Real-Time and Store-and-Forward Delivery of Unmanned Airborne Vehicle Sensor Data

PI: Will Ivancic/GRC

Co-PI: Don Sullivan/ARC

Initial Goals

- Improve the data throughput and utilization of current UAV remote sensing by developing and deploying technologies that enable efficient use of the available communications links. Such technologies may include:
  - Some form of Delay/Disruption Tolerant networking
  - Improvements to the Saratoga and/or other reliable transport protocols such as implementing rate-based and congestion control features.
  - Development of a protocol that advertises link properties from modem to router or host (not addressed in the paper)
- Develop and deploy a mobile communication architecture based on Internet Technologies that will be utilized on the Global Hawk Unmanned Arial Vehicle (UAV) for atmospheric research.

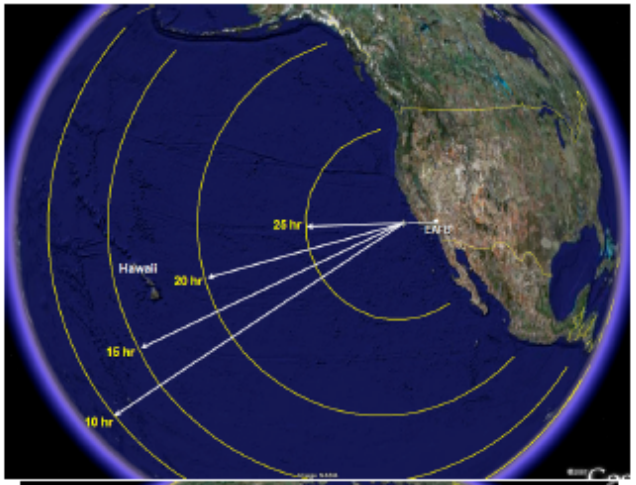
Work Items

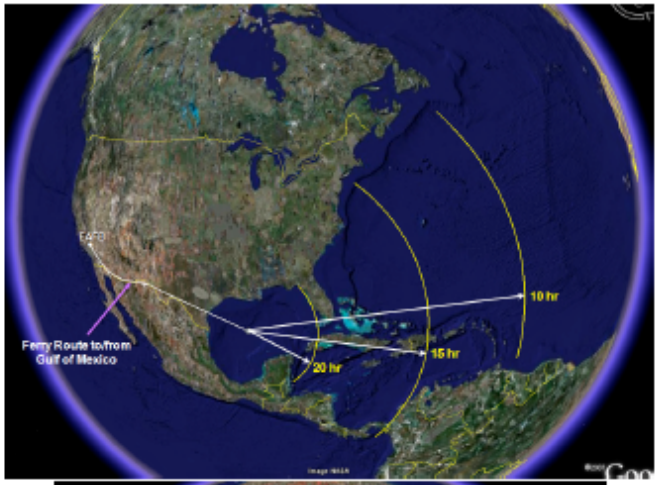
- GRC
  - Mobile communication architecture,
  - Rate-based transport protocol
  - Store-and-forward protocol(s)
  - Layer-2 triggers. (Not addressed in this presentation)
- Ames
  - Development and testing of software for the command and control of the sensor packages onboard the Global Hawk
  - Integration of GRC developed communication software with command and control Software

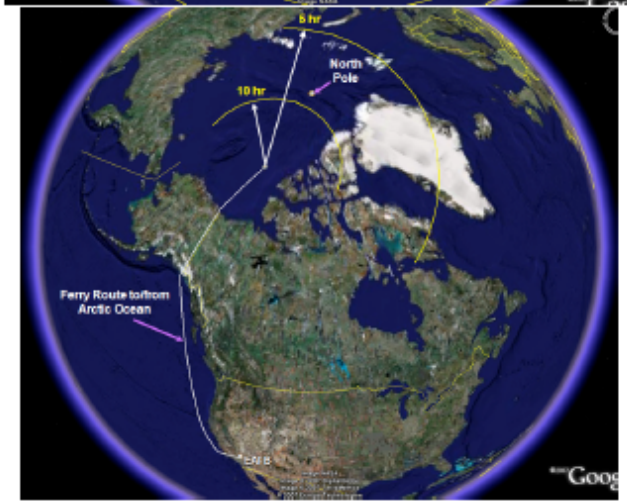
Global Hawk Operational Capability

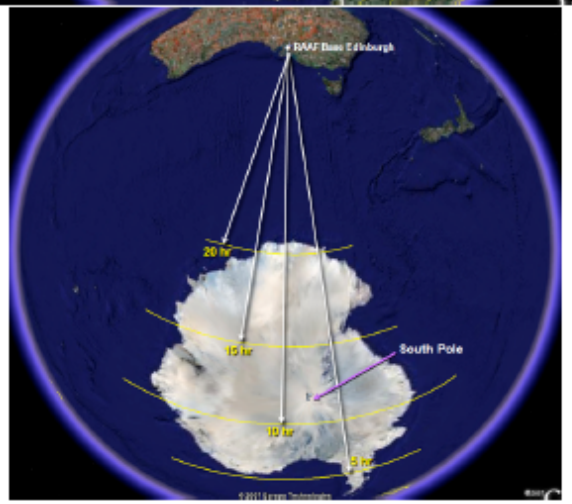
Four Mission Regions, with Arcs of Constant On-Station Times

← GLOPAC →









GRIP

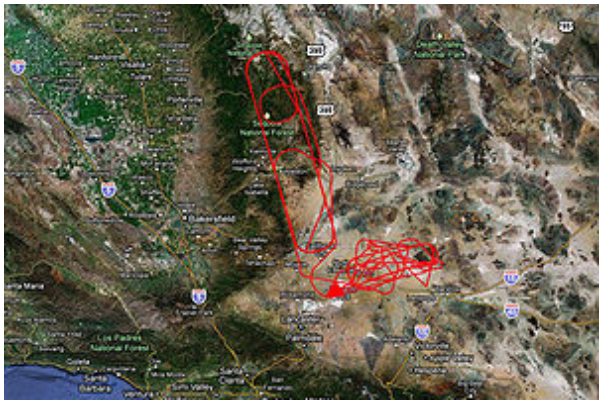
GloPac Mission
(March – April 2010)

- Conducted in support of the Aura Validation Experiment (AVE).
  - Aura is one of the A-train satellites supported by NASA Earth Observation System.
- Encompassed the entire offshore Pacific region with four to five 30 hour flights.
- Flew over the Pacific ocean, from the North Pole to the equator for its first Atmospheric Chemistry experiment.
- The flights were designed to address various science objectives:
  - Validation and scientific collaboration with NASA earth-monitoring satellite missions, principally the Aura satellite,
  - Observations of stratospheric trace gases in the upper troposphere and lower stratosphere from the mid-latitudes into the tropics,
  - Sampling of polar stratospheric air and the break-up fragments of the air that move into the mid-latitudes,
  - Measurements of dust, smoke, and pollution that cross the Pacific from Asia and Siberia,
  - Measurements of streamers of moist air from the central tropical Pacific that move onto the West Coast of the United States (atmospheric rivers).

GLOPAC Missions
(Ames/Dryden)

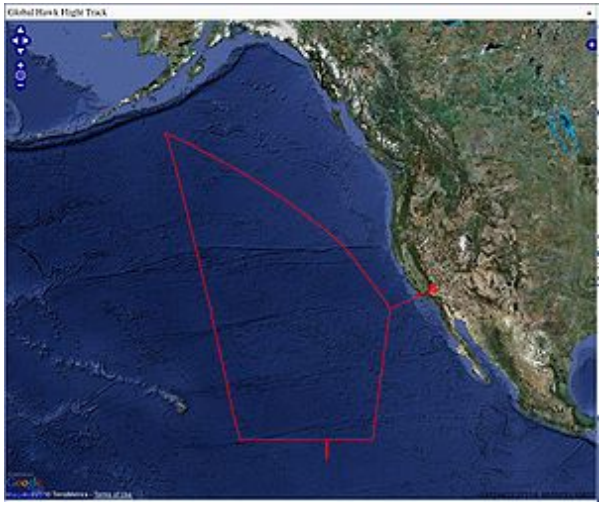
- Mission integration and operations March – April 2010 (Four Flights)
- Test Flight #1: April 2, 2010
  - Test in-flight operation of payload instruments
  - Refine Global Hawk Operations Center (GHOC) / Payload Operations Room (POR) payload C3 procedures
  - Demonstrate that information can be transmitted from the aircraft and displayed in GHOC POR
- Science Test Flight #1, 2010-04-07
  - Demonstrate long range capability of the Global Hawk
  - Measure polar vortex fragment
  - Under fly Calipso and Aura satellites.
  - Continue development of GHOC/POR procedures
  - Improve instrument displays and situational awareness in GHOC POR
- Science Flight #2: April 13, 2010
  - Under fly Aura satellite.
  - Measure 2nd polar vortex fragment (1st measured on 7 April)
  - Sample Asian dust plume.
  - Sample region of stratospheric tracer mixing over a region to the south of California
  - Extended sampling of tropical tracers in cold temperatures
  - Demonstrate 24-hour endurance of the Global Hawk
  - Demonstrate vertical profile maneuver
- Science Flight: Tuesday, April 22, 2010
  - Demonstrate an Arctic flight.
  - Demonstrate vertical profile maneuver
  - Possible overflight of volcanic plume
  - Extended sampling of tracers to high northern latitudes.
  - Demonstrate at least a 26-hour endurance of the Global Hawk

Flight Track Images
(Ames/Dryden)

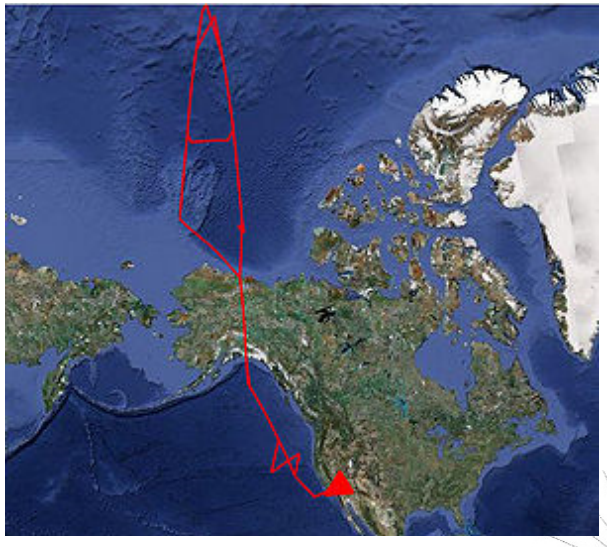


Test Flight 1, April 2, 2010

Science Flight 1, April 7, 2010



Science Flight 2, April 13, 2010



Science Flight 3, April 22, 2010

Communication System Lessons Learned
(Ames)

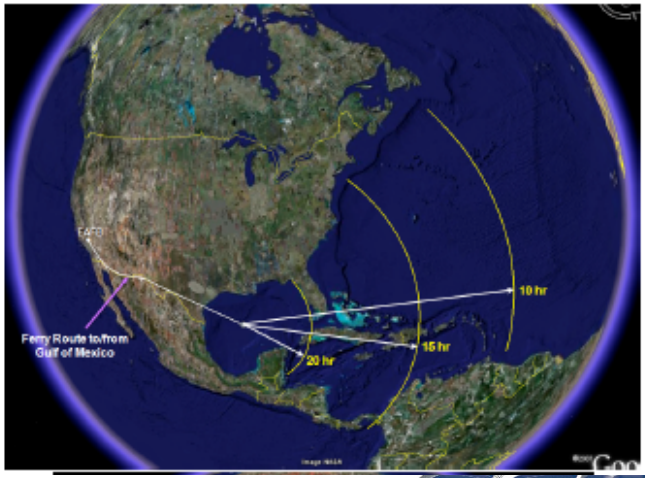
- Iridium (payload link) was unreliable relative to Ku-Band link
  - But Iridium does provide Global Coverage
- INMARSAT system and UHF system used for redundant backup for command and control mainly for takeoff and landing
  - Low rate ~ 16 kbps
  - INMARSAT unreliable at high latitudes (GEO Satellite)
- Ku-Band worked extremely well
  - Data rate was 2 Mbps bidirectional
  - Link was reliable to 75 degrees north latitude (3 degree view angle!)
  - Moved / duplicated some Iridium payload operations to Ku-Band operations
- Modified software that controls the Satellite Modem Assembly to enable programming of the Ku-Band system via Iridium
  - Ku-Band system can be reconfigured on the fly to change satellites, polarization, data rates, etc....
- Used standard TCP and UPD protocols (no rate-based for these flig

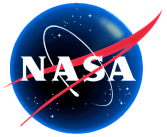
Principle Investigators were ecstatic to get real-time control of their payloads!

Genesis and Rapid Intensification Processes (GRIP)

- Better understand how tropical storms form and develop into major hurricanes.
- Deployment of new remote sensing instruments for wind and temperature that can lead to improved characterization of storm structure and environment.
- NASA plans to use the DC-8 aircraft and the Global Hawk Unmanned Airborne System (UAS)
- The spaceborne, suborbital, and airborne observational capabilities of NASA put it in a unique position to assist the hurricane research community in addressing shortcomings in the current state of the science.

Anticipated Start August 2010





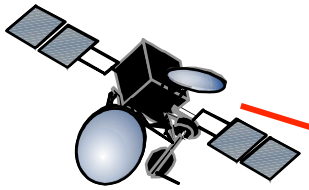
Global Hawk Communications Architecture Investigation

Command and Control Communications

- Aircraft Command and Control (C2) communications.
  - LOS -- 2 UHF/LOS links.
  - BLOS -- 2 Iridium links and 1 INMARSAT link.
    - INMARSAT is a GEO satellite and does not cover the poles
- Payload C2 and Status communications.
  - Multiple multiplexed Iridium links.
    - Multiplexing low-rate links is a non-trivial problem
    - Current implementation is functional, but some technical issues are still being worked
  - Investigate for potential to use this link for Metadata and Prioritized Queuing of payload data.

GloPac Payload Communication Network

GE 23

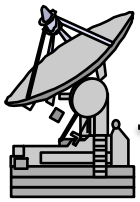


Disconnection Over the North Pole

No Network Mobility and Single Hop therefore: No need for DTN or Mobile Networking

3 Mbps Bidirectional Link

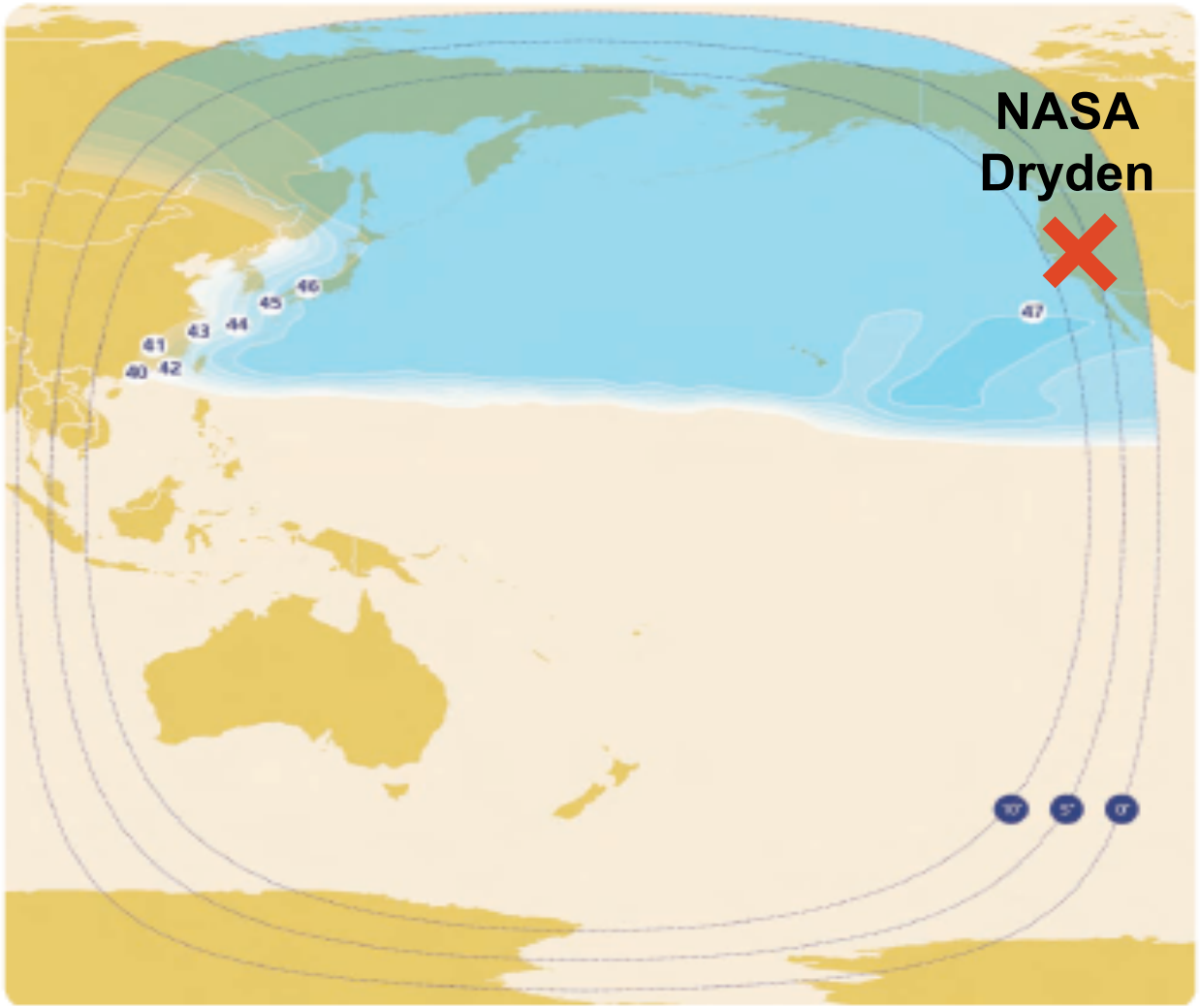
L3-Com Ku-Band Transportable Terminal



NASA Dryden

GE-23 Coverage

North Pacific Ku-band Beam



GRIP Communication Network

Ku Band Satellite - A

Ku Band Satellite - B

> 3 Mbps Bidirectional Link

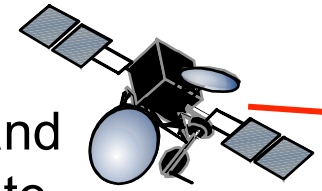
No Network Mobility and Single Hop therefore: No need for DTN or Mobile Networking

Disconnection During Satellite Handover Due to Repointing

NASA Dryden

L3-Com Ku-Band Terminal

Future Communication Network

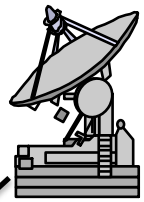


Ku Band Satellite

Network Mobility and possible multi-hop therefore: Need for Mobile Networking and possible DTN to accommodate rate-mismatch problems.

Possible Rate Mismatch between RF link and ground link

Disconnection During Handover Between Service Providers



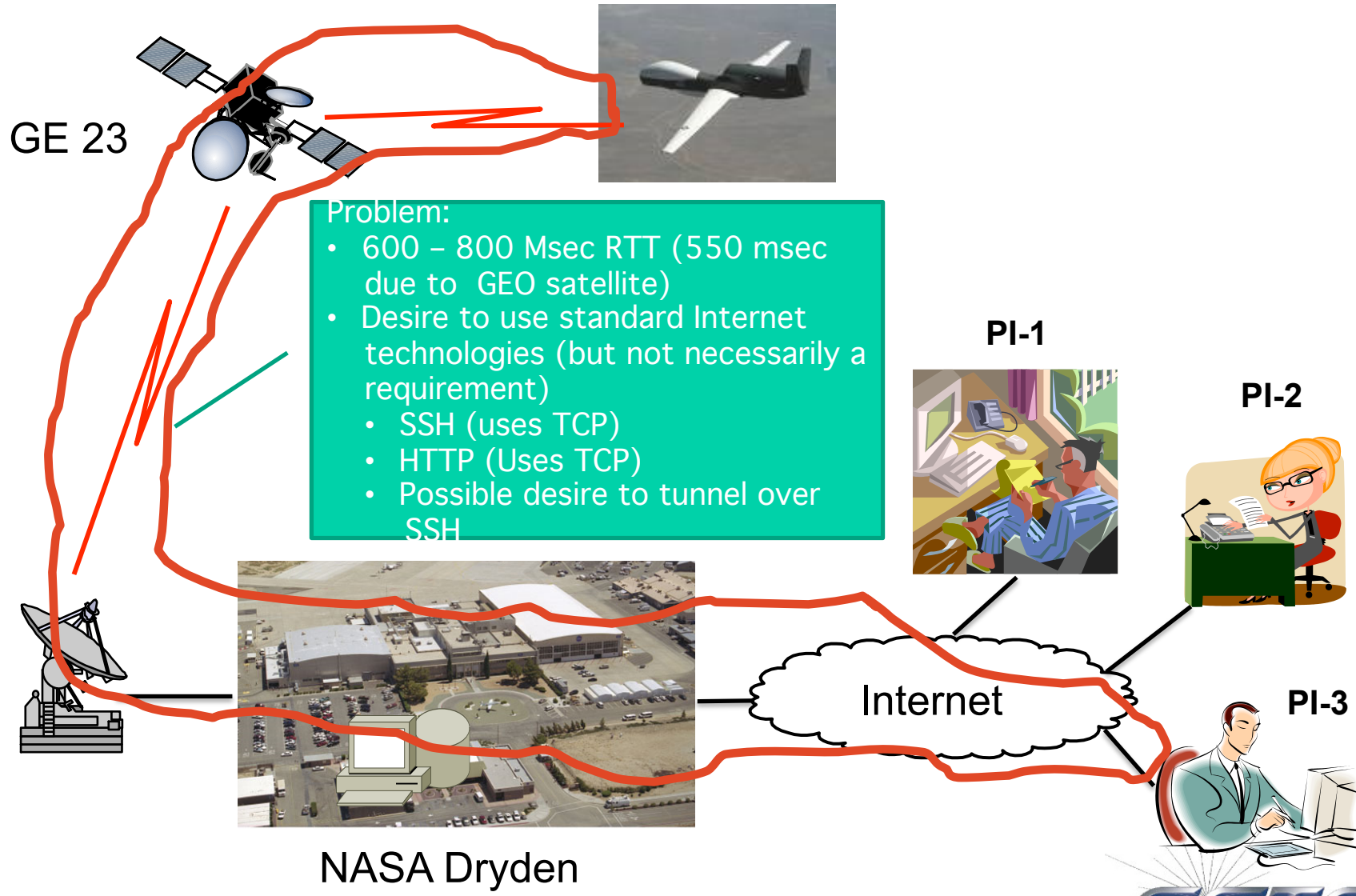
Service Provider A

Service Provider B

Internet

NASA Dryden

New Requirement (Remote Access and Control over long delay)

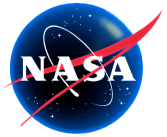


New Requirement (Remote Access and Control over long delay)

- Key Questions:
  - What does the PI want to do?
  - What does the PI need to do?
  - How does the PI want to operate?
  - How is the PI willing to operate?
  - What is the anticipated user experience?
  - What is the acceptable user experience?

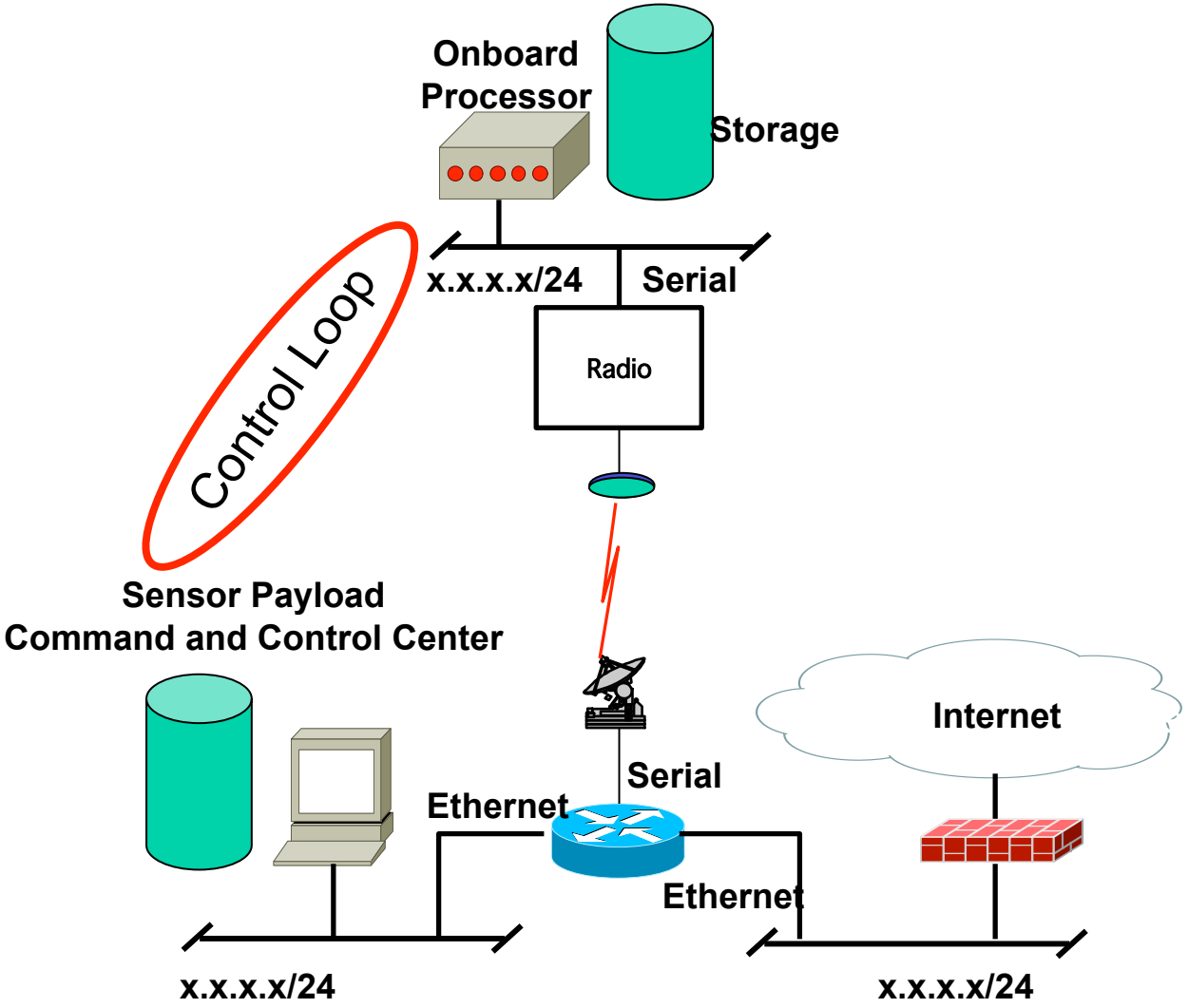
Mobile Communications Architecture

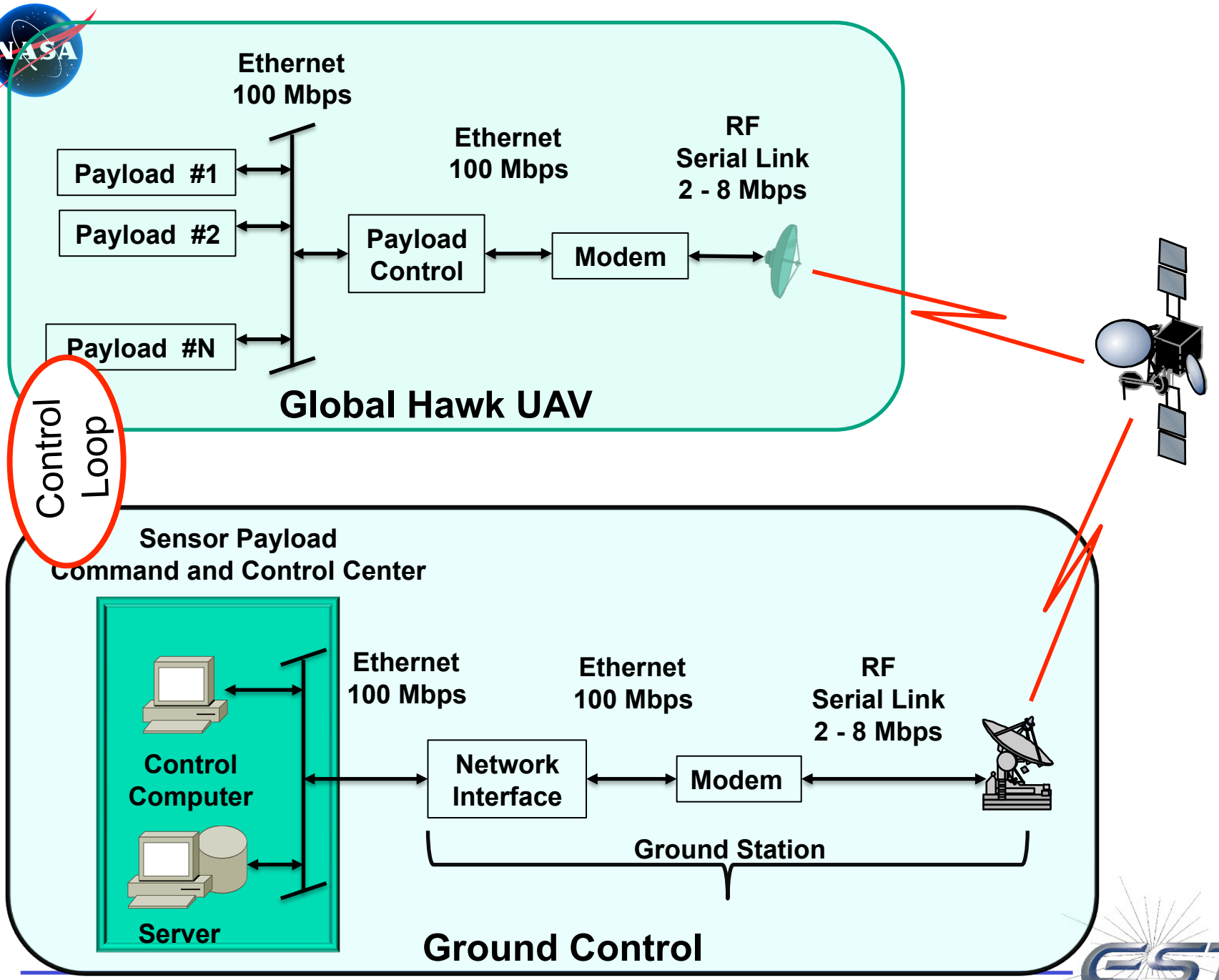
- Requirements
  - Provides connectivity via the Internet
    - Current infrastructure under NASA control and single hop (no Network Mobility. We only need efficient transport protocols)
      - Initial Deployment for GLOPAC
      - Also current architecture for GRIP
    - Future infrastructure may be owned and operated by third parties and multi-hop. (True Network Mobility)
      - Possible architecture for future missions
  - Addresses security needs
- Possible solutions
  - Store and Forward over Mobile-IP
    - Advantage is Mobile-IP registrations provide a trigger to the transport protocol that connectivity has been established
  - Direct Store and Forward
    - Issue – how to determine connectivity is established?
      - Saratoga transport protocol provides such functionality



Rate-Based Transport Protocol

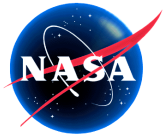
SSTL Disaster Monitoring Constellation Imaging Sensor Satellites




Ethernet
100 Mbps
Payload #1
Payload #2
Payload #N
Payload Control
Ethernet
100 Mbps
Modem
RF
Serial Link
2 - 8 Mbps
Global Hawk UAV
Control Loop
Sensor Payload
Command and Control Center
Control Computer
Server
Ethernet
100 Mbps
Network Interface
Ethernet
100 Mbps
Modem
RF
Serial Link
2 - 8 Mbps
Ground Station
Ground Control

Reliable Rate-Based Protocols

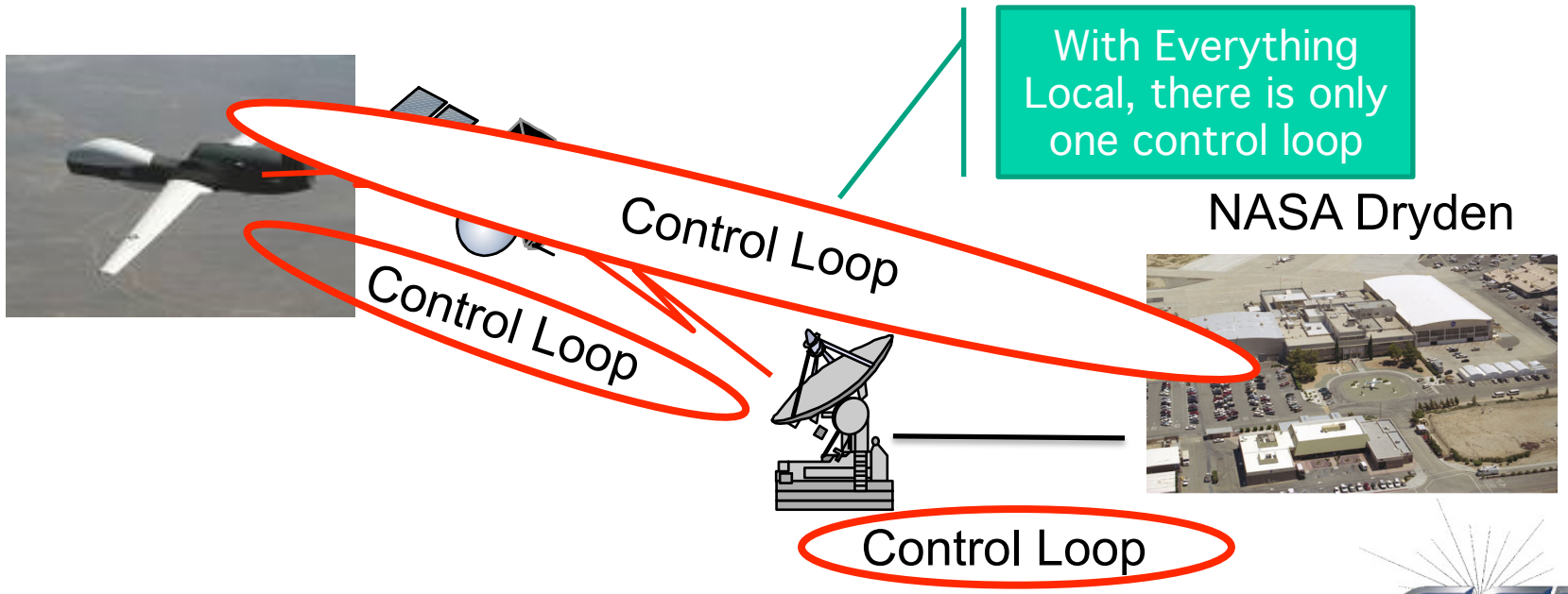
- Saratoga version 1
  - Saratoga version 0 implemented by Surrey Satellite Technology Limited for simple file transfer over highly asymmetric links
    - Used to transmit images for satellite to ground
    - Proven and operational
    - Full utilization of the RF channel
  - Saratoga version 1 is and Internet Draft that include improvements include unidirectional transfer and use of UDPlite
- Negative Acknowledgement (NACK) - Oriented Reliable Multicast (NORM)Transport Protocol
  - Uses a selective, negative acknowledgment mechanism for transport reliability
  - Leverages the use of forward error correction (FEC) repair and other IETF Reliable Multicast Transport (RMT) building blocks
  - Can operate in unicast mode
  - Used on Naval Research Lab's MidStar-1 Satellite for unidirectional link file transfer
- CCSDS File Delivery Protocol (CFDP) – Class 2
  - Class 2 provides for the reliable delivery of bounded or unbounded data files from the source to the destination.
- CFDP – Class 1 over DTN over LTP over IP
  - CFDP provides the file transfer application while LTP Provides the reliability



Store and Forward Protocols

Why Store and Forward

- Global Hawk has large periods of disconnection from the network and needs to store data during disconnection and transmit data during times of connectivity
- Store and forward can break control loops
  - Allows for link by link transport protocol optimization.



Store and Forward Protocols
Delay/Disconnection/Disruption Tolerant Networking (DTN)

- Bundling Protocol (RFC5050) – really just a container specification
  - DTN2 (code exists)
    - Considered the Reference Implementation
    - Includes numerous routing protocols, convergence layers and security
  - Interplanetary Overlay Network (ION) (code exists)
    - Developed by JPL
    - Targeted for deep space
  - Spindle III (code exists)
    - Developed by BBN
    - Targeted for DARPA Wireless after Next program (military ad hoc networks)
    - Network synchronization not required (deviates from RFC5050)
- HTTP DTN (just an idea to date, no code currently exists)
  - Uses HTTP protocol as basis for store and forward
  - Simple and takes advantage of existing infrastructure

DTN Bundling Fixes

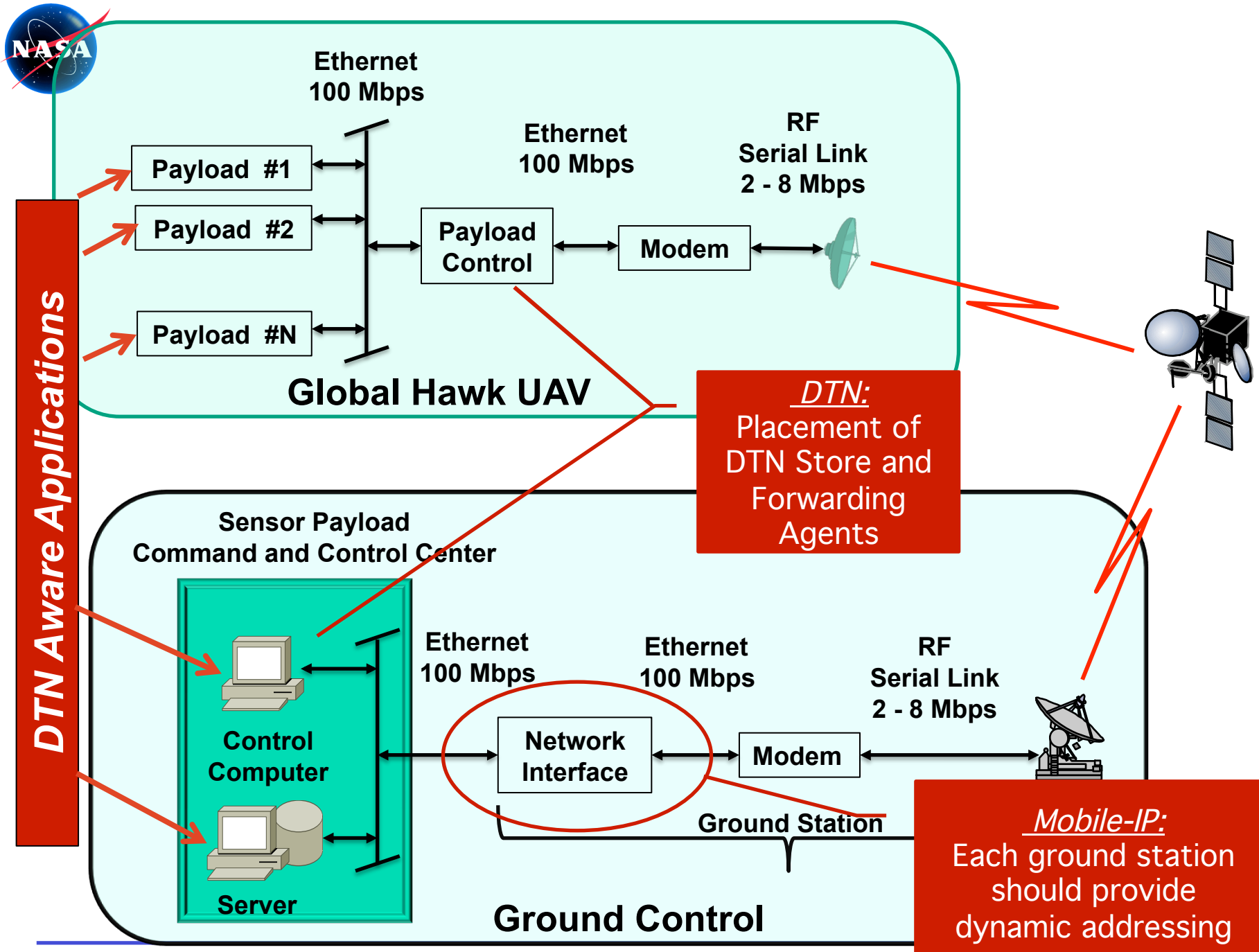
- Add ability to process bundle using relative time
  - DTN currently requires network synchronization to some fraction of the smallest lifetime bundle processed for the protocol to work. This can be non-trivial.
  - Numerous problems with synchronization have been identified during field trials
- Add simple CRC check capability in an extension block or the header
  - Current No checksum is included in the basic DTN Bundle Protocol
    - It is not possible to verify that bundles have been either forwarded or passed through convergence layers without error.
  - Current solution is to use reliability-only Checksum Ciphersuites
    - Requires the Bundle Security Specification be implemented
  - Previously proposed solution is to have reliability implemented as its own extension block
    - Separates reliability from security
    - Does not require node with limited processing power to implement security

RFC5050 Needs a Redo

- Delay Tolerant Networking Research Group (DTNRG) at the Internet Engineering Task Force (IETF) 77th Meeting in Anaheim, CA
  - Discussion on RFC5050-bis (bis is latin for repeat or twice – second version)
    - Not enough energy
    - To early
    - Is BIS an IETF responsibility
    - IETF would probably not move RFC5050 to any standard
      - Mixes application and protocol
      - Lots of other stuff (checksums, synch, etc…)
- Current implementation is nice for research due to extension blocks and flexibility, but poorly engineered
- Current implementation does not scale
- Overly complex
  - Tries do to more than store and forward
    - i.e. secure content distribution and storage
    - An attempt at content-based routing

Technical Issues

- Mobile-IP
  - Custom Global Hawk payload design requires “buy in” from communication system design team to implement mobile-IP or at least dynamic addressing on Space/ Ground link.
- DTN
  - Cannot assume control of Service Provider clocks
    - Requires modification to DTN to solve time-sync problem
    - Issue is being worked in Internet Research Task Force (IRTF)
      - This is a recent resolution decided in March 2010
  - Current DTN has no CRC check requirement
    - Current solution is to use Bundle Security Protocols Bundle Confidentiality Block with known shared keys.
  - Expired proposal to use “Reliability” Extension Block to ensure point-to-point reliability.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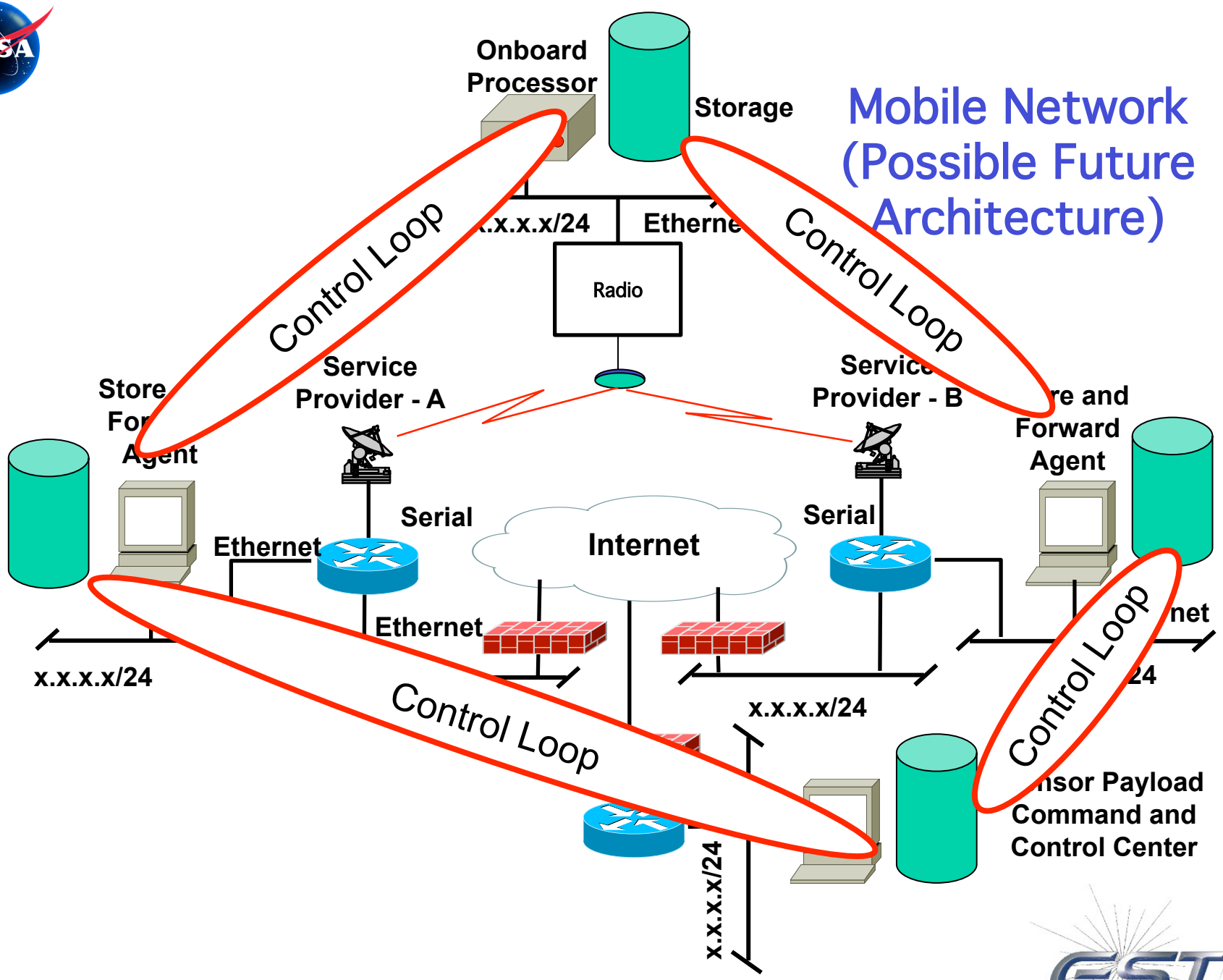
Global Hawk UAV
DTN Aware Applications
DTN:
Placement of
DTN Store and
Forwarding
Agents
Sensor Payload
Command and Control Center
Control
Computer
Server
Ethernet
100 Mbps
Ethernet
100 Mbps
RF
Serial Link
2 - 8 Mbps
Network
Interface
Modem
Ground Station
Ground Control
Mobile-IP:
Each ground station
should provide
dynamic addressing

Mobile Network (Possible Future Architecture)



Information Request / Recommendations

- Current NASA Global Hawk Architecture does not require network mobility or DTN
  - **Information Request:** Do other users of the Global Hawk have network mobility or DTN requirements (NASA, DOD or others)
    - If yes and if we can obtain buy-in from the Communication System supplier, work with appropriate entities to implement changes
    - Otherwise, implement network mobility and DTN in a testbed, but not on the Global Hawk
- ESTO has many instances where point-to-point "reliable" high rate file transfer is required
  - **Recommendation***:* Investigate performance, ability to handle highly asymmetric links and ease of implementation of reliable transport protocols (this is part of the "convergence layer" in the DTN world).
    - Protocols: Saratoga, NORM, CFDP-class 2 and CFDP-class 1 over DTN over LTP over IP
    - Parameters include: Asymmetry, speed, ease of use, delay, BER, disruption

Acronyms

- ARC – Ames Research Center
- BBN – Bolt, Beranek and Newman
- BLOS – Beyond Line of Sight
- BOF – birds of a feather, at the IETF this is an informal meet-up, where the attendees group together based on a shared interest and carry out discussions to decide if a formal workgroup is warranted C2 – Command and Control
- CRC – Cyclical Redundancy Check
- DARPA – Defense Advanced Research Program Agency
- DTN – Delay Tolerant Network
- E2E – End-2-End
- FEC – Forward Error Correction
- FTE – Full Time Equivalent
- GLOC – Global Hawk Operations Center
- GLOPAC – Global Hawk Pacific
- GRID – Genesis and Rapid Intensification Processes
- GRC – Glenn Research Center
- HTTP – Hypertext Transport Protocol
- IETF – Internet Engineering Task Force
- IRTF – Internet Research Task For
- ION – Interplanetary Overlay Network
- IP – Internet Protocol
- IPC – Interprocess Communications
- MANET – Mobile Ad hoc NETwork
- NEMO – NEtworks in MOtion base on mobile-ip
- LOS – Line of Sight
- Mbps – Megabits per second
- MD5 – Message-Digest algorithm 5
- MIME – Multipurpose Internet Mail Extensions
- NACK – Negative Acknowledgement
- NORM – NACK Oriented Reliable Multicast
- PERL – Practical Extraction and Report Language
- POR – Payload Operations Room
- RF – Radio Frequency
- RFC – Request For Comment
- RMT – Reliable Multicast Transport RTEMS – Real-Time Executive for Multiprocessor Systems, a free open source real-time operating system designed for embedded systems.
- SCTP – Stream Control Transport Protocol
- SMA – Satellite Modem Assembly
- S/MIME – Secure Multipurpose Internet Mail Extensions
- SOAP – Simple Object Access Protocol
- TCP – Transmission Control Protocol
- UAS – Unmanned Air System
- UAV – Unmanned Airborne Vehicle
- UDP – User Datagram Protocol
- UHF – Ultra-High Frequency
- VHF – Very-High Frequency
- WYE – Work Year Equivalent