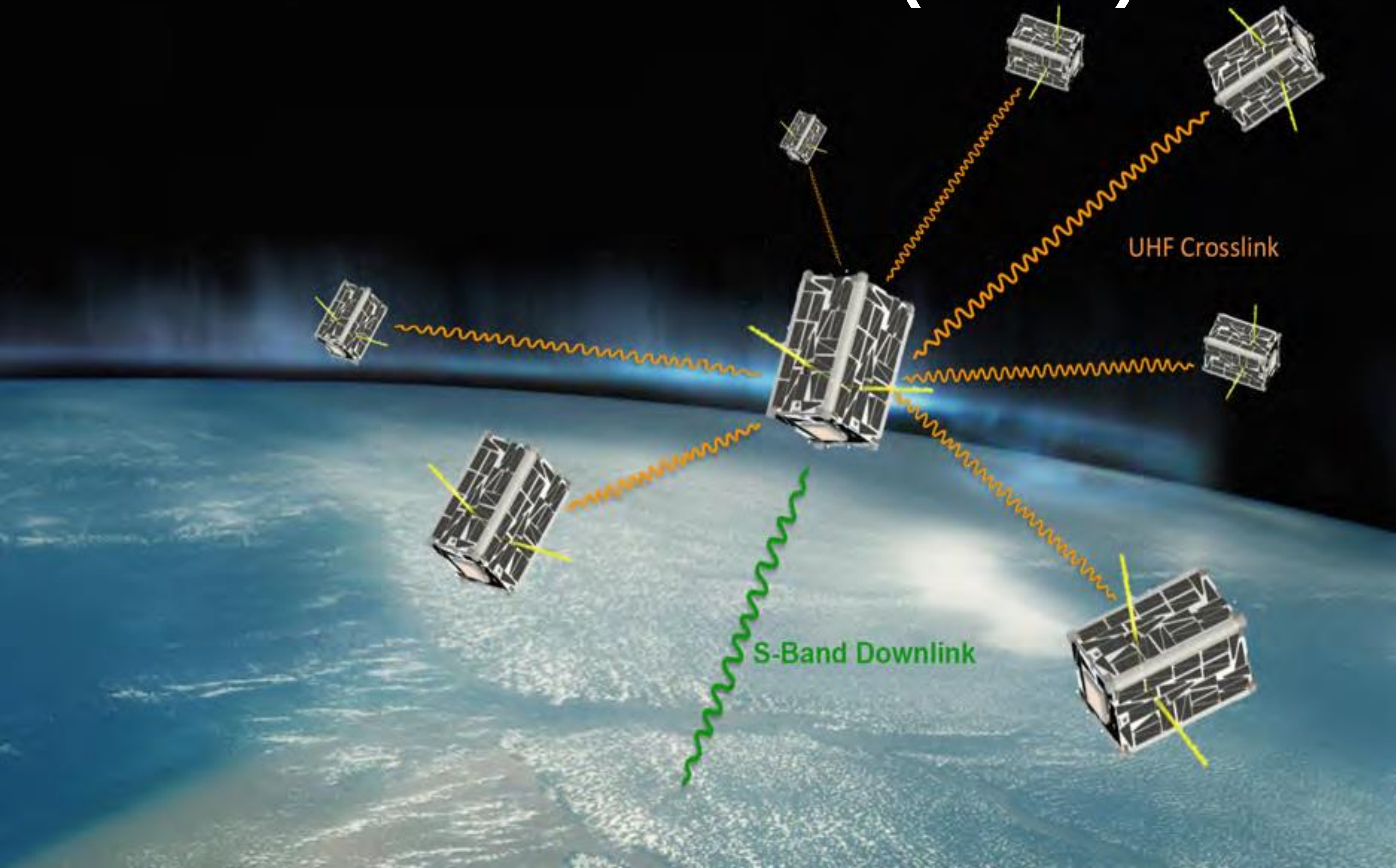
Telecommunications

Tech Demonstrations

www.QB50.eu

von Karman Institute for Fluid Dynamics

NASA’s Edison Demonstration of Smallsat Networks (EDSN)



EDSN

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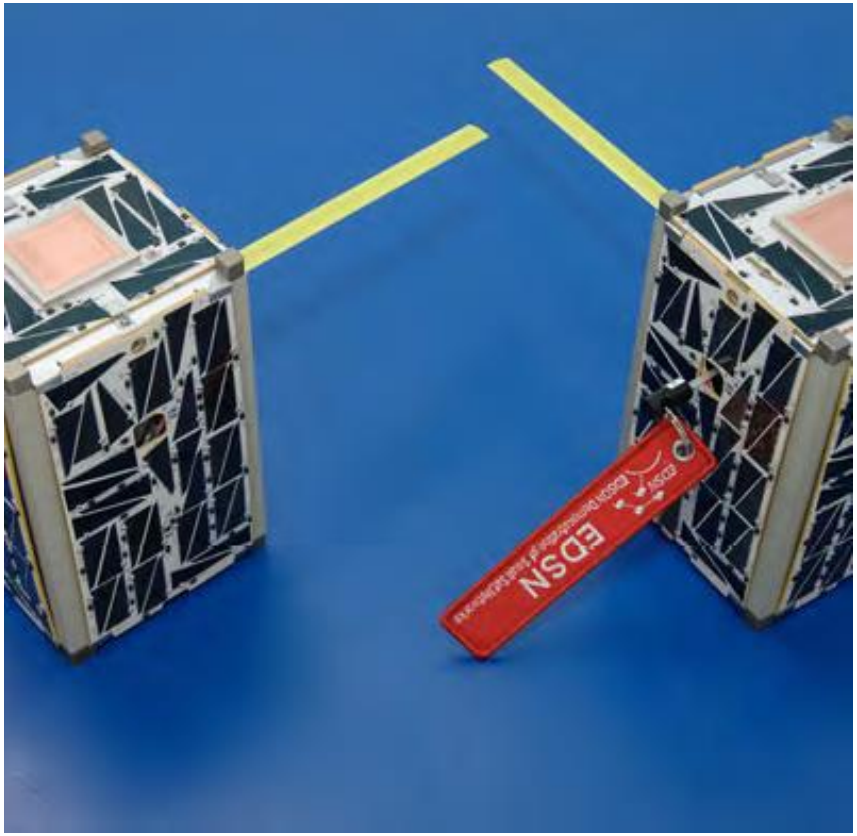
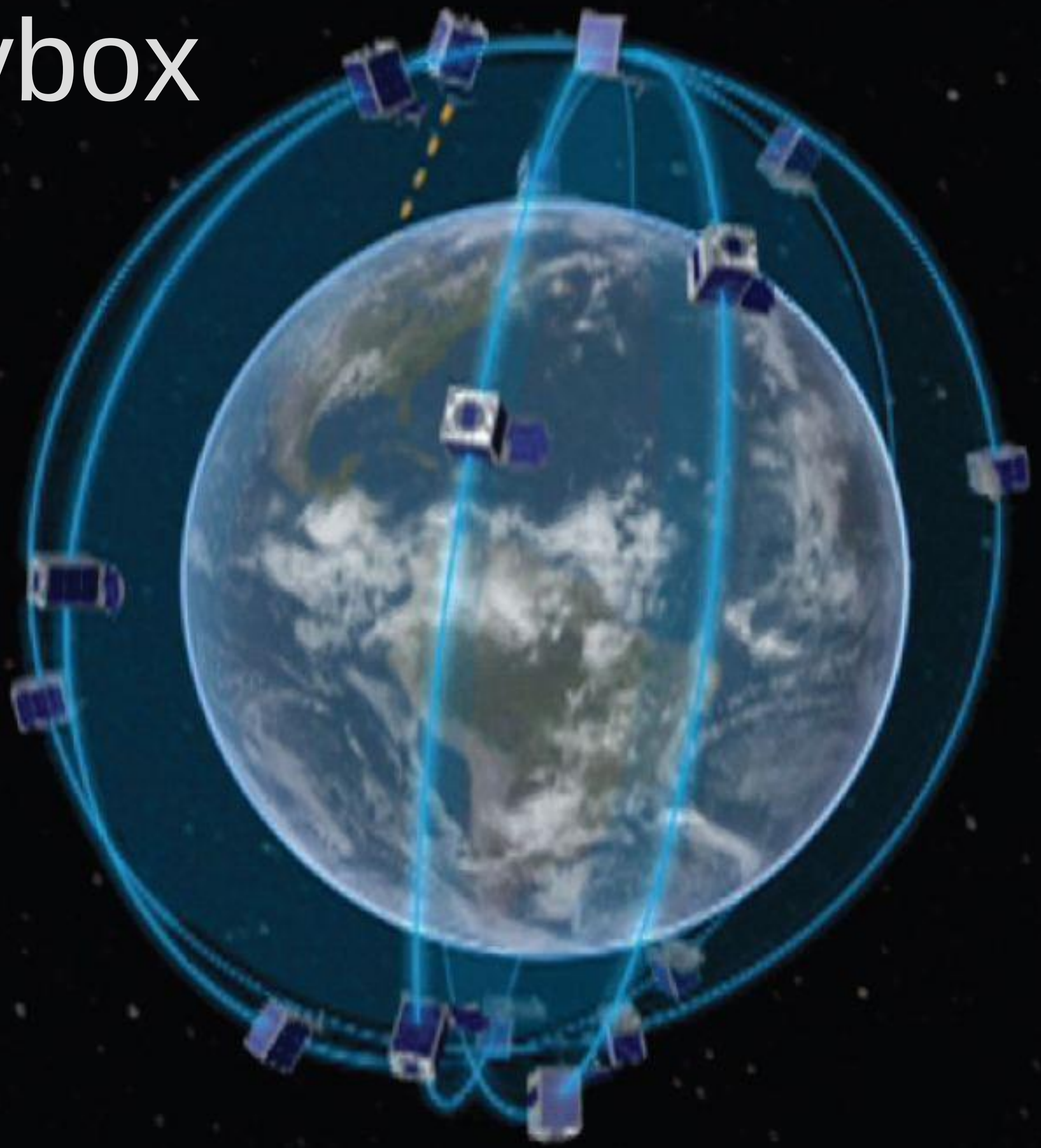
Enable Cross-Link Communication and Multipoint Physics

- **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.**
- **Science is to make distributed, multipoint space radiation measurements.**
- **Demonstrate advanced communications, including a network that allows for data to be sent between satellites as needed.**
- **Launch date, end or 2014**

Completed EDSN Spacecraft



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
- Uplink Feed S-band, 2025-2110 MHz
- Satellite revisit rates of five to 10 times per day
  - Critical to applications such as change detection
- 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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Planet Lab "Dove" CubeSat

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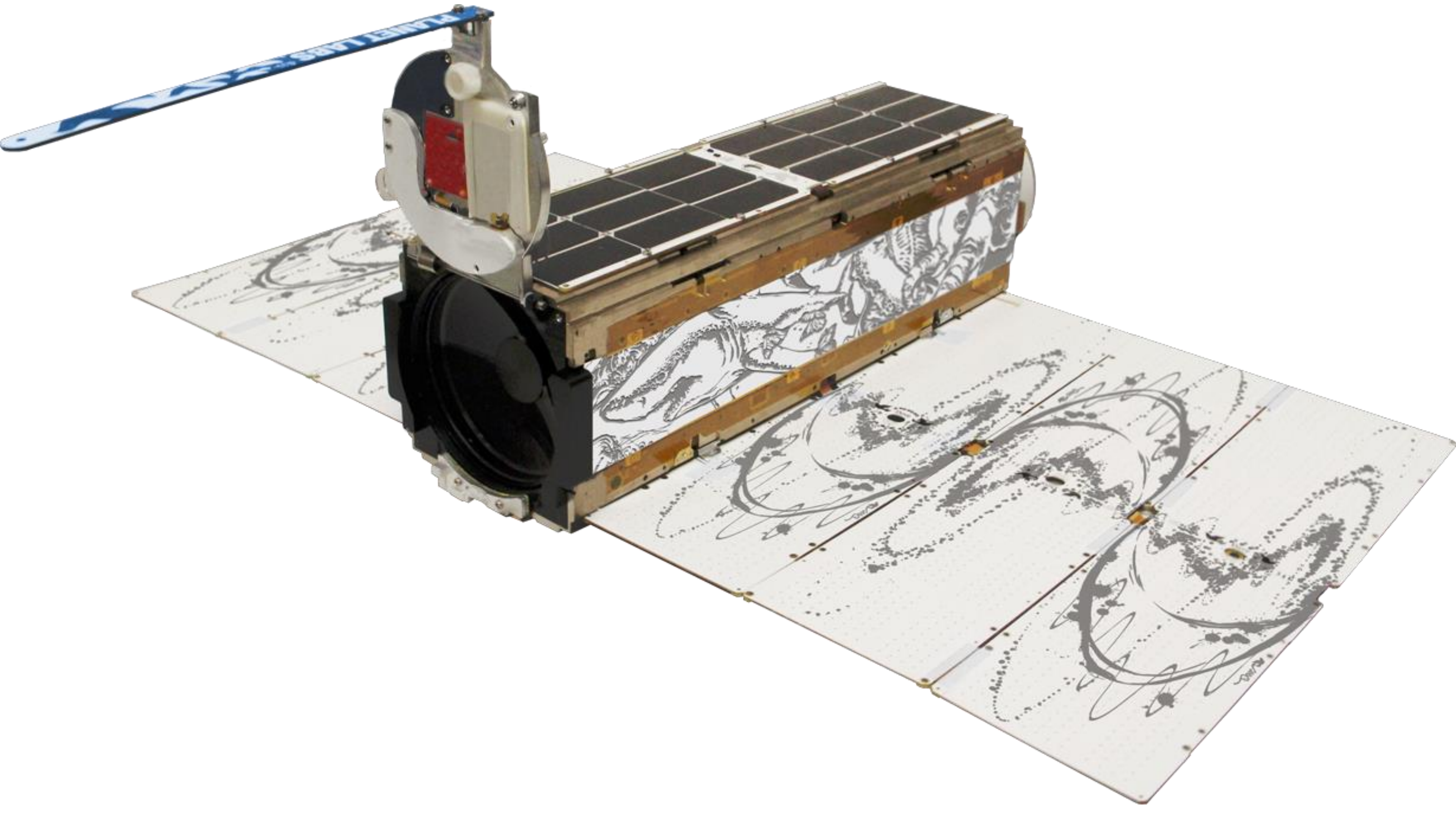

Planet Lab

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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
- Dove 2 Communications
  - UHF
  - MHX-2400 (2.4-2.5 GHz ISM band) Spread Spectrum used 21 meter dish (poor link quality)
  - X-Band Radio DVB-S2 format used 6 meter dish (good link)
- Currently launches from the International Space Station
- Fresh data from any place on Earth
- Business Case: Global sensing and analytics

6 Meter Dish

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RapidEye

(by BlackBridge merged GeoEye and DigitalGlobe)

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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.**
  - **GeoEye-1 acquires 50 cm TRUE* panchromatic and 2.0 meter multispectral 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.**
  - **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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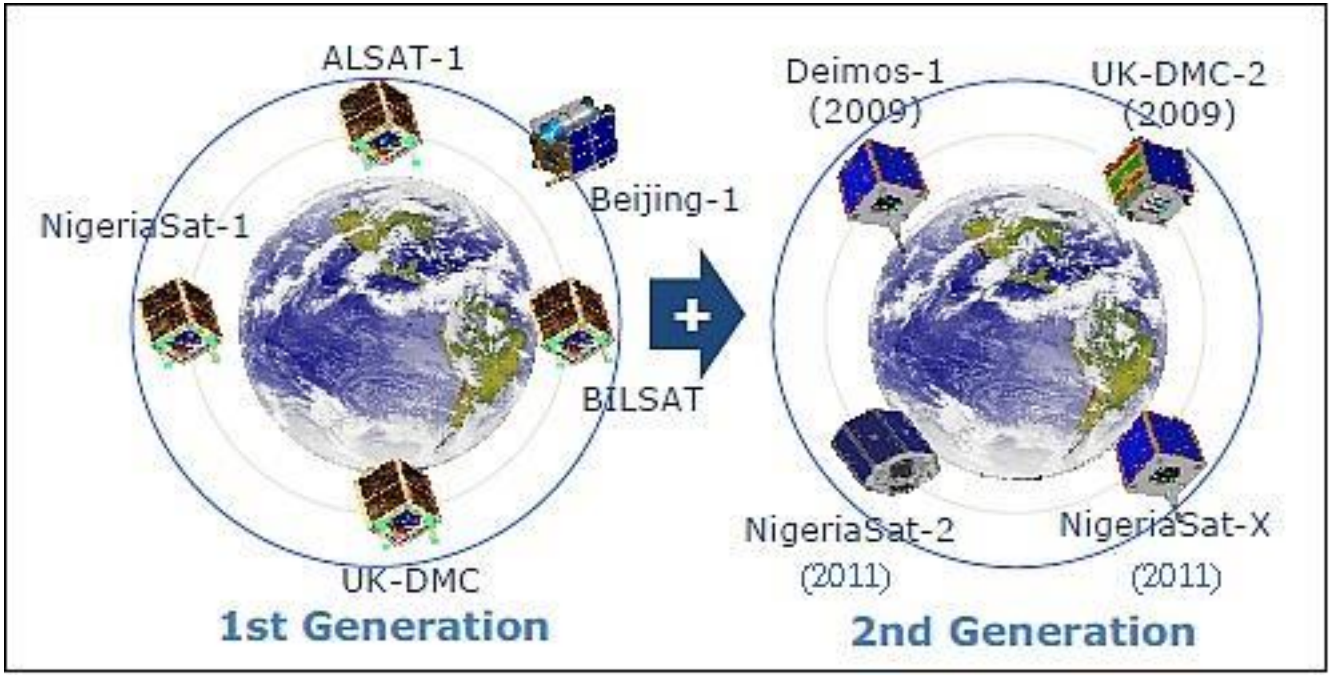

The sun-synchronous orbits of these satellites are coordinated so that the satellites follow each other around an orbital plane, ascending north over the Equator at 10:15 am local time (and 10:30 am local time for Beijing-1).

Virtual Mission Operations Center

http://roland.grc.nasa.gov/~ivancic/papers_presentations/papers.html

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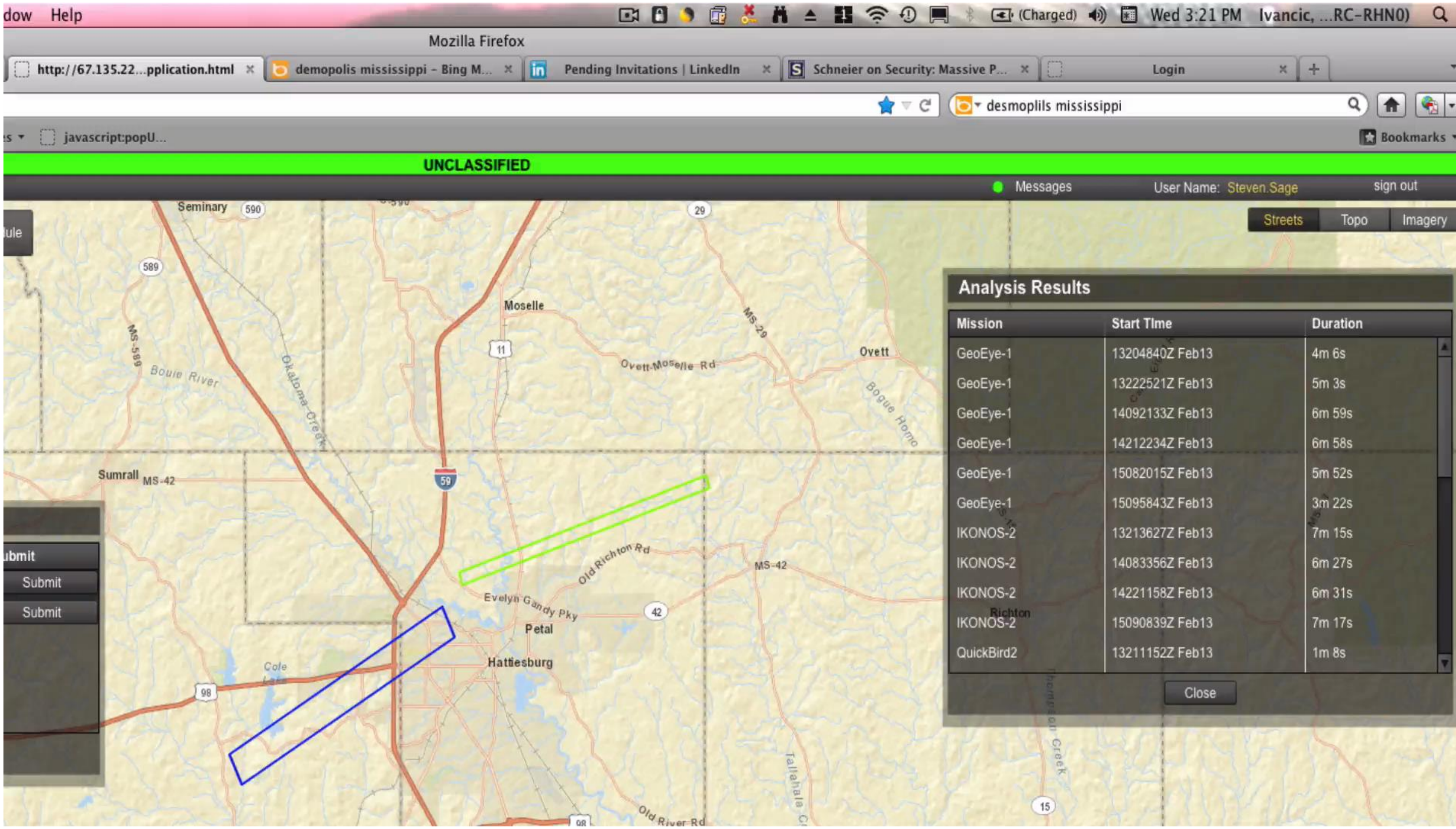

Protocols

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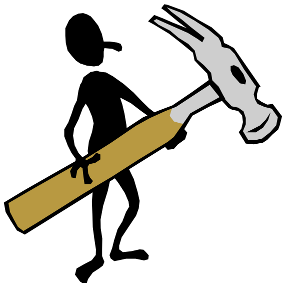
Protocols are tools for communication

Some should not be used.



Some work OK

Some are designed for the job at hand

One size does not fit all.

Reliable, High-Rate Transport Protocols for Highly Asymmetric Private Links

Theoretical Steady State Throughput

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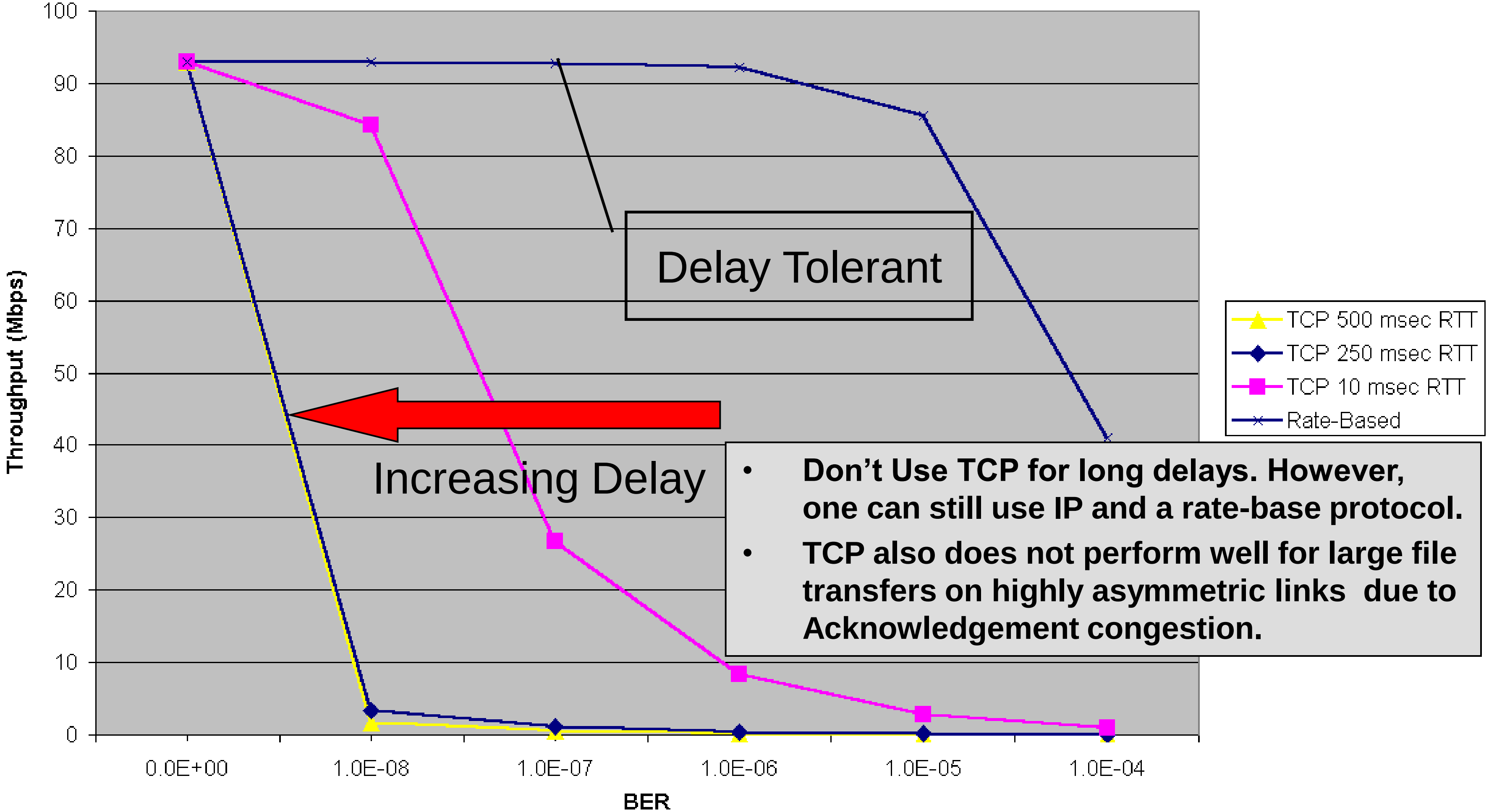
LEO satellites do not have long propogation delay, but do have high asymmetry



- **Don’t Use TCP for long delays. However, one can still use IP and a rate-base protocol.**
- **TCP also does not perform well for large file transfers on highly asymmetric links due to Acknowledgement congestion.**

DTN Layering (RFC 5050)

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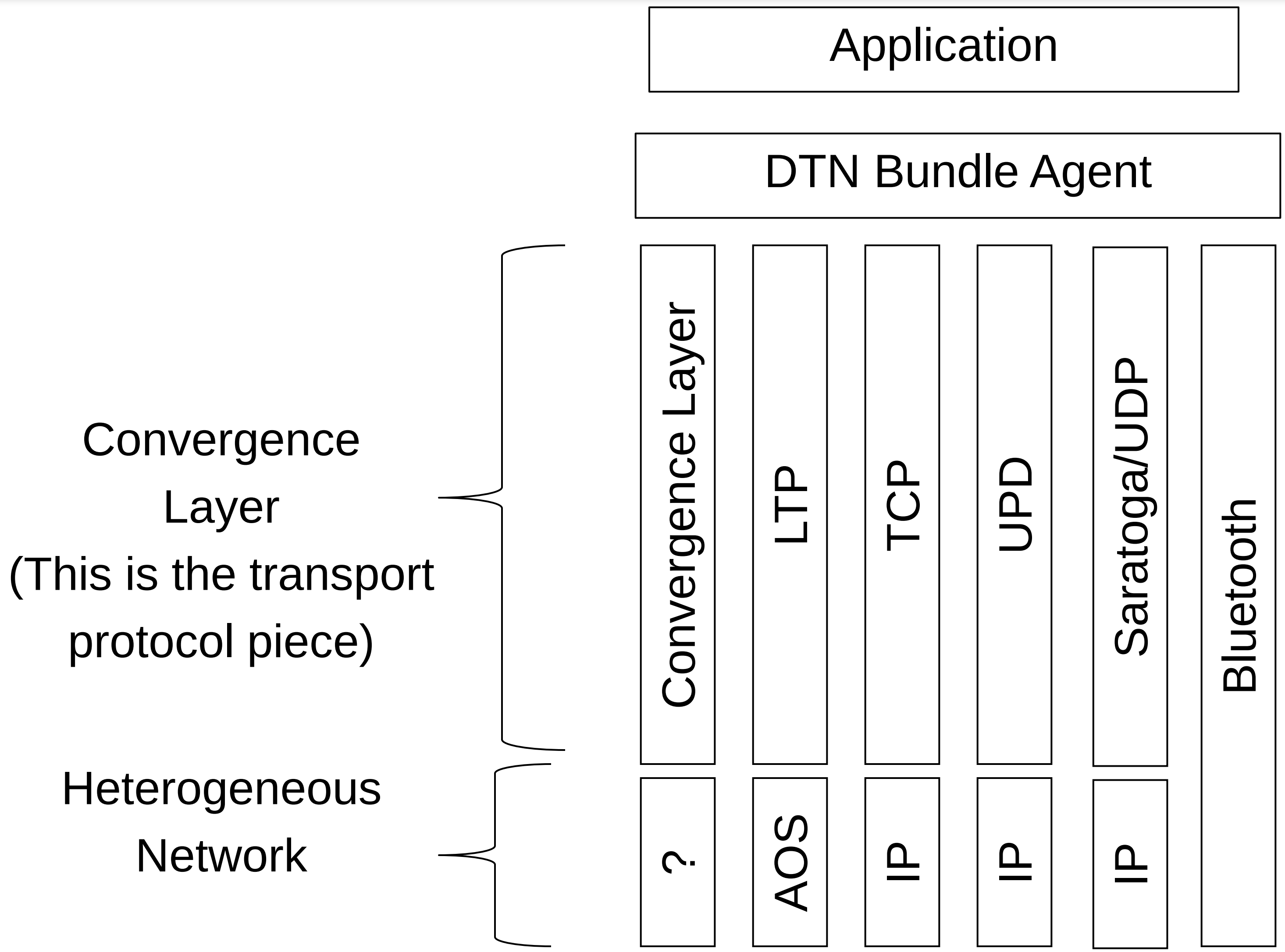

"PROTOCOLS FOR STORE-AND-FORWARD MESSAGE SWITCHING VIA MICROSATELLITES"

J. W. Ward and H. E. Price - 1991

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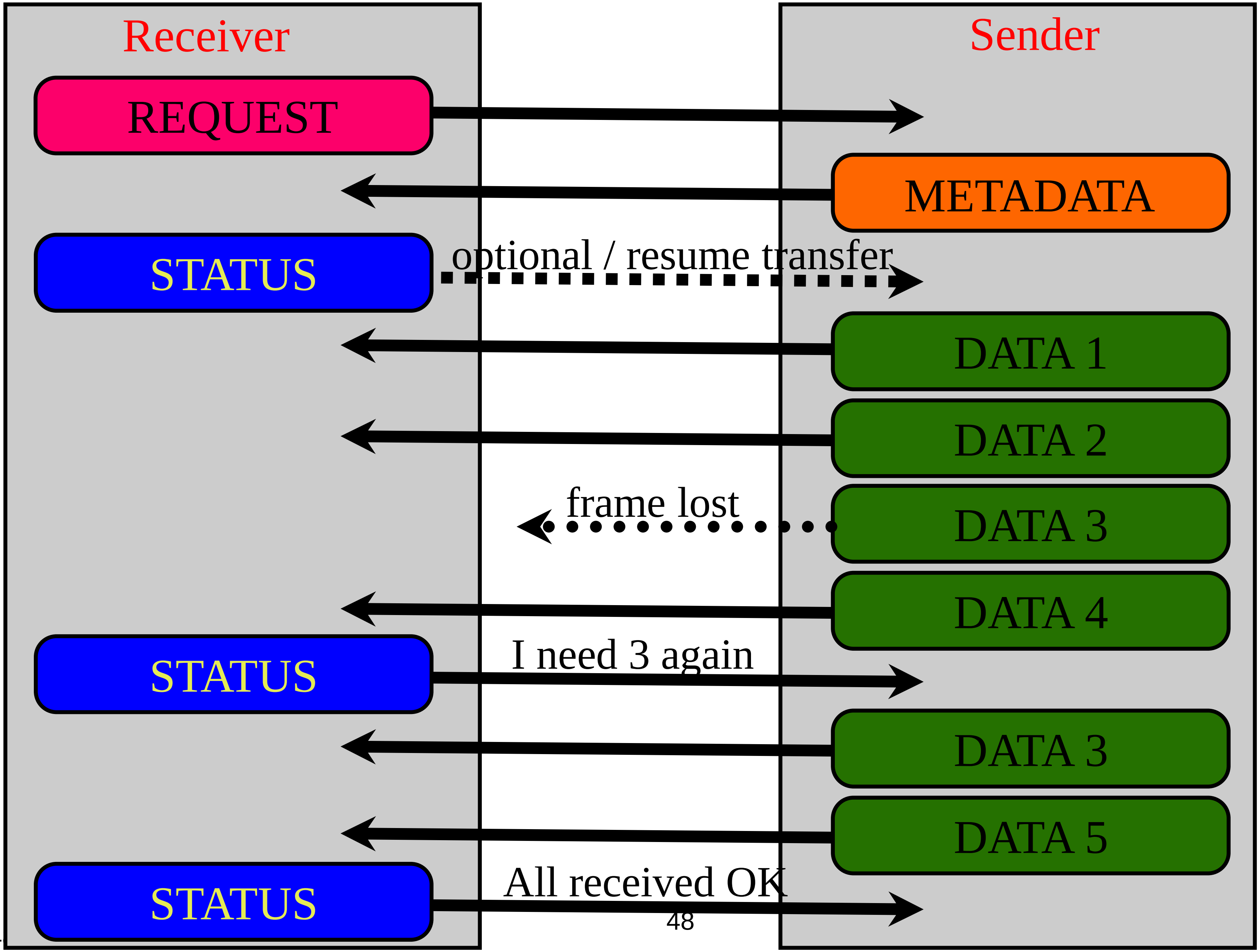
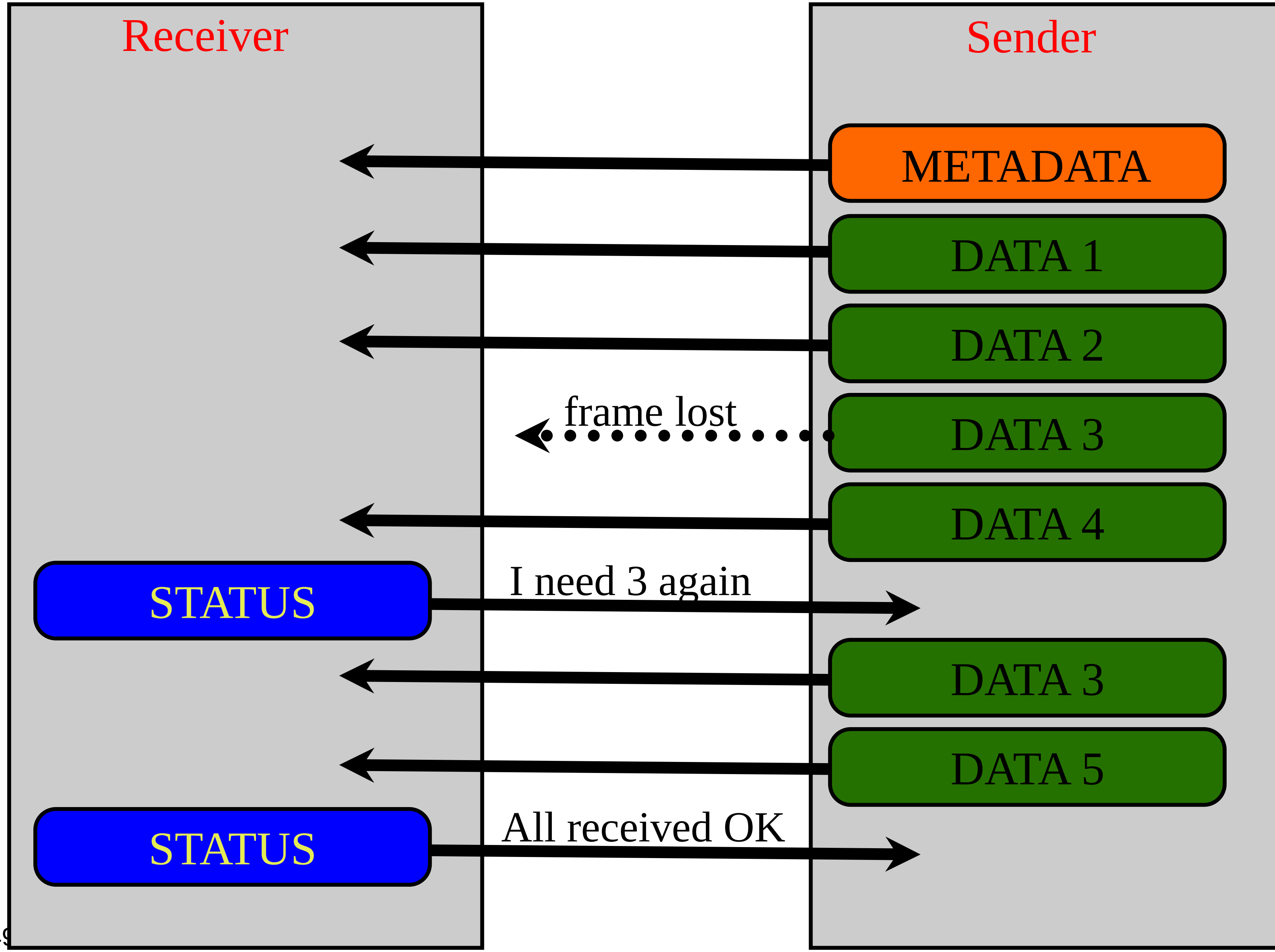
- **A suite of protocols specifically optimized for use on store-and-forward microsatellite communications missions.**
- **Design the spacecraft software so that there was one generic data entity that it knows how to deal with and deal with well**
- **Leave all routing decisions to the ground segment.**
- **A client identifies a message which it requires and sends a broadcast request to the server.**
- **The client will receive some or all of the datagrams from its request. Upon receiving these (or other) datagrams, the client places them at the indicated byte offset in the appropriate file.**
- **When a client wishes to have the server retransmit missing datagrams, the client composes and transmits a repeat request datagram. If some of the desired datagrams are not received, then the client sends the request again.**
- **The client repeats this process until the message is complete.**

Generic SNACK GET Concept



Generic SNACK PUT Concept



Selective, Negative Acknowledgment (SNACK) Protocols – not all inclusive

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Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol (CFDP) - CCSDS 727.0-B-2:

- Selective Negative Acknowledgement
- Designed for Space Applications (Highly Asymmetric Links, Suspend/Resume timers during known outages) **Highly stateful**
- Private Links (No Congestion Control)
- Designed for File Transfers (really an application and transport protocol)
- Reliable or Unreliable file transfer
- Routing Capabilities (Preconfigured Next Hop – Static Routing)

Licklider Transport Protocol (LTP)

- Based on CFDP
- Distinguishes between important and unimportant data
- Timers work together with communication schedules and can be suspended whenever a scheduled link outage occurs
- Needs to be informed about link layer availability, round-trip time and communication schedule, basically requiring a management information base, Thus**, Highly stateful**

Saratoga (used buy SSTL daily)

- Based on "Protocols For Store-and-forward Message Switching Via Microsatellites"
- CFDP proved overly complex
- High-speed, UDP-based, peer-to-peer protocol, providing error-free guaranteed delivery of files, or streaming of data.
- No specified timers means no timeouts, so Saratoga is ideal for very long propagation delay networks (such as deep space)
- Able to cope with high forward/back network asymmetry (>850:1)

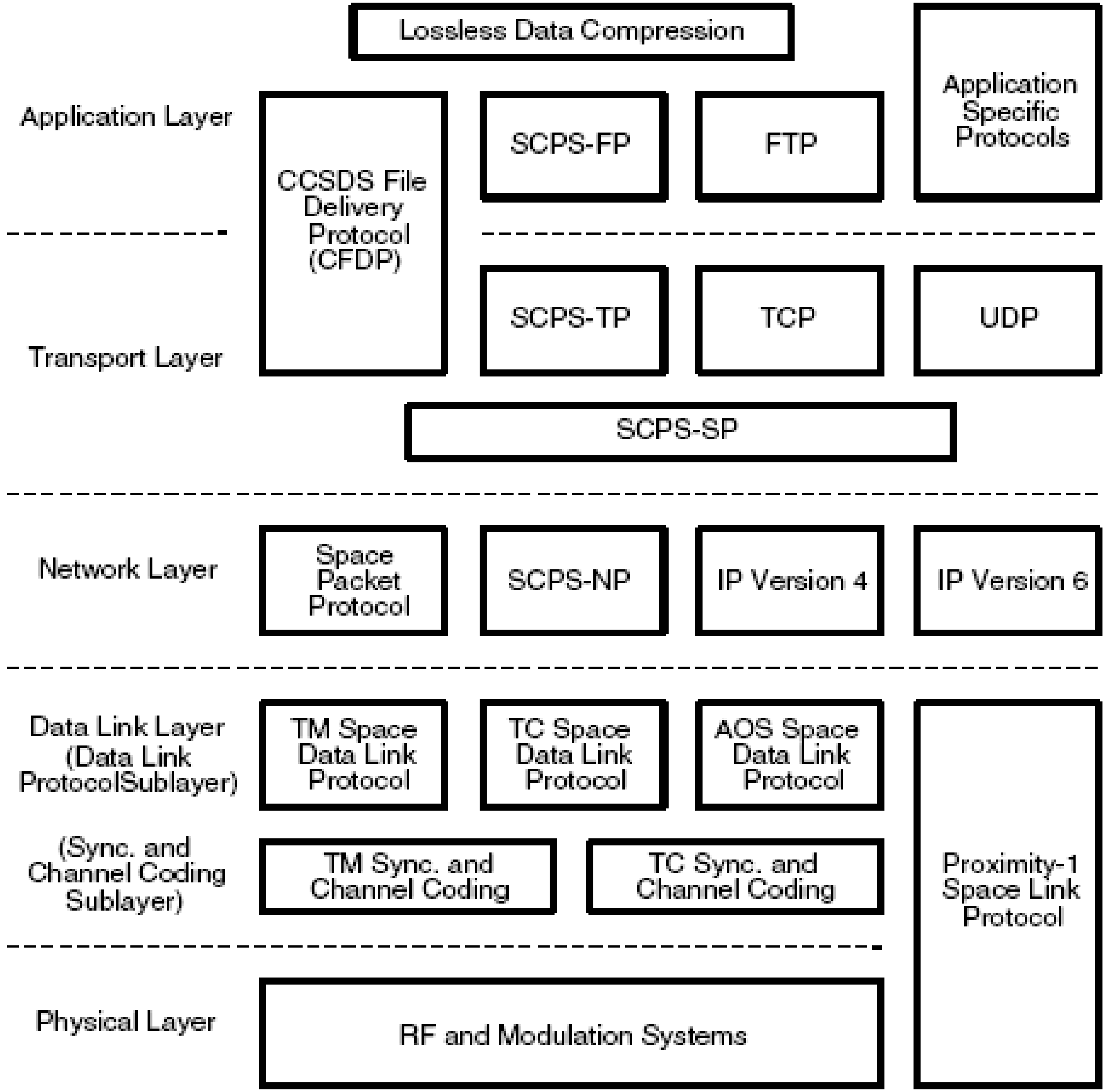

Figure 2-1: Space Link Protocols

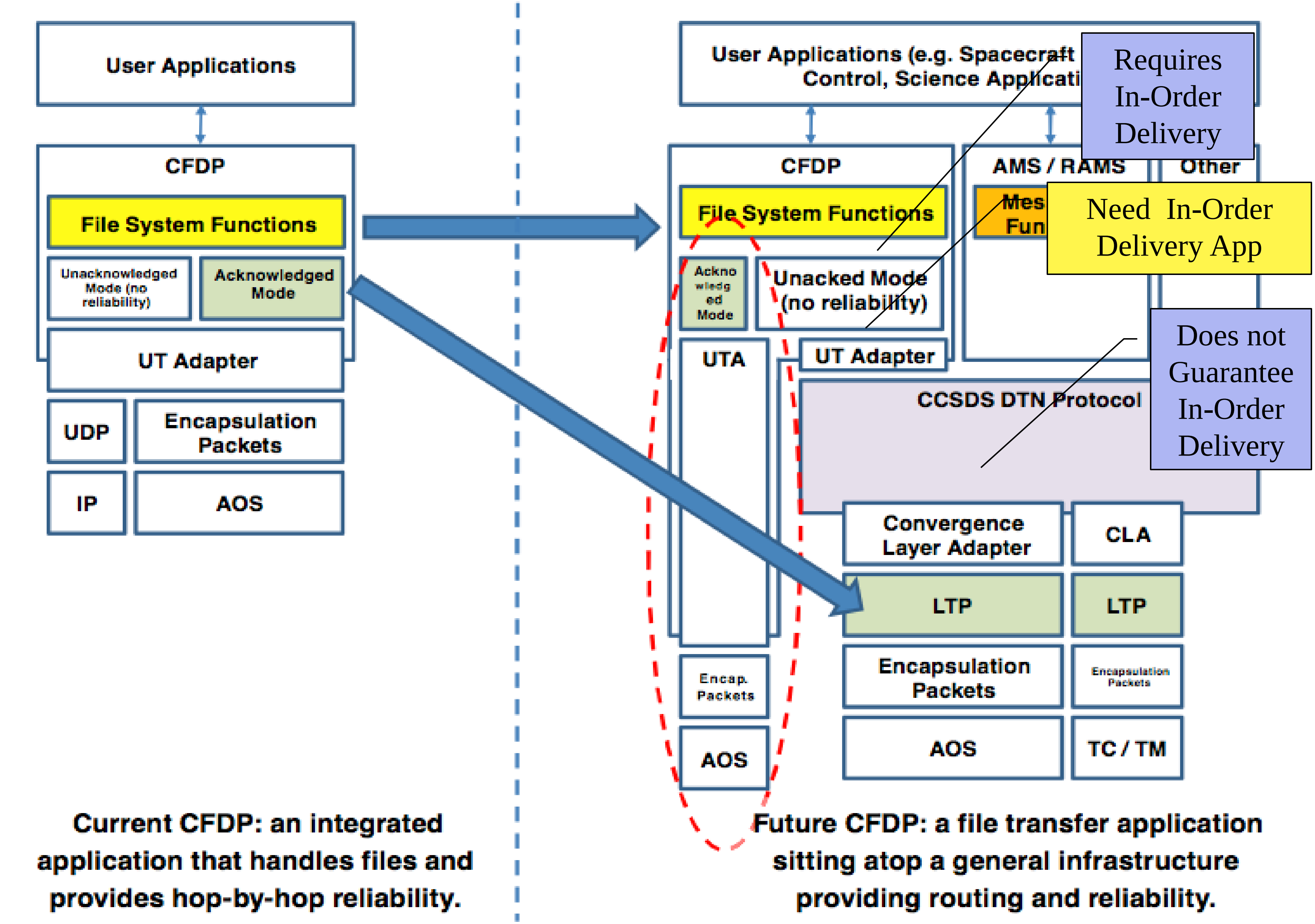

Figure 4-4: A CFDP Evolution Path to Use DTN as the CFDP Unitdata Transfer Service

Aggregation (or Not?)

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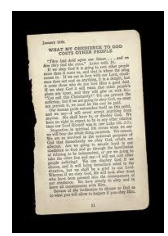
Requiers Topological Addressing

64K Bundles
(De-aggregation)

Bundles Table
Explosion



64K Bundles
(Re-aggregation)

Delay/Disruption Tolerant Network (DTN)

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- Goal: A standardized store and forward protocol and routing protocol
- Designed for extreme environments
  - Large transmission link delays
  - Extended periods of network partitioning
  - Routing capable of operating efficiently in the following environments
    - Frequently disconnected
    - Pre-scheduled or Opportunistic link availability
    - Heterogeneous underlying network technologies (including non-IP-based internets)
- The architecture operates as an overlay network

Applications must be able to tolerate disconnection / disruption

Why DTN?

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- **Pros**
  - Flexibility
  - Reliability
  - Robustness (in that it can handle disconnection and disruption)
  - Automates routing for multi-hop, multi-path network topologies
- **Cons**
  - Added complexity
  - Not needed for single hop systems
  - Adds Overhead (~70 bytes)
  - Network overlay
    - Needs all the functions found in any network and more
      - Routing
      - Discovery
      - Name/Address Binding
      - Security
      - Network Management
      - Resource Management

DTN Layering (RFC 5050)

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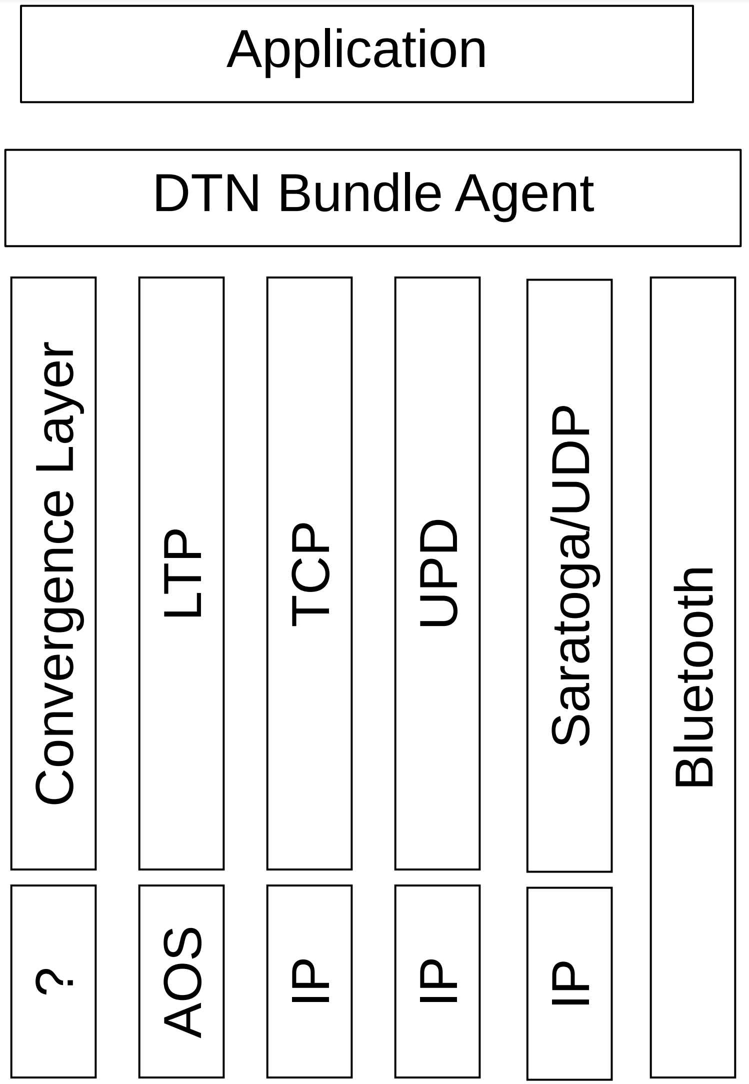
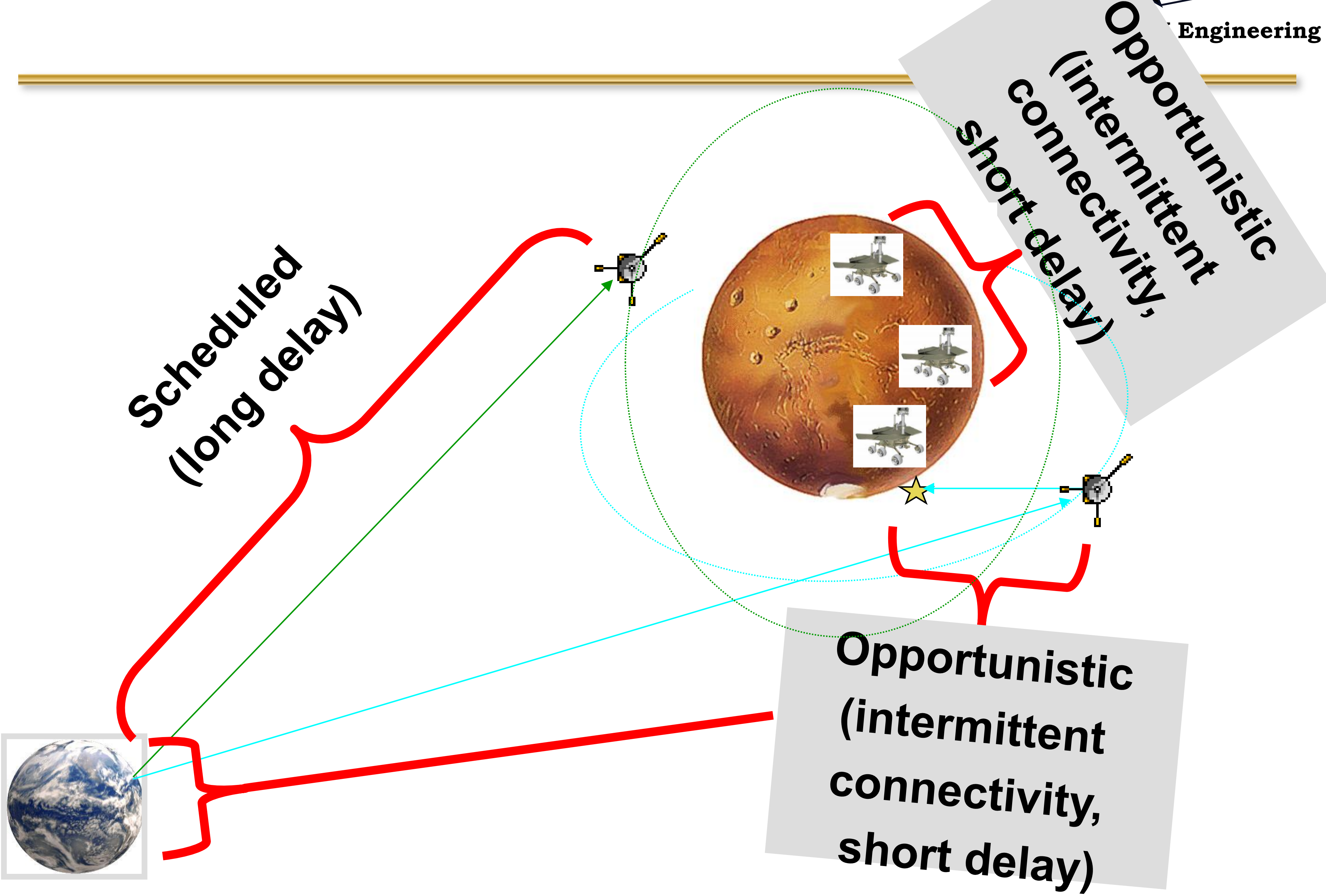


Convergence Layer (This is the transport protocol piece)

Heterogeneous Network

DTN Environments



Single-Hop Architecture

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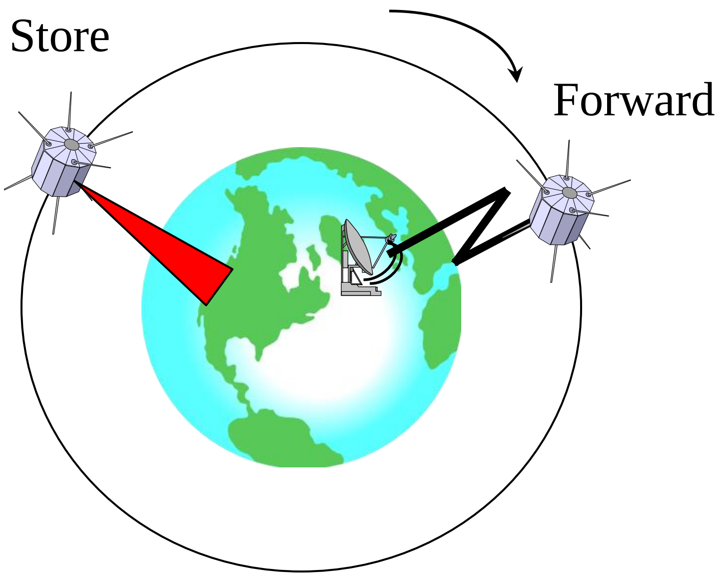
- CFDP
- LTP
- Saratoga
- Others (e.g., 9P)
- No Need for DTN Complexity
  - DTN is most useful for multi-hop networks



Known Issues with Current Bundling Specifications

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- Note: IRTF generated Request For Comments (RFCs) are standards.
  - RFC5050 is an Experimental Specification not a Standard
- Requires loose time synchronization
- No reliability checks on the header
- No way to terminate routing loops
- Naming is addressing
  - Flat name space makes scalability hard if not impossible
  - No identified way to aggregate routes
- Dynamic Routing is incomplete
- Discovery is incomplete
- Bundle Security Protocol
  - Specification is overly complex
  - Cases have been identified were it is broken
  - Security does not work with reactive fragmentation
  - Key exchange and key management is an open issue

DTN ON THE INTERNATIONAL SPACE STATION

ISS History

SYZYGY Engineering

- Design dates back to 80s and early 90s
  - pre-Internet era
- Phase 0
  - Commanding via low rate S-Band uplink
    - Uplink bandwidth is limited resource that must be managed.
  - Payload data downlink via Ku-Band at 50 Mbps
  - Highly asymmetric links ***and both may not be on simultaneously***
- Phase I
  - KuBand uplink at 3 Mbps
  - Orbital communication adapter (introduced Internet
    - 3 Mbps Up, 6.5 Mbps down IP in CCSDS packets
- **KuBand Upgrade**
  - **30 Mbps Up, 300 Mbps Down Ku-Band**
  - **IP onboard with IP encapsulated in CCSDS up/down**

NASA ISS DTN Project

SYZYGY Engineering

- ISS Disruption Tolerant Networking (DTN) Architecture for flight, ground, and test/simulation
- Increased reliability of payload data transfers between ISS and remote payload control centers during Acquisition of Signal (AOS) / Loss of Signal (LOS) transitions
- Increased automation of Payload Developer (PD) requests for data transfers
- Mechanism to alleviate extensive support to plan payload transfers around AOS/LOS and operator required transfers
- Mechanism to use standard, publicly available protocols, avoiding the use of costly custom protocol implementations
- Opportunity to gain valuable experience using DTN, which is the expected communication protocol of choice for future space exploration

Current Payload Operations

SYZYGY Engineering

- Uplink/Downlink request
- Entire files have to be re-transmitted when transfer errors occur
- Manual transfer by operations required for file transfers across AOS/LOS
- 24x7 continuous support operations to ensure access to science data
- Data recorded to Outage Mass Memory unit requires operators to playback
- Custom file transfer protocols utilized. Currently many payloads use a custom method or protocol to transfer data reliably between on-orbit and ground
  - Ex. Alpha Magnetic Spectrometer (AMS) and custom AMS Crew Operations Post (ACOP) system to store and buffer data in a proprietary implementation

DTN Benefits to Payload Communications

SYZYGY Engineering

- Provides capability to automate operations and ensure science delivery with little regard for link or facility outages
  - MSFC, MCC-H, and ISS DTN nodes will store user file uplinks/downlinks and forward bundles as Ku-Band becomes available
- Reduce real-time support to access and downlink science data
- DTN stores data during LOS and automatically initiates transfer upon AOS
- A download transfer can span Ku-Band AOS periods without any special scheduling or scripting
- Reduces need for duplicate storage and extra retrieval actions

DTN Benefits to Payload Communications

SYZYGY Engineering

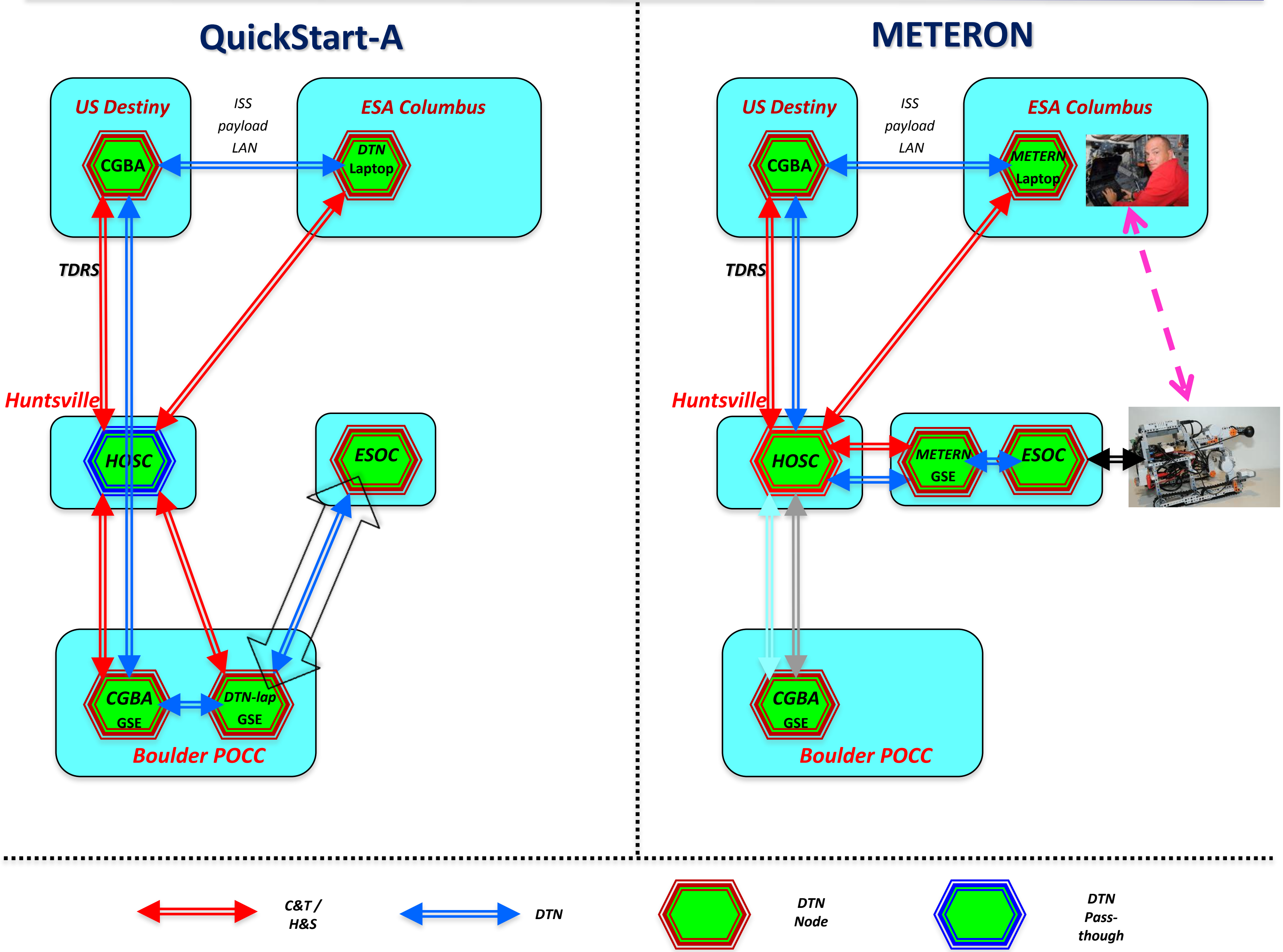
- Reliable data transfer for ISS during LOS/AOS cycles
  - Automatic verification of bundle receipts, retransmissions reduced
  - When transmission errors occur only the bundles that have errors are retransmitted
  - Maximizes use of bandwidth by reducing the amount of data that has to be retransmitted
- Allows Payload Developers to use DTN protocols for their own applications
- Efficient use of downlink stream through DTN Quality of Service (QoS)
- Tolerance for high network latency (600 ms Round Trip Time (RTT) delay is typical on Ku link)

Current/Future ISS DTN Use Cases

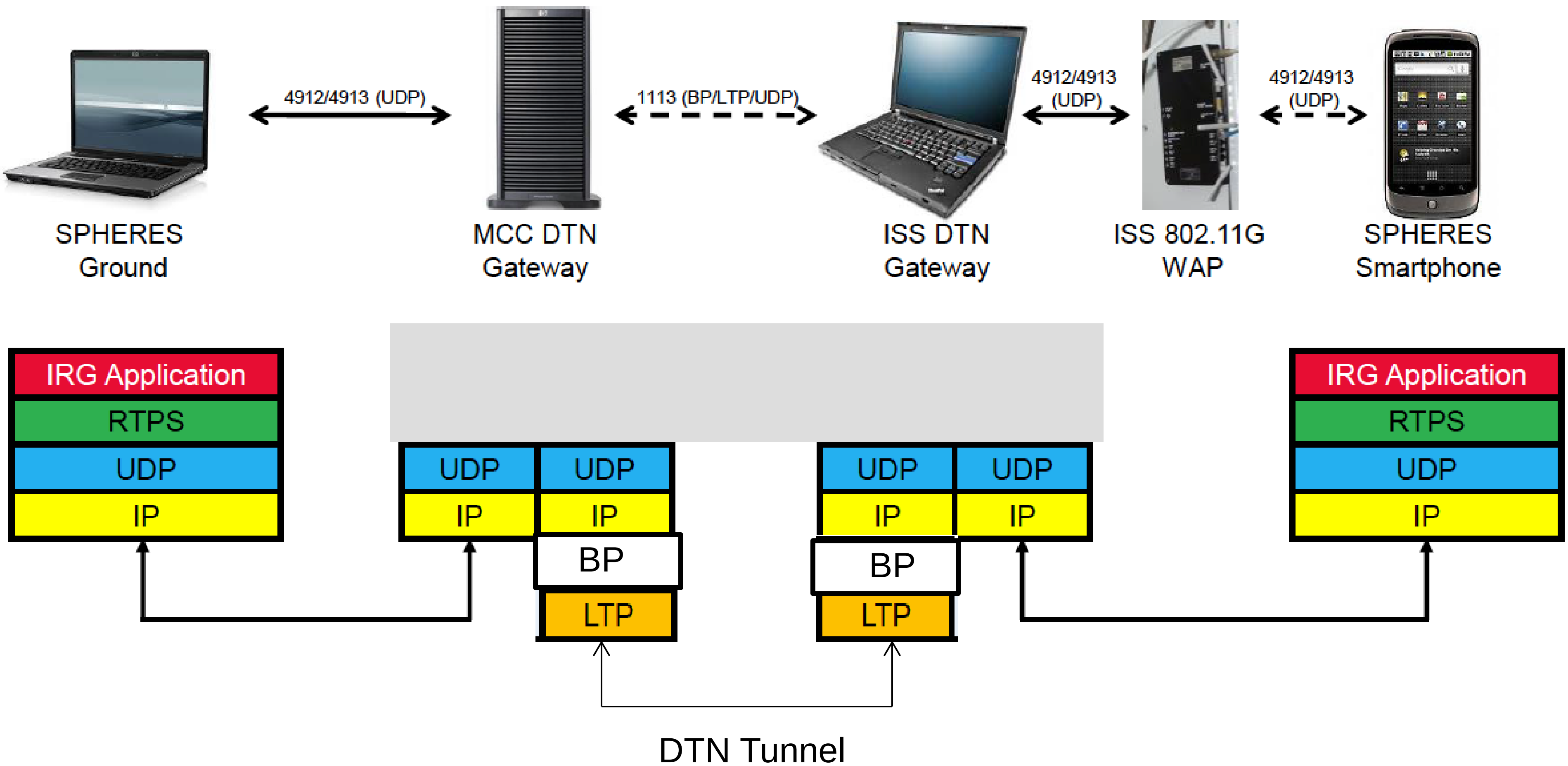
SYZYGY Engineering

- Current Users of DTN on ISS:
  - Various “developmental” DTN configurations have been in use on ISS in support of payload activities for several years
  - DTN is or has been used in support of the following Payloads
    - BioServe Commercial-Grade Bioprocessing Apparatus (CGBA)
    - DARPA Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) Smartphone
    - ESA Quickstart and OPSCOM I
    - ESA’s METERON (Multi-Purpose End-To-End Robotic Operation Network)
- Additional Payloads discussing use of DTN include:
  - Multiple User System for Earth Sensing (MUSES)
  - Human Exploration Telerobotics (HET) Surface Telerobotics
  - JAXA Kibo KaBand Rain fade mitigation
  - Other payloads are becoming interested

ESA QuickStart-A and METERON topologies



Spheres



4912/4913 (UDP)
1113 (BP/LTP/UDP)
4912/4913 (UDP)
4912/4913 (UDP)
SPHERES Ground
MCC DTN Gateway
ISS DTN Gateway
ISS 802.11G WAP
SPHERES Smartphone
IRG Application
RTPS
UDP
IP
UDP
UDP
IP
IP
BP
LTP
UDP
UDP
IP
IP
BP
LTP
IRG Application
RTPS
UDP
IP
DTN Tunnel

Summary

SYZYGY Engineering

- The implementation of DTN on ISS will provide a standard method of communication for payloads that is reliable, autonomous and more efficient than current techniques, resulting in better utilization and more science return from ISS
- The use of DTN by payloads will significantly ease Payload Development of both onboard and ground communication systems and could reduce payload operator costs