Initial Results from ACCESS: an Autonomous CubeSat Constellation Scheduling System for Earth Observation

Andrew "Kit" Kennedy, Prof. Kerri Cahoy

akennedy@mit.edu

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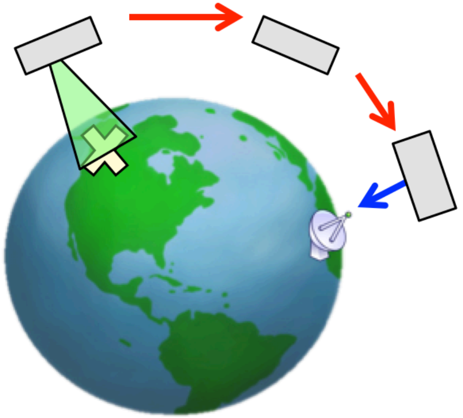
SmallSat Session V - Ground Systems

Outline

- **Motivation**
- Approach
  - EO Constellation Scheduling
  - ACCESS architecture
  - Data Routing
  - Simulation cases
- Results
  - Data Routing latency
  - Urgent Data Routing latency
  - Execution Time
- Conclusion



Earth Observing Constellations

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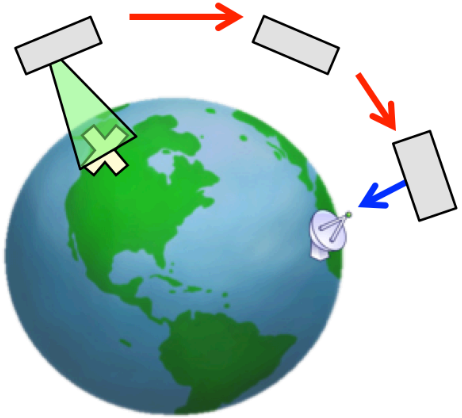
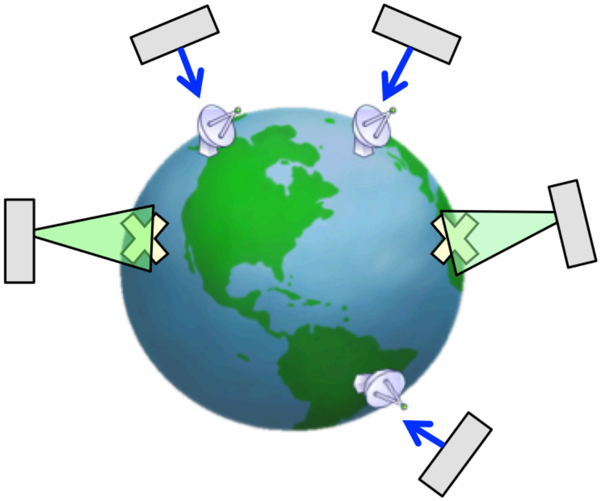
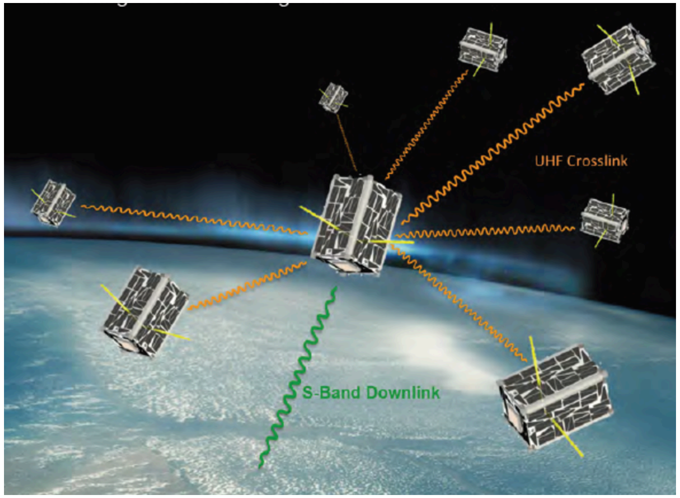


EO Constellation Scheduling

- Existing tools: observation and downlink scheduling
  - Planet Inc. algorithms
  - Multi-Sat Multi-GS scheduling
  - STK Scheduler
- Crosslink usage with tight-knit satellite clusters
  - Task allocation (e.g. market based)
  - Local or mesh networks



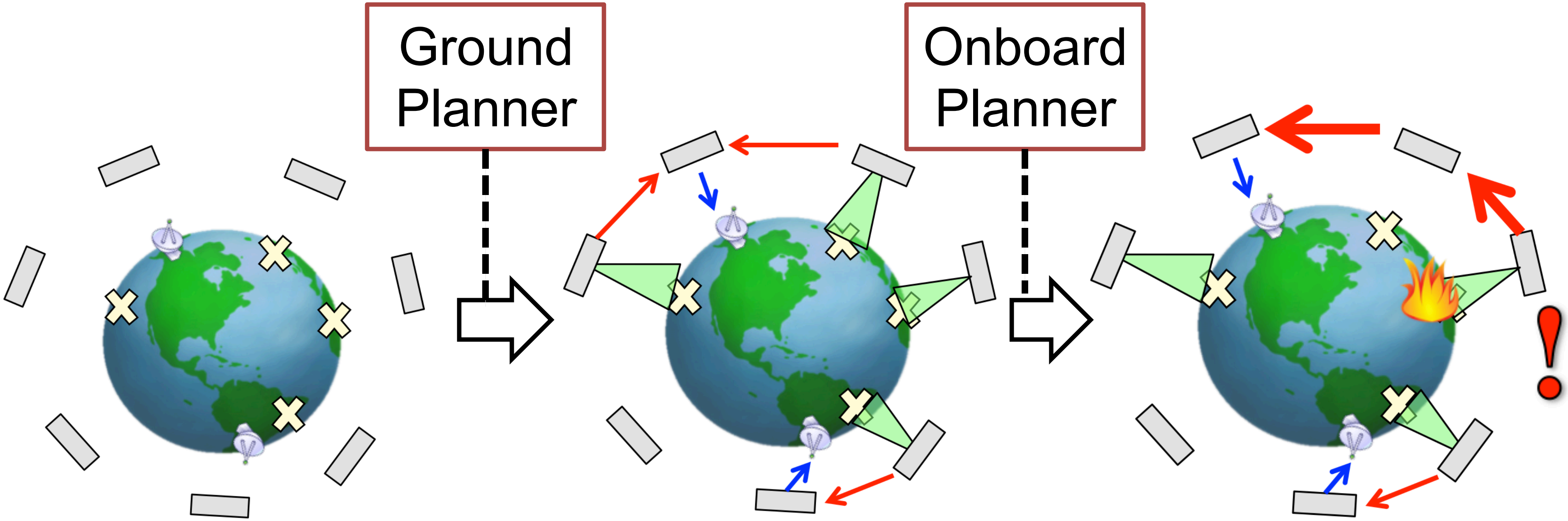
NASA Edison Demonstration of Smallsat Networks (EDSN)



NASA, 2013

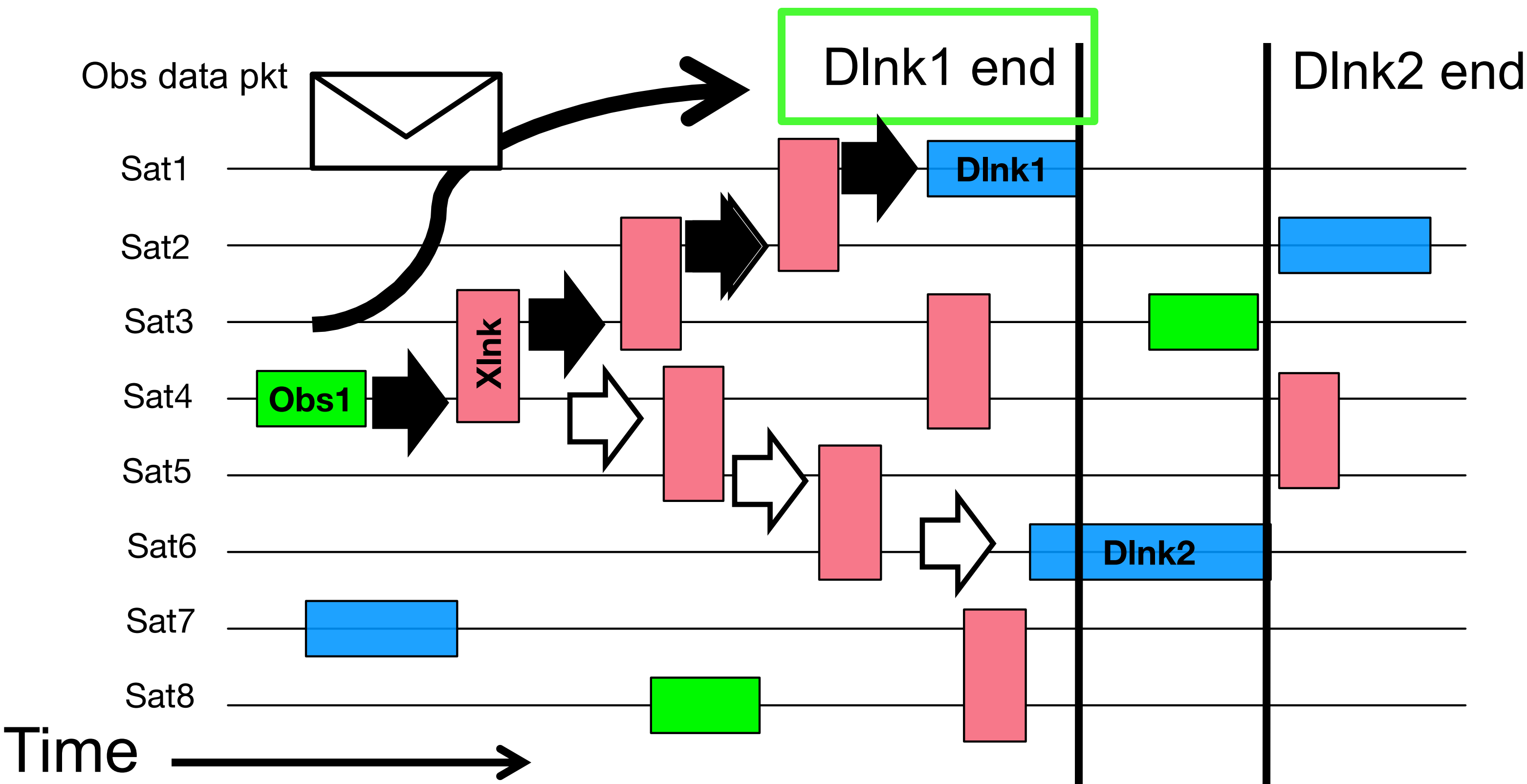
ACCESS Architecture

1. Simulate a “spread-out” satellite constellation
2. Schedule with a centralized ground planning system
   – *Key: utilize long-distance crosslinks for low-latency bulk data routing*
3. Distribute plans to sats via ground and crosslink network
4. Reactive observation replanning onboard sats
   – *Key: distribute updates through network*



Data Routing Approach

- Optimize metric: observation latency to downlink
- Implemented a greedy algorithm
  - Downlink observations in temporal order
  - Use earliest downlink possible each time



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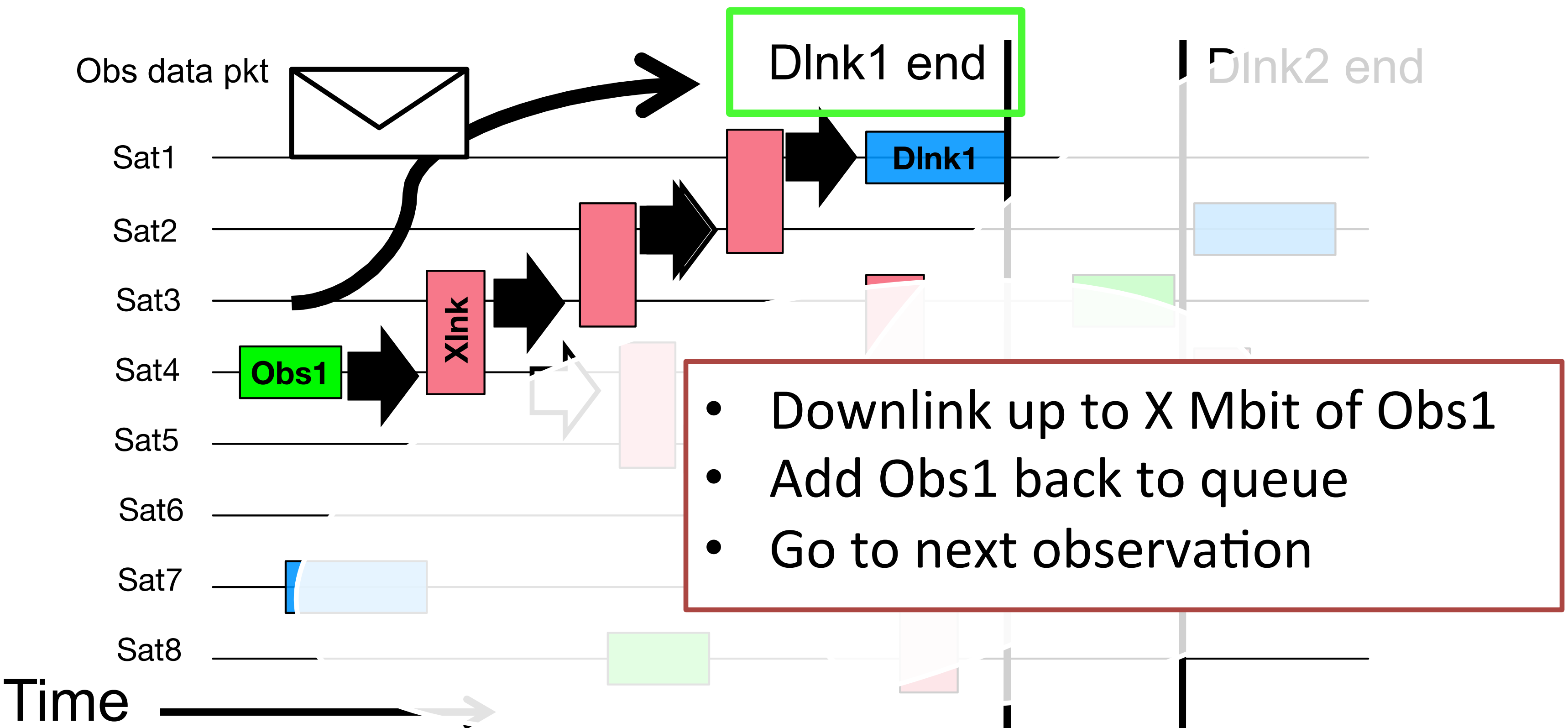
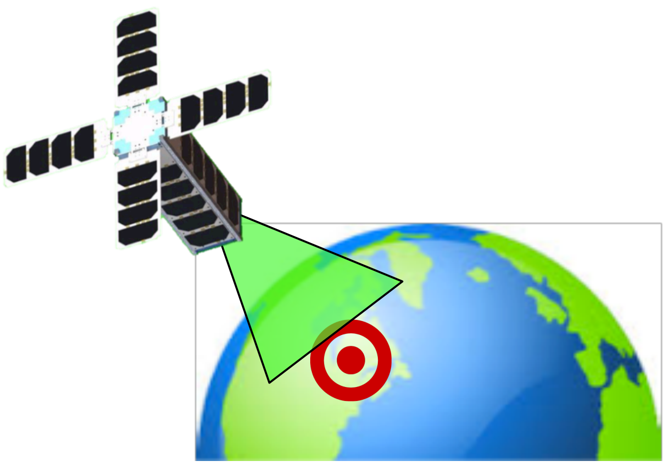
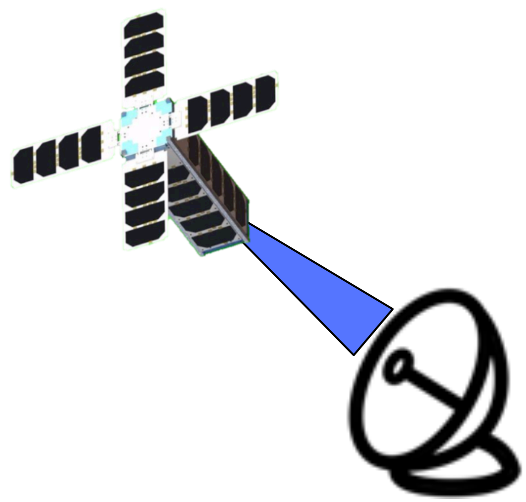
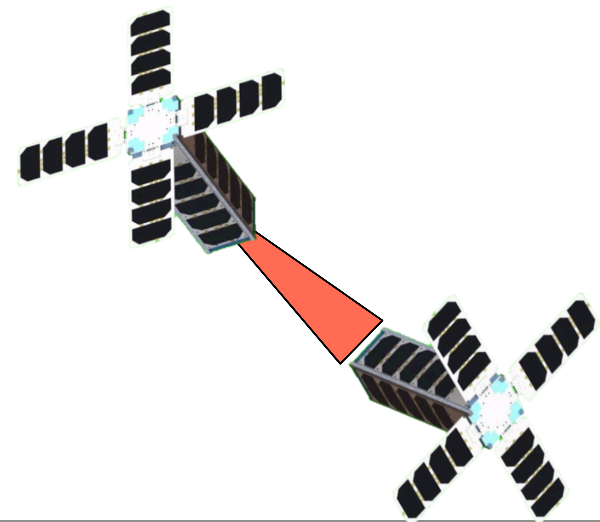


Payload and Link Models

- **High data rate EO payload**
  - 5 spectral bands, optical and NIR
  - 127.5 Mbps compressed data
  - 60 s average flyover
- **X-band Downlink**
  - 1 W Tx
  - 0.25U
  - 5.5 m Rx diam.
  - Adaptive data rate
  - 25-45 Mbps
- **Optical Crosslink**
  - 1 W Tx
  - 1U
  - 8.5 cm Rx diam.
  - Adaptive data rate
  - 10 Mbps @ **4,300km range**





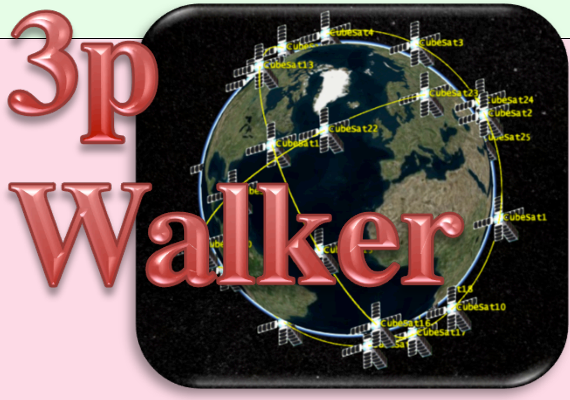


Simulation Cases

- **24h window for routing**
- **Set of 33 obs. targets**
- **3 orbital geometries**
- **3 GS networks**

Targets

Orbits



Networks

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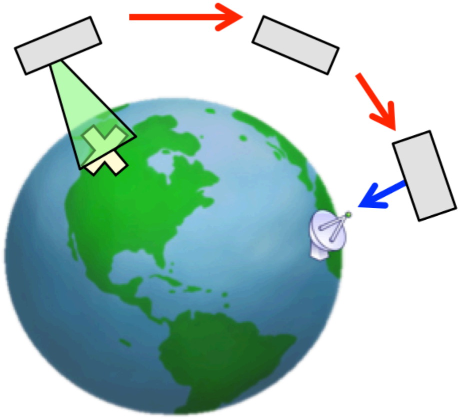
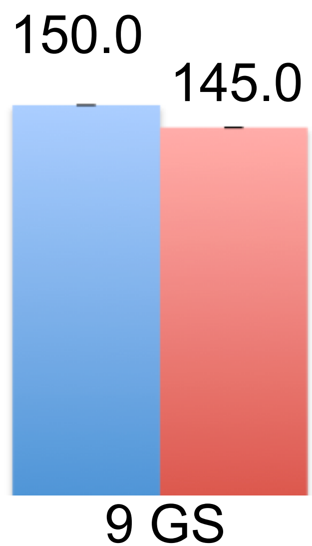


Routing Latency

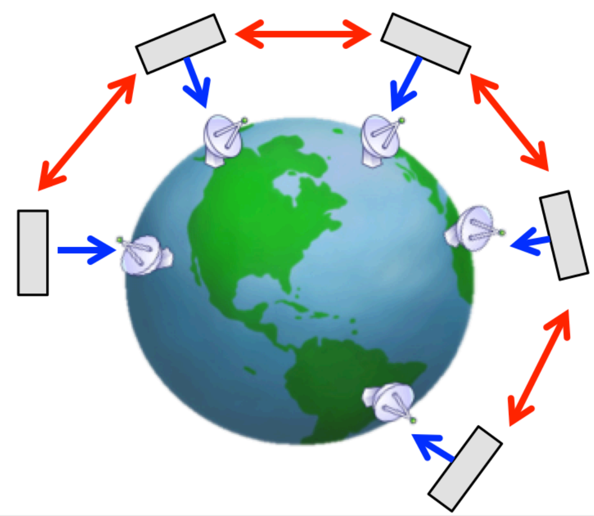
- Routing Latency results
  - For first 1 Gbit of data from each observation
  - Average of latencies for all obs data packets
- Do not yet consider satellite energy constraints

Downlink only: Blue

Example

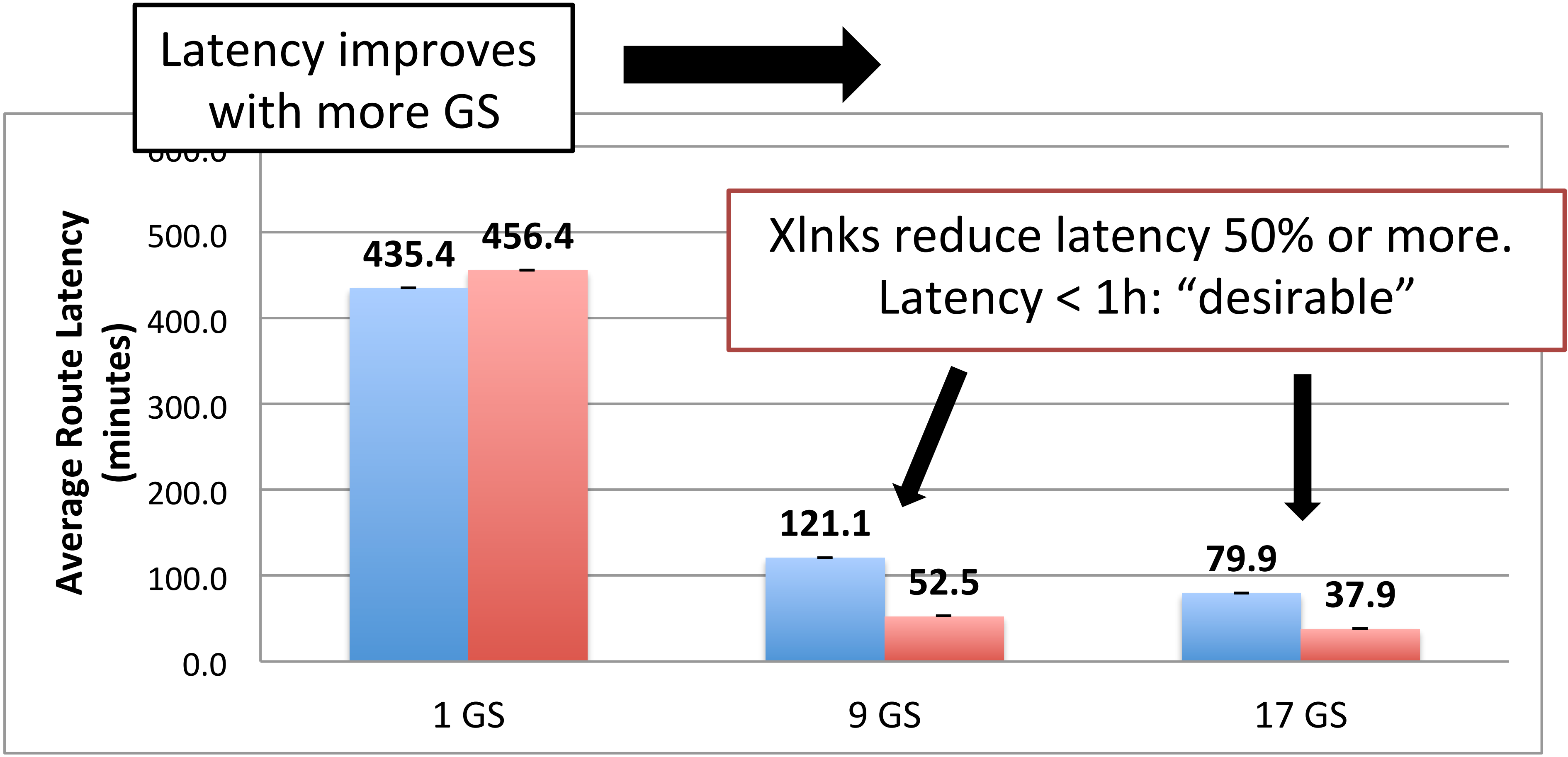


Downlink + Crosslinks: Red



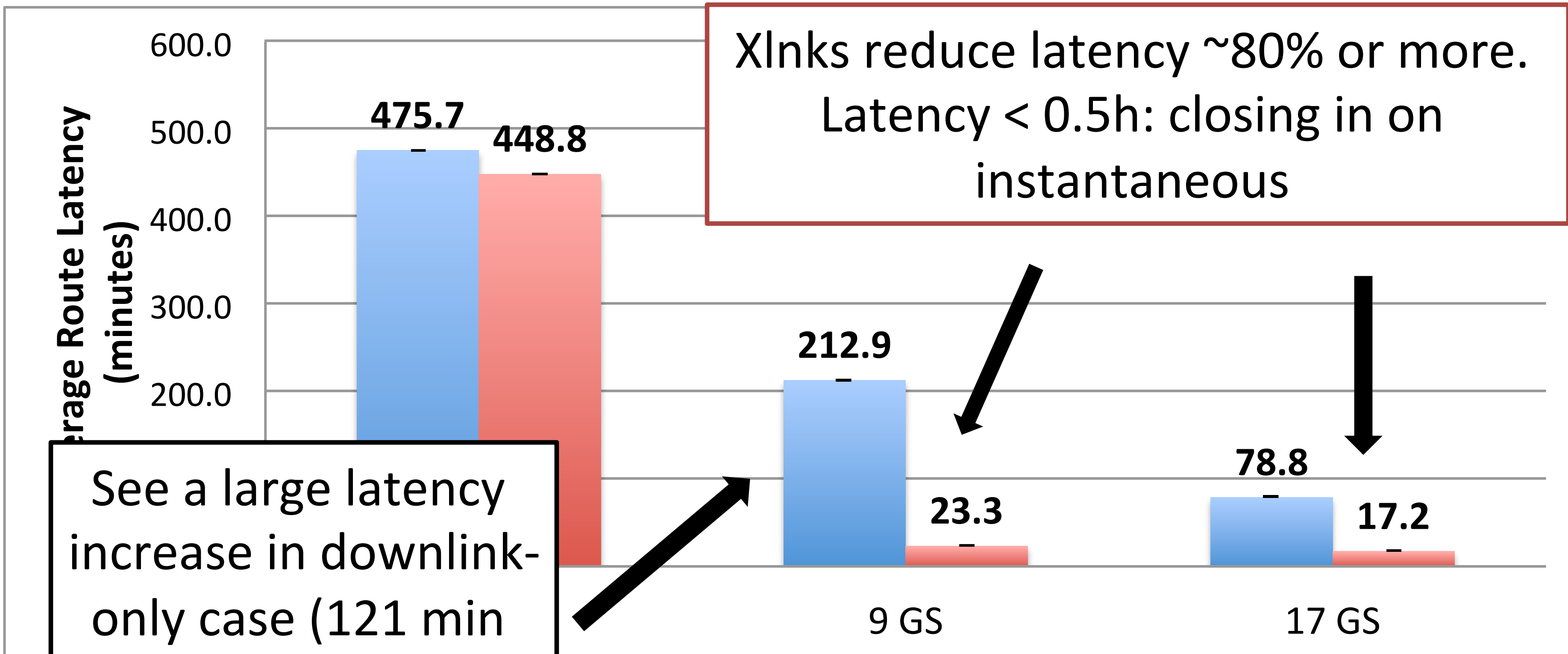
Routing Latency: 10 Sat SSO

- 10 satellites in single 10:30 LTAN SSO



Better Latency: 30 Sat Walker

- 30 satellites in a 3 plane Walker Delta pattern, 60° inc.

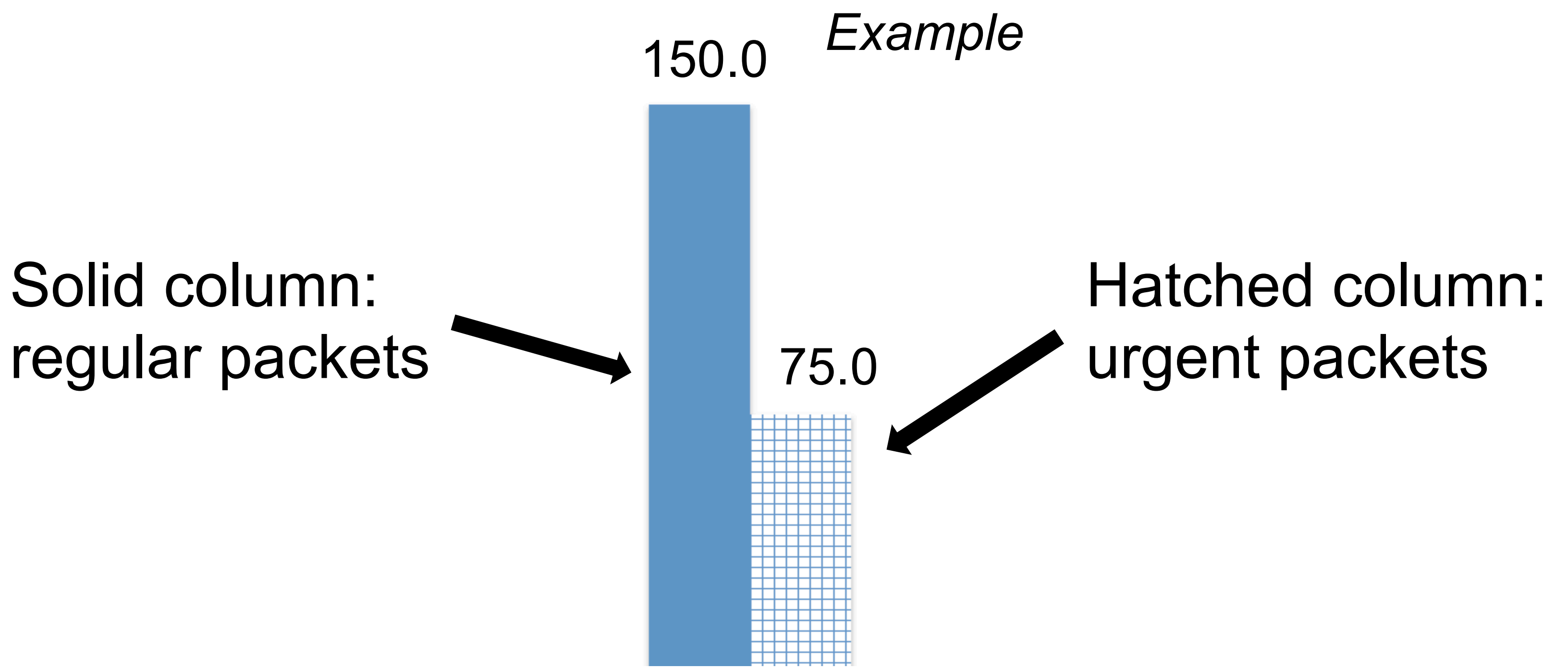


Xlnks reduce latency ~80% or more. Latency < 0.5h: closing in on instantaneous

See a large latency increase in downlink-only case (121 min for 10 sats SSO)

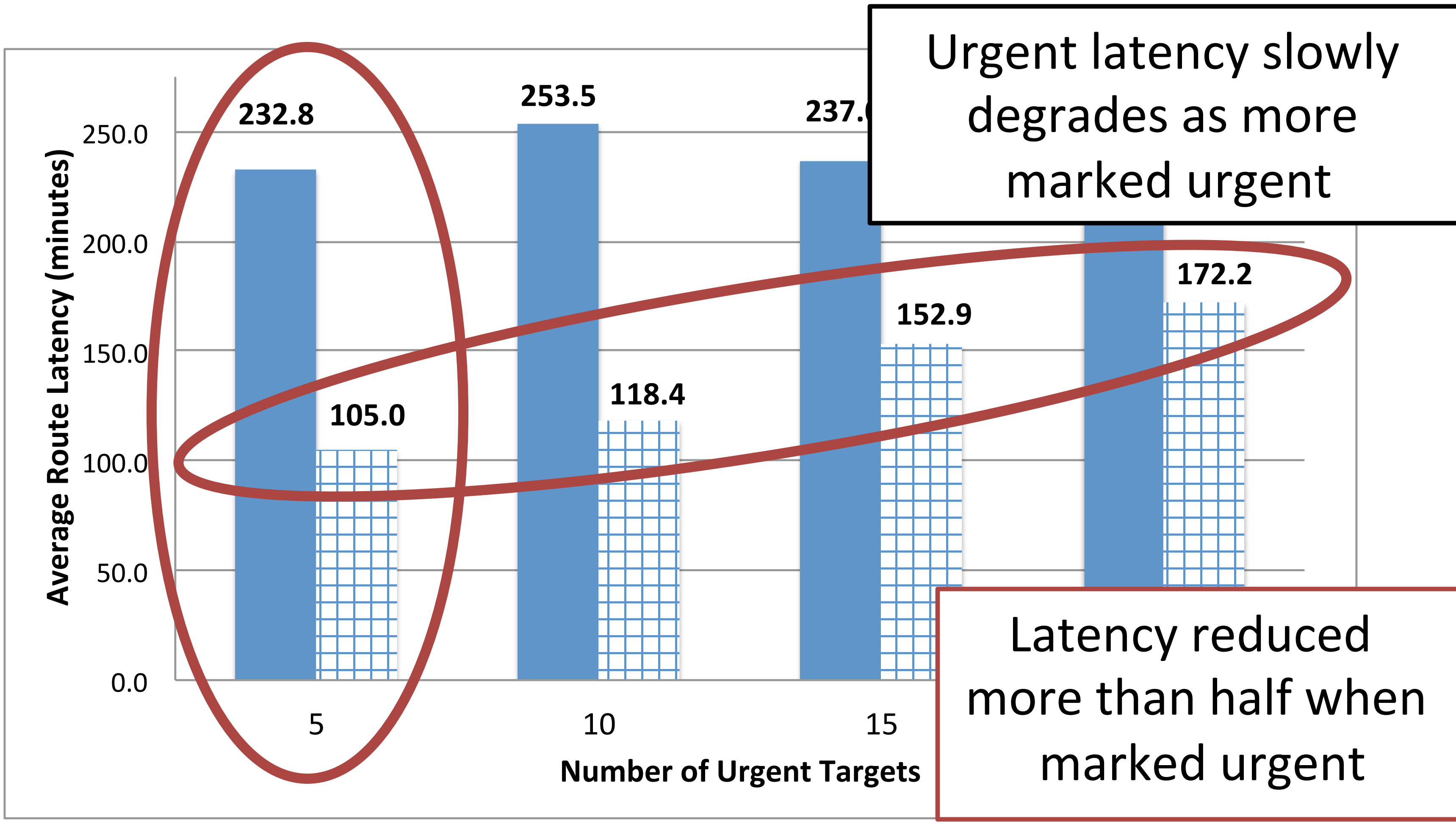
Urgent Data Routing

- Same 33 targets
- Subset of targets designated “urgent” for ~2 h durations
  - Downlinked before all other obs
  - Simulates changing observation priorities



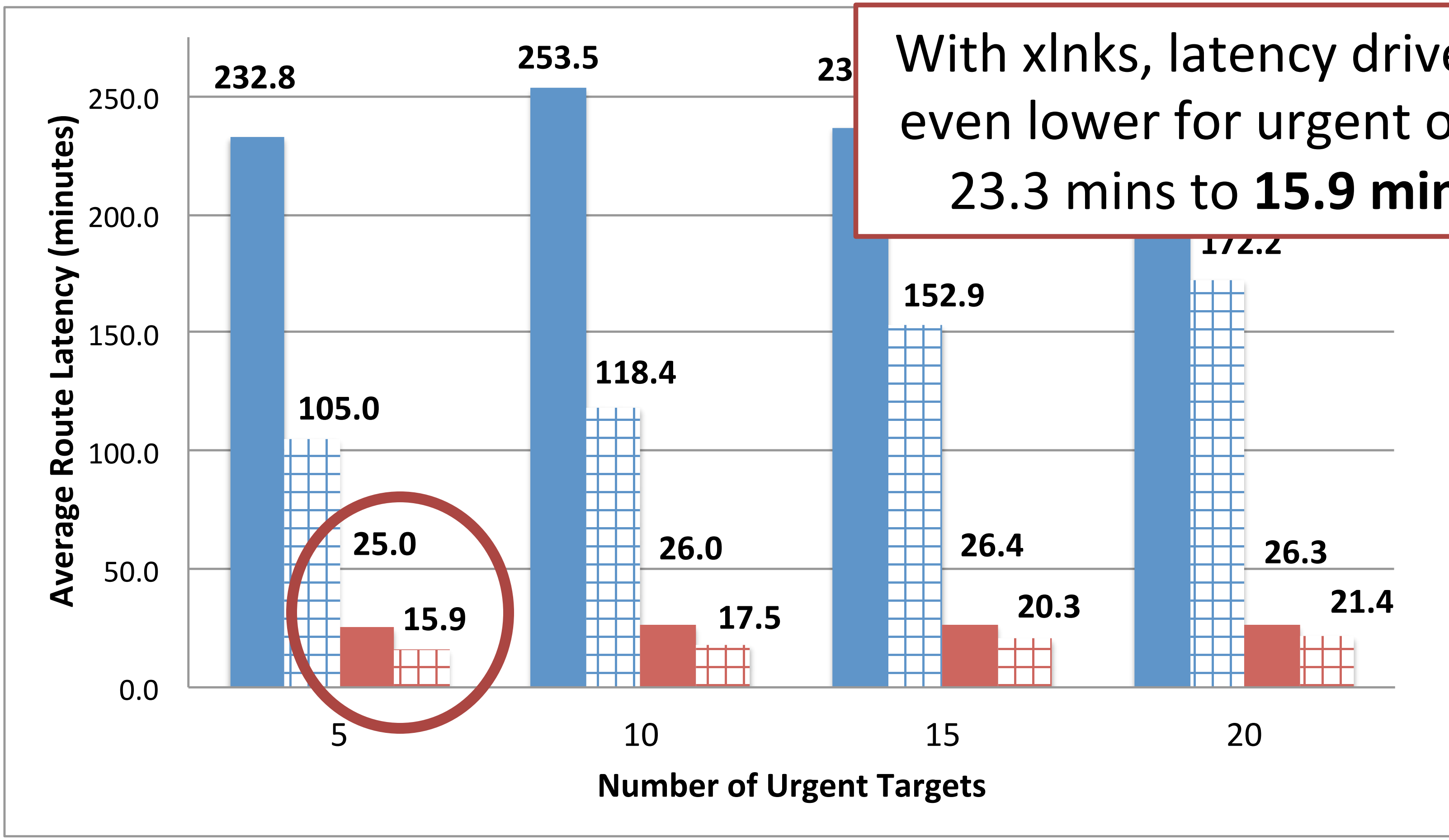
Urgent Latency, Downlink Only

- Plot with downlinks only, 9 GS



Xlinks Reduce Urgent Latency

- Plot with downlinks and crosslinks, 9 GS



With xlnks, latency driven even lower for urgent obs 23.3 mins to **15.9 mins**

Data Routing Execution Time

- Measured algorithm execution time
  - Scheduling of obs, dlinks, xlinks; data packet routing
  - Custom Python code
- For increasing constellation size
- For two planning window durations: 12 hours and 24 hours
- Run on a 2013 Macbook Pro laptop (2 GHz, 8 GB RAM)

Number of Satellites	Execution Time (mins)	
	12 Hour Window	24 Hour Window
30	0.18	0.56
60	0.94	2.92
100	4.57	13.23

Planning execution time appears tractable for scalability.

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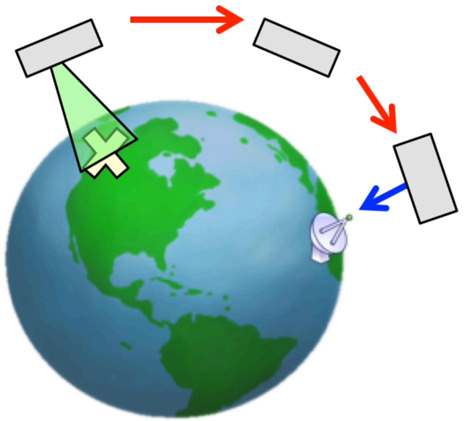

Conclusion

- Summary of results
  - Regular latency, Walker Delta with xlnks: **23 and 17 mins**
  - Urgent latency, Walker Delta with xlnks: **16 mins**
  - **Execution time of 13 mins** for 24 h window with 100 sats
- Long range crosslinks promising for low latency bulk data delivery
- Future work
  - **Algorithm improvements**: energy-aware planning, data routing optimization (utilizing e.g. MILP), onboard replanning.
  - **Additional metrics, sensitivity studies** (particularly: crosslink range and data rate, simplex vs duplex)
  - **Incorporation in operations SW stack**
  - **Open-sourcing**

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- **Slide 5**

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- **Slide 9**

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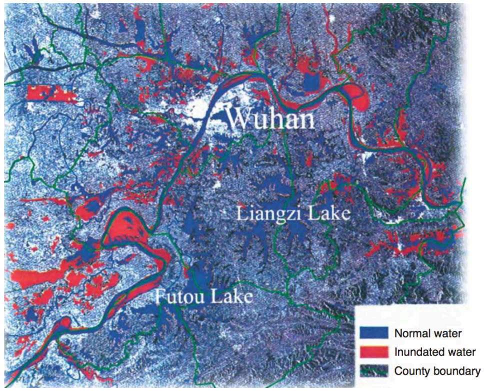
Backup

The Problem: EO Data Delivery

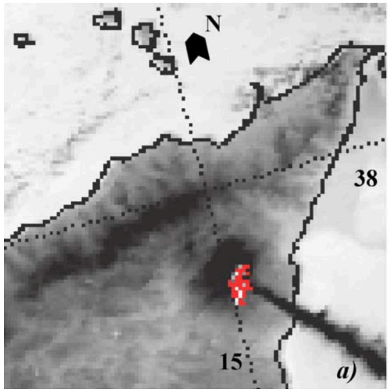
- To effectively monitor events on Earth, we need "almost instantaneous data availability" [3,4]
  - 0.5 to 1 hour [5]
  - Benchmark: 90min latency, Disaster Monitoring Constellation [3]

Floods



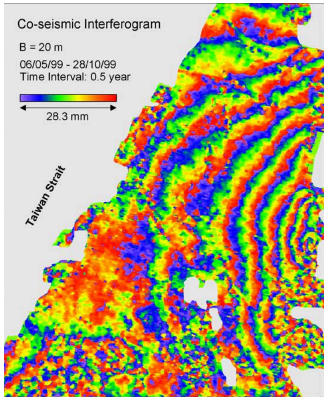
Zhang et al. [6]

Eruptions, Fires



Pergola et al. [7]

Earthquakes



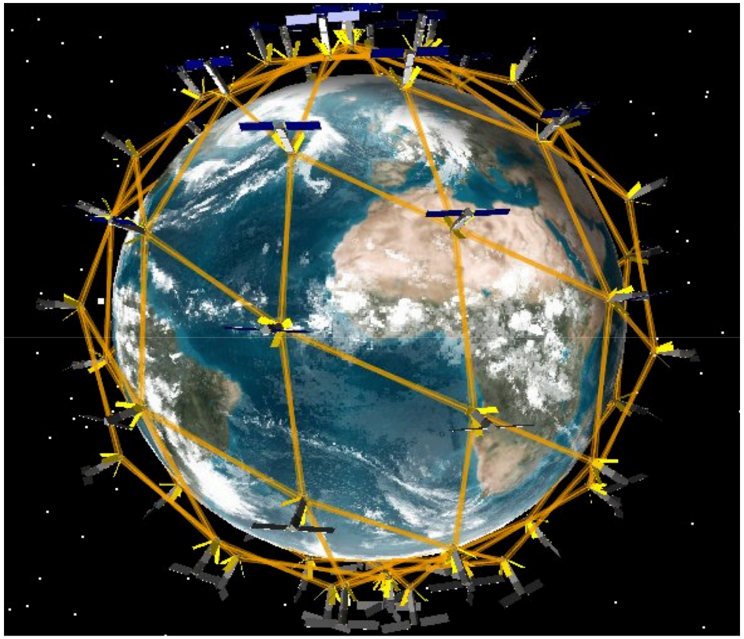
Liu et al. [8]

and more…

Constellation Crosslinks

- Inter-satellite crosslinks
  - TLM and CMD
  - Bulk data routing
- Crosslinks stress operations
  - Energy usage [9]
  - Satellite scheduling complexity
  - Constellation scheduling complexity

Crosslinks in Iridium Constellation



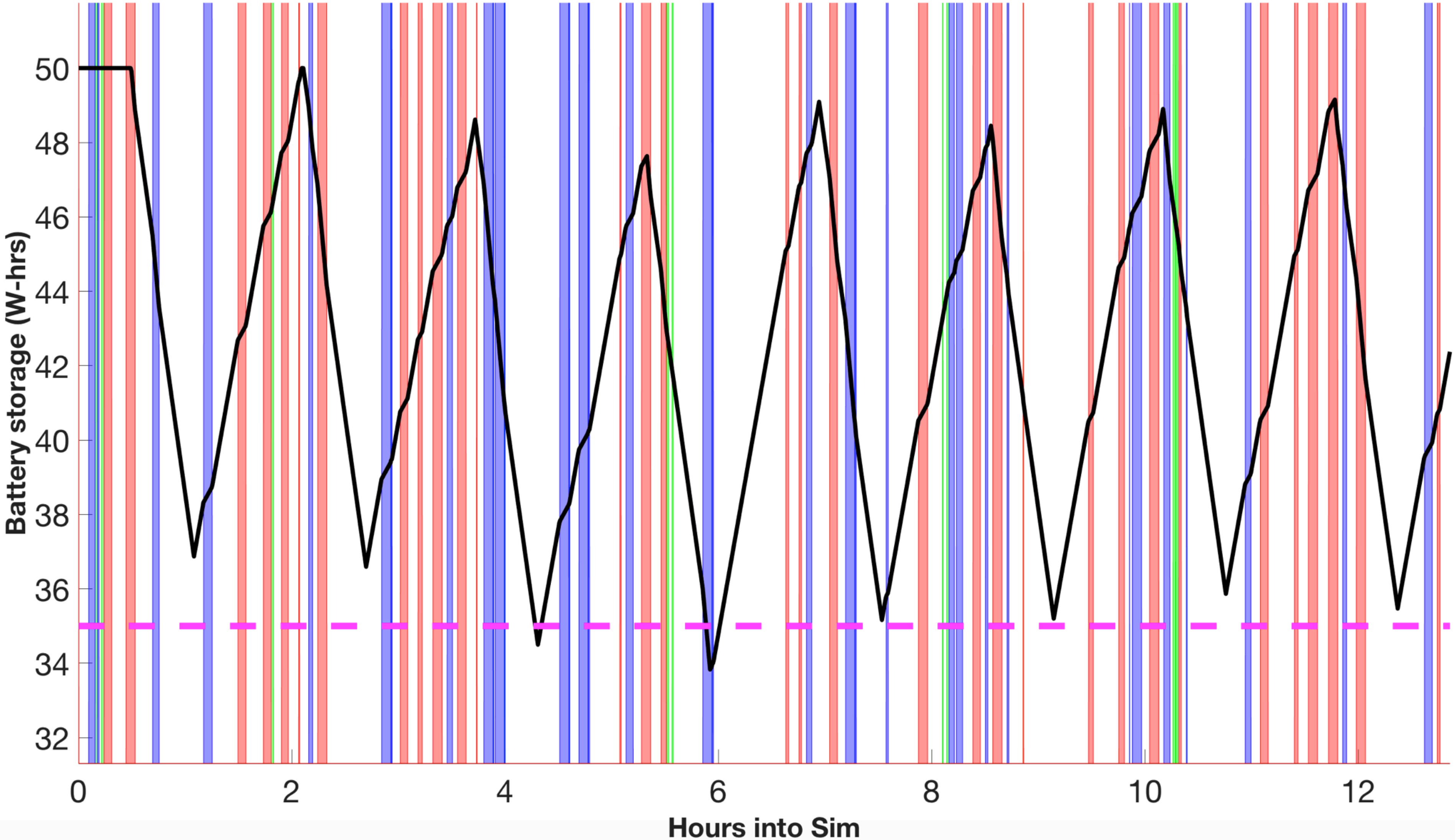
Gupta, 2007 [22]

Imaging Payload Details

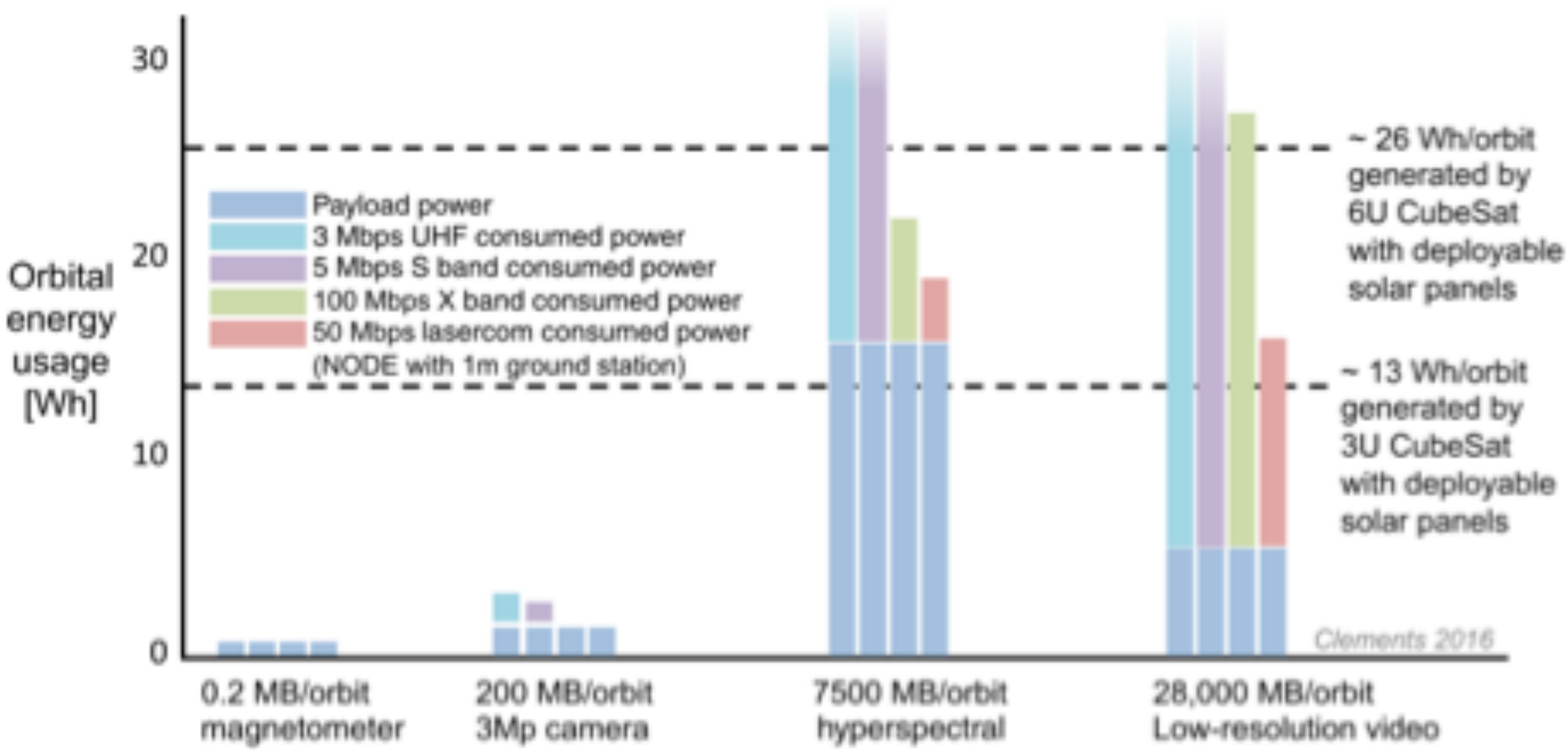
- From commercial 6U CubeSat design by Tsitas and Kingston [x21]
  - Designed to be competitive with DMC and RapidEye EO satellites
  - 600 km SSO, GSD of 6.5m and swath width of 26km
- Imager
  - Questar 3.5 telescope (89mm aperture, 20.3cm length, 1.4 kg)
  - Fairchild imaging CCD5061 (4000 pixels, 12 bit digitization)
- 5 spectral bands, 255 Mbps uncompressed
  - 2:1 lossless compression -> 127.5 Mbps

Altitude and orbit	Nadir GSD	Swath	Spectral bands	Optical MTF	Imager MTF	Digitisation	SNR
600km Sun synchronous	6·5m	>25km	440-510nm (Blue)			12 bits	154
			520-590nm (Green)				168·4
			630-685nm (Red)				142
			690-730nm (Red edge)				117
			760-850nm (NIR)				174·6
				@ 1/2 Nyquist (0·7 field) > 55% @ Nyquist (0·7 field) > 20%	@ Nyquist (0·7 field) ≥ 7%		

Example Plot of Battery Level



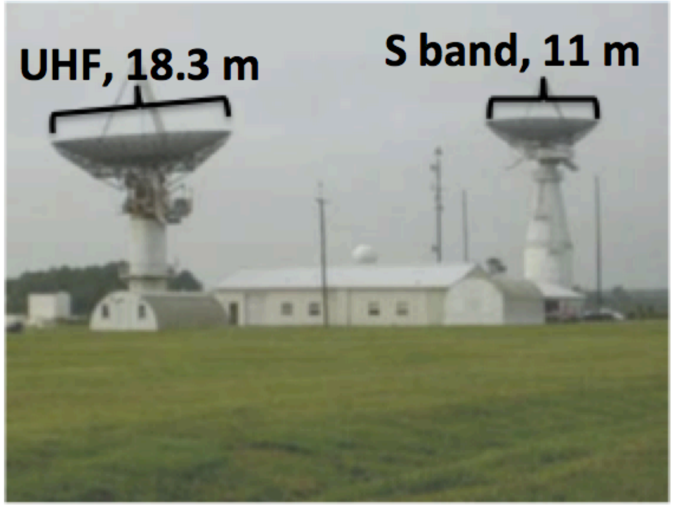
Payload/Comm Energy Usage



Clements et al, 2016

Motivation

- What if there were a **low cost** way for a CubeSat to downlink 100 Gb/day?
  - Most CubeSats downlink << 10 Gb/day (UHF or S-band systems) [1]
- Radio frequency (RF) downlinks challenged by resource constraints
  - E.g., ground station size, transmitter power, or spectrum
- **Lasercom is less resource constrained and could scale to Gbps[3]**
  - More power-efficient for given size, weight, and power (SWaP)
  - More bandwidth available
  - Many groups working on it: MIT, Aerospace Corporation, Sinclair, UF, DLR, JAXA, …

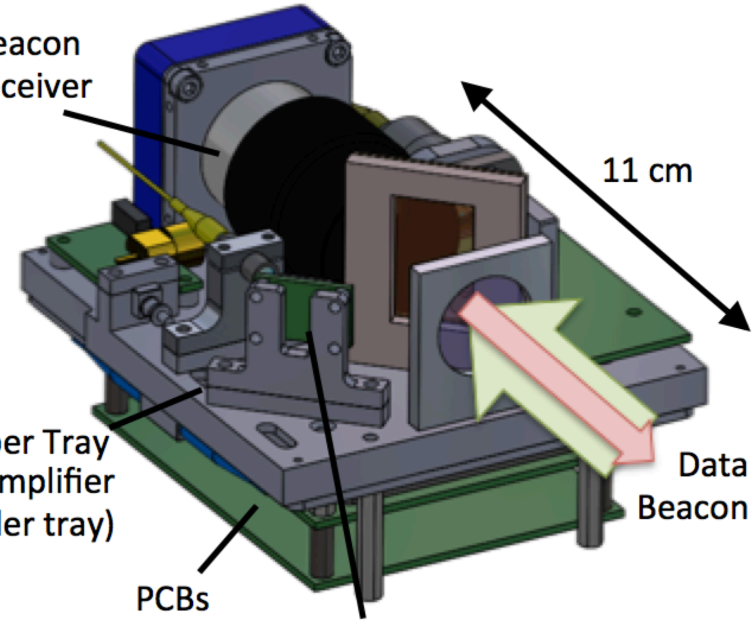


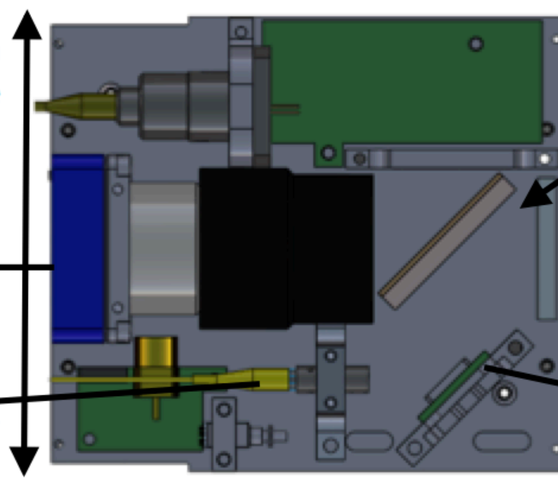
Wallops CubeSat Comm. Antennas[2]

MIT Lasercom Ground Station

NODE Space Terminal Overview

Scope	CubeSat **Low-Cost** Payload (<$15k parts)
Architecture	Direct detection MOPA COTS telecom parts (1550 nm)
Downlink data rates	10 Mbps (30 cm amateur telescope) 100 Mbps (1 m OCTL)
Power	0.2 W (transmit power), 15 W (consumed power)
Beamwidth	1.3 mrad half power (initial demo)
Modulation	PPM
Coding	RS(255,239)
Mass, Vol.	1.0 kg, 1 U
Control architecture	• Bus coarse pointing (<0.5°) • FSM fine steering (+/- 2.5°) • Beacon receiver (976 nm) for pointing knowledge (20 arcsec)
Current Status	• Pointing control testing • Component-level environmental tests • Functional testing • End-to-end over the air demo



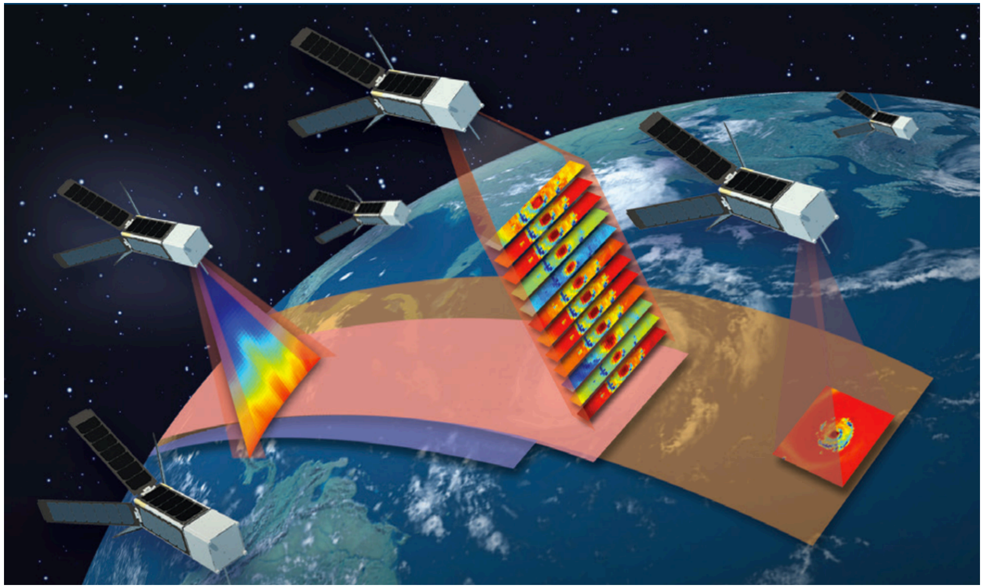


Future Work

- Deployment of global planner algorithm on ground software stack (e.g. Ball Aerospace's COSMOS)
- Deployment local (satellite) planner algorithm on flight software stack (e.g. NASA Goddard's cFS)
- Incorporate more versatile observation payload and satellite operations modeling
- Open source release of ACCESS software for use by the wider small sat community.

Earth Observing Constellations

- Advantages [1]:
  - Higher temporal resolution
  - Multi-point instrument coordination
  - Low-latency data availability



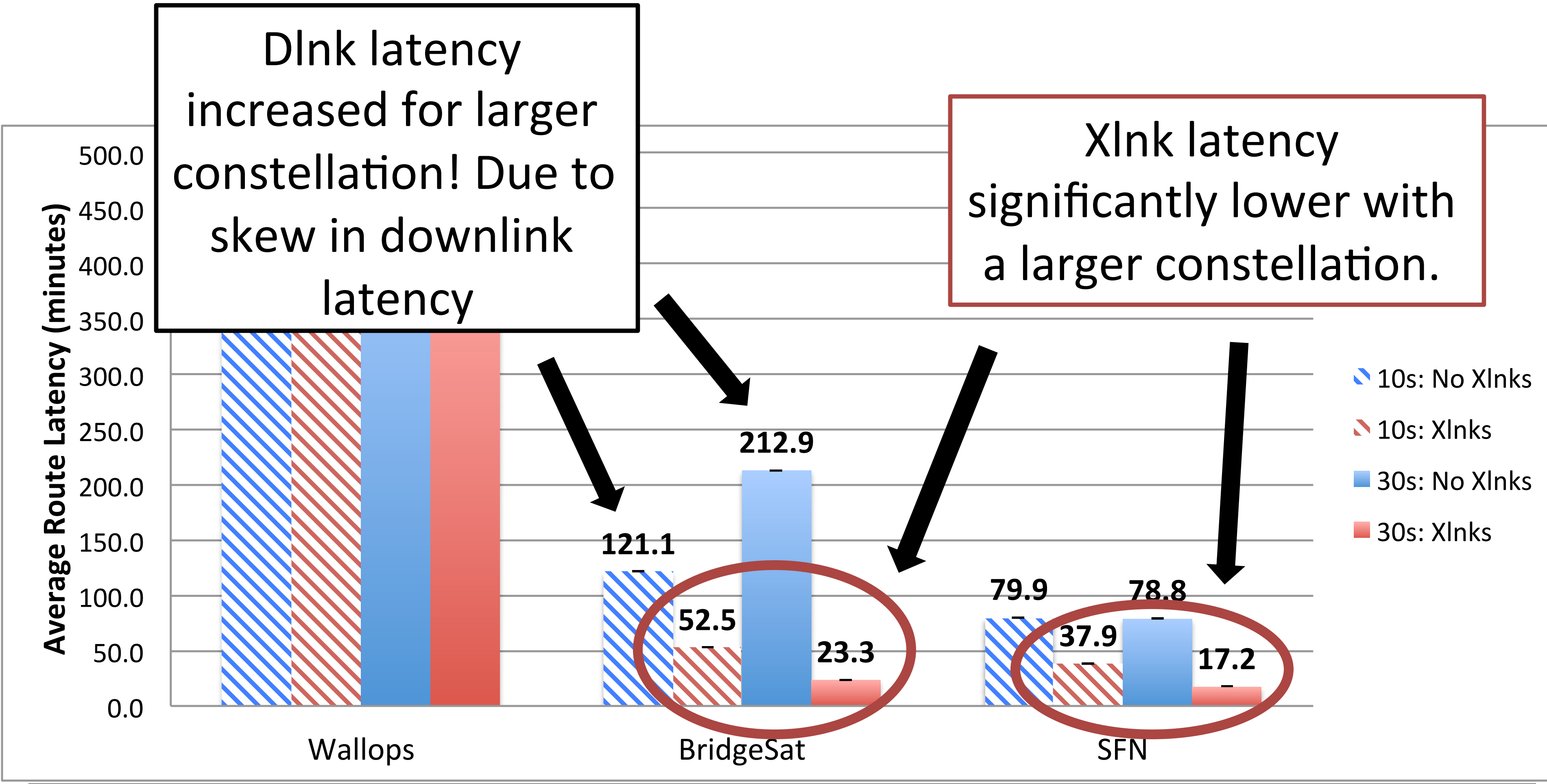
TROPICS Mission, MIT LL [2]

Large GS Network Deployment

- Ground Stations
  - Expensive to deploy
  - Lots of organizational/legal overhead
  - Very hard to deploy across oceans
  - For lasercomm, clouds can hinder downlink
  - For commercial networks
    - Still have to pay for usage
    - Have to worry about schedule access

Latency: Both Geometries

- Combined latency plot of 10 sat SSO, 30 sat Walker



More revisits, lower latency

- What we need:

Lower inter-revisit times to targets

Less time from data collection to delivery

- How we get there

Larger constellations → • More frequent flyovers of targets

More ground stations → • lower wait time for downlink
• more total volume to ground

Inter-satellite crosslinks → • route data to downlinks
• distribute bandwidth over ground stations

Scaling Operations

Need an automated operations approach that:

Scales to many satellites (tens to hundreds)	• Human-in-the-loop planning scales linearly with number of satellites [x3]
Efficiently balances data collection and routing	• EO Data rates of 100 MB to TB per orbit [x2,x4,x5] • Often impossible to fully downlink all data
Handles unique constraints of CubeSat platform	• Limited comm. availability • Low energy generation, storage • Multi-modal measurements

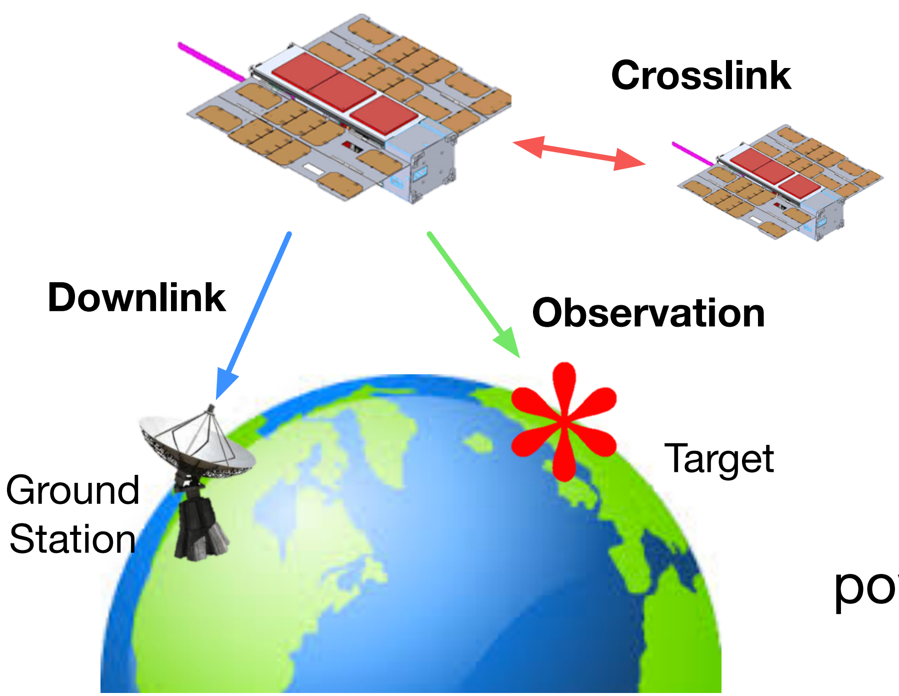
ACCESS Design Goals

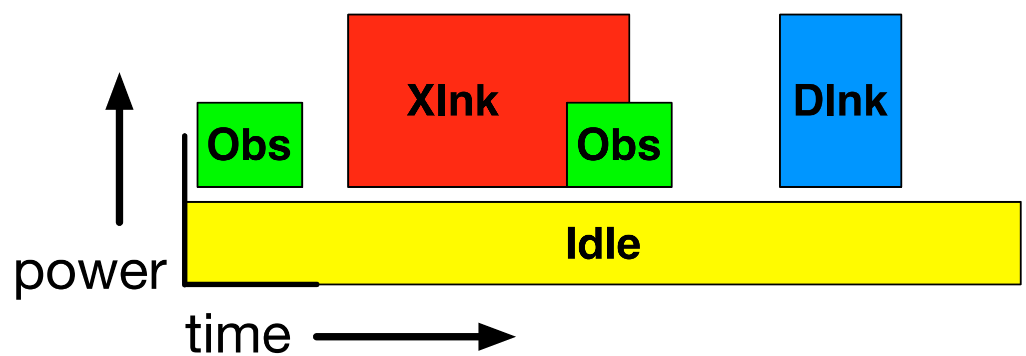
- Efficiently manage data collection and routing to ground
  - Schedule observations, downlinks, and crosslink to balance fast downlink of key data with bulk data delivery
  - “efficient” – not optimal scheduling, but close enough
  - **Key advantage: crosslink routing built directly into algorithms**
- Allow scalability to 100s of satellites
  - Scheduling divided based on constellation-level and satellite-level constraints
  - Sacrifices some degree of optimality in scheduling for better tractability
- Enable reactive and federated constellation operations
  - Satellites have some freedom to replan activities
  - Allows reactivity for disaster monitoring, multi-constellation cooperation
  - **Key advantage: loose coupling of planning responsibility between ground and satellites**

ACCESS CubeSat Ops Model

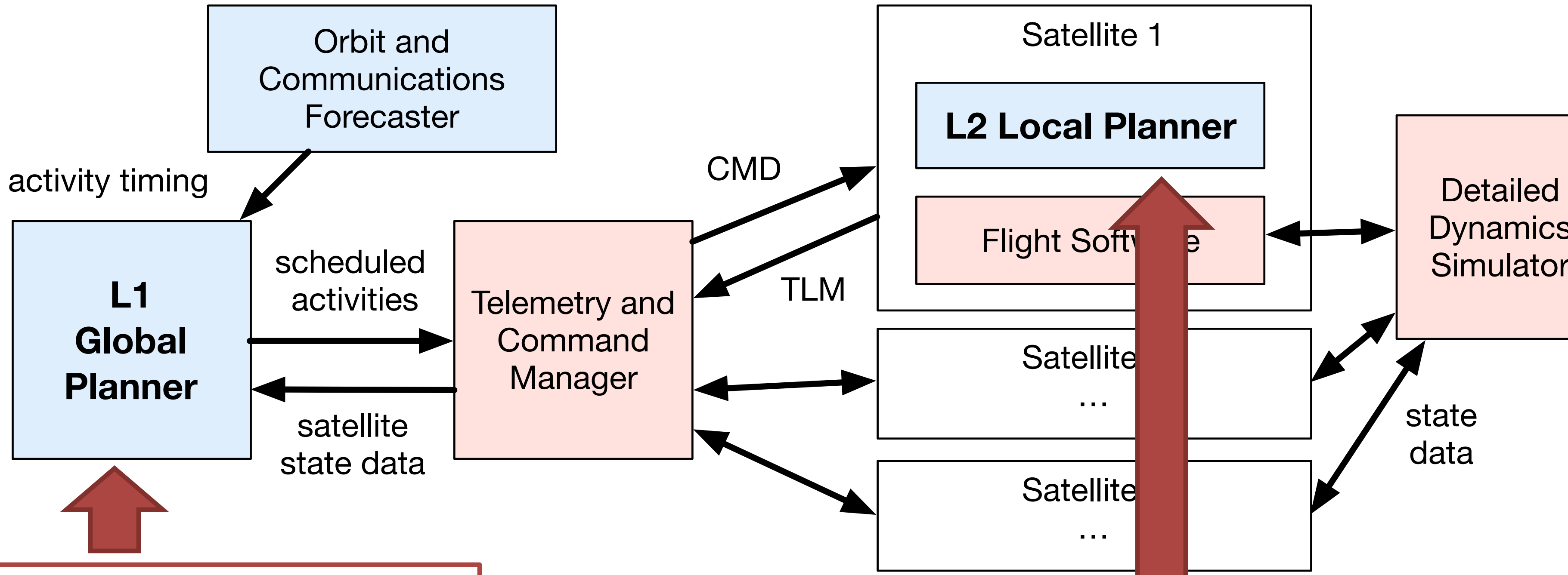
- 3 activities
  - Observation
  - Crosslink
  - Downlink

- Power usage for activities added on base-level (“idle”)





ACCESS Architecture



Ground. Considers:

- Data collection
- Data routing through xlnk, dlnk

Activity timings, weightings ⇒

Satellite. Considers:

- Current sat state
- New observation opportunities

Background: Scheduling

- Algorithms and software exist for small satellite scheduling
  - Manage activity timing and limited onboard resources
  - e.g. Planet Inc. [x8], Multi-Sat Multi-GS scheduling [x9], ASPEN/ CASPER [x10], STK Scheduler [x6,x7]
- EO constellation management adds difficult logistics
  - Tasking satellites with observation targets [x8]
  - De-conflicting downlinks between satellites [x8,x9]
  - Maintaining schedule synchronization across constellation [x11,x12,x13,x14,x15]
- Using crosslinks as data routes add more complexity
  - At first glance, number of connections between satellites grows as N^2