Smart Small Satellite Constellations

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Overview

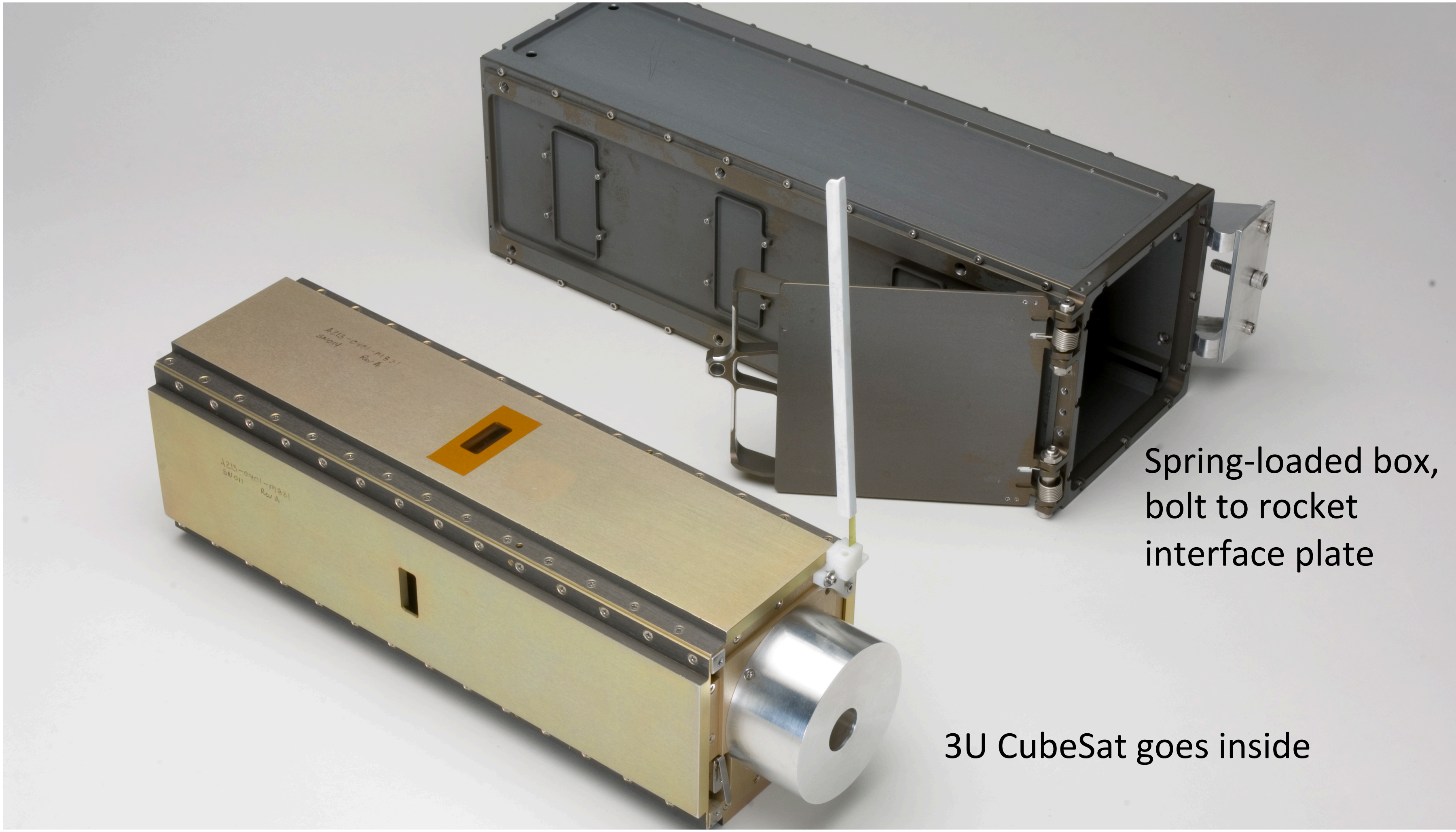
- What is a CubeSat?
- What is the difference between a SmallSat and a CubeSat?
- What are the benefits of SmallSat or CubeSat constellations?
- Example Commercial constellation
- Example Research constellation
- Approach for Smart Small Satellite Constellations
- Enabling Technologies
- Future Vision

What is a CubeSat?

- On the scene in 1999
  - Jordi Puig-Suari (Cal Poly SLO)
  - Bob Twiggs (Stanford)
  - "OPAL" Orbiting Picosatellite Automatic Launcher
  - *"Too complicated"*
  - Beanie babies vs. Klondike bars
- 1 standard CubeSat unit (1U)
  - Volume: 10 x 10 x 10 cm
  - Mass: < 1.33 kg
  - Common sizes: 1U, 1.5U, 2U, 3U…
  - Now 6U… 12U?
- Low cost and short development time
- **Increased accessibility to space**

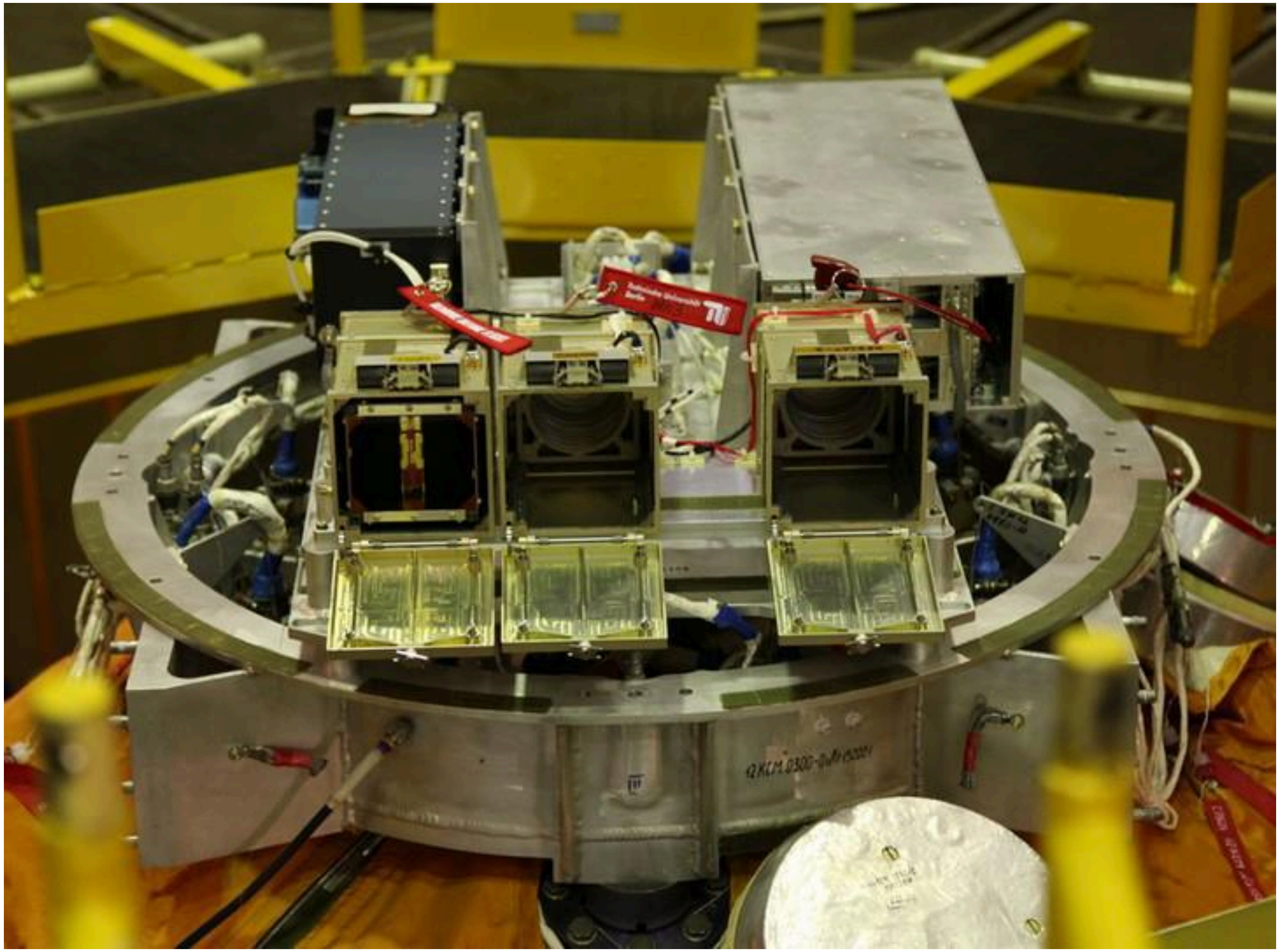
https://directory.eoportal.org/web/eoportal/satellite-missions/o/opal, credit SSDL

Poly-Picosatellite Orbital Deployer



http://www.nasa.gov/centers/ames/images/content/152693main_genebox-015.jpg

Launch integration on Rocket

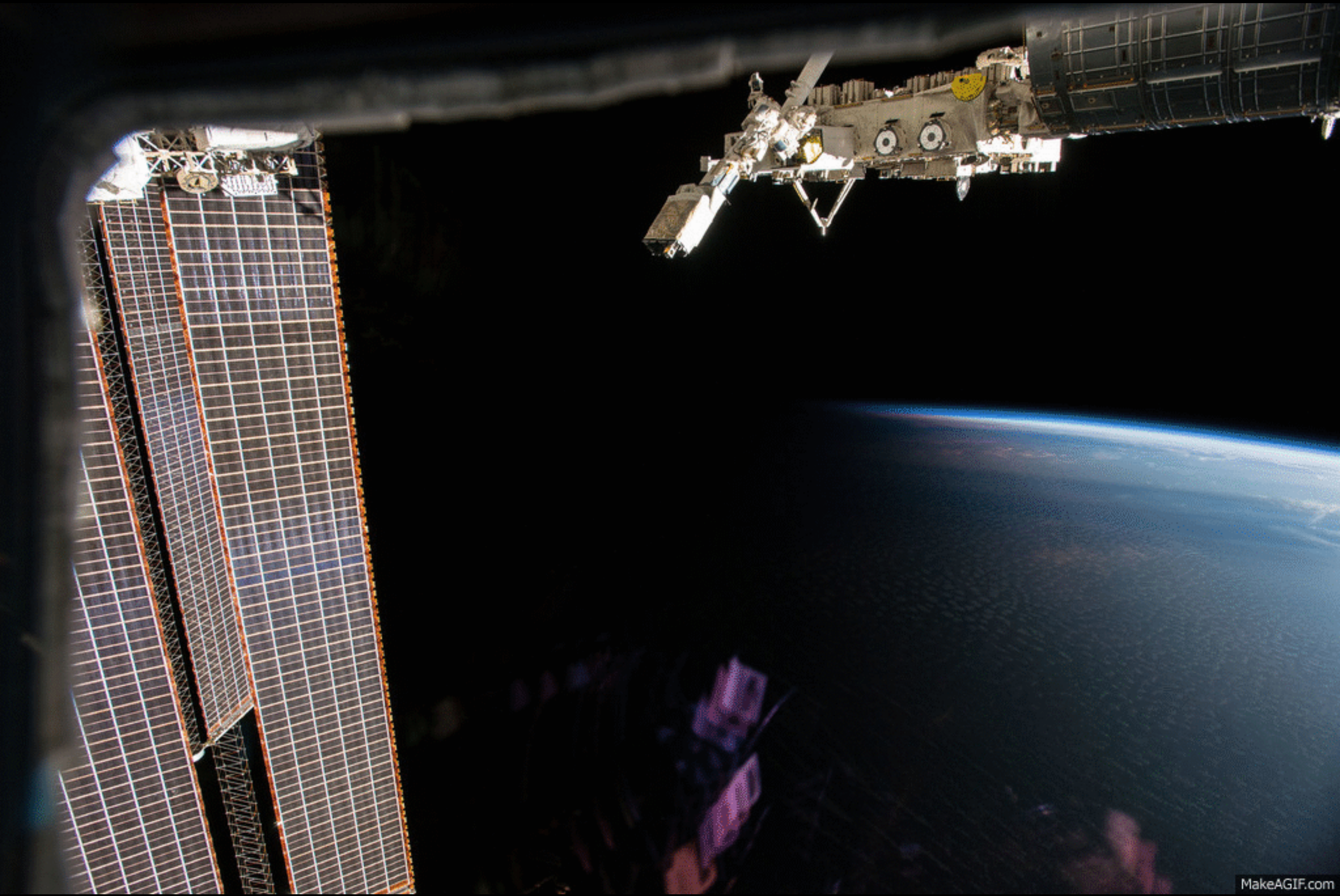


CubeSat deployment pods on top of the Bion-M1 spacecraft: BeeSat-2, BeeSat-3 and SOMP in front; OSSI-1 (1U) in a 3U-Pod back left; DOVE-2 (3U) in back right. *http://amsat-uk.org/tag/beesat-2*

Also can launch from Space Station

- Deliver to NanoRacks
- Get integrated into NRCSD
- Get integrated into Cargo
- Cargo integrated into spacecraft (here, Cygnus, or Dragon, etc.)
- Spacecraft shipped to launch site
- Spacecraft integrated into rocket
- Rocket launch (here, Antares, or Falcon-9, etc.)
- Spacecraft separation
- Spacecraft rendezvous with ISS
- Spacecraft unpacked
- Cargo unpacked
- NRCSD integrated to slide table
- Slide table through airlock
- NRCSD onto JEMRMS
- Deployment

Cygnus being unberthed from Harmony module
http://www.flickr.com/photos/nasa2explore/12644390754/


MakeAGIF.com

- Space is **hard**
  - Rocket vibration, shocks
  - Rockets can fail/explode
  - It's far away
  - Vacuum
  - Microgravity
  - Hot / cold temp. swings
  - Radiation / solar storms
  - Things break – *how to fix?*
  - Hard to find small objects
  - Lots of paperwork
  - Expensive to get there
  - Expensive ground staff

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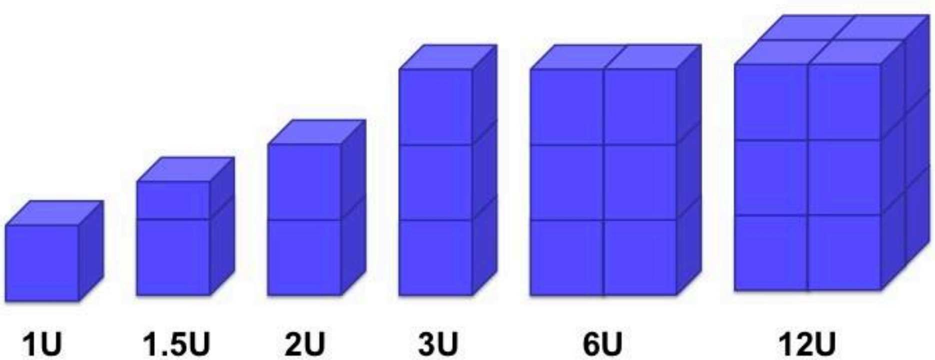
- **<u>Space is also awesome</u>**
  - Helps us answer "why are we here?"
  - Incredible ability to observe Earth
  - Persistent, global access

SmallSat vs. CubeSat

- Small Satellites have total (wet) mass less than 180 kg
  - About the size of a small refrigerator
- Minisatellite, 100-180 kilograms
- Microsatellite, 10-100 kilograms
- Nanosatellite, 1-10 kilograms
- Picosatellite, 0.01-1 kilograms
- Femtosatellite, 0.001-0.01 kilograms

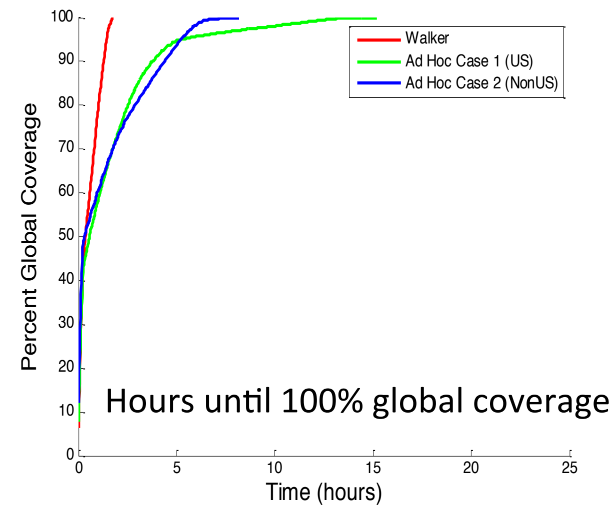


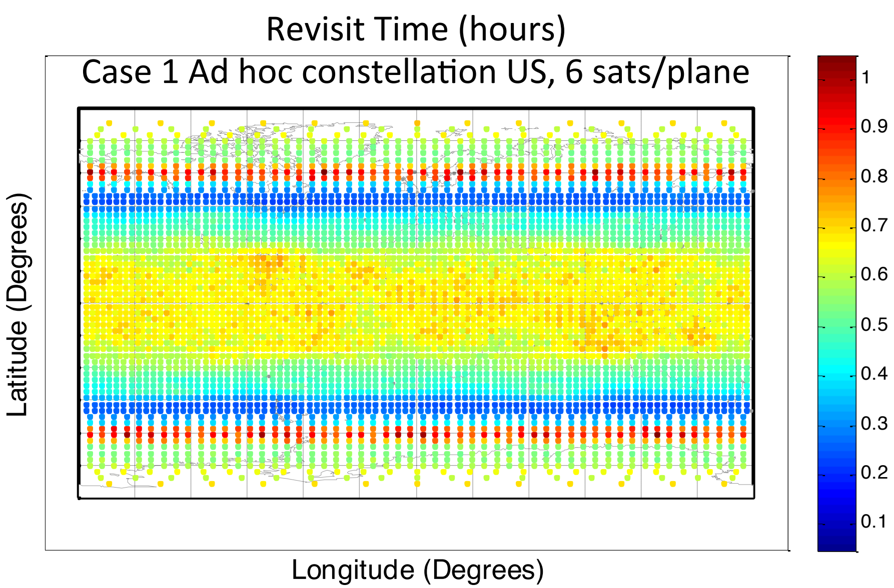
http://www.nasa.gov/content/what-are-smallsats-and-cubesats
https://directory.eoportal.org/web/eoportal/satellite-missions/d/dubaisat-2

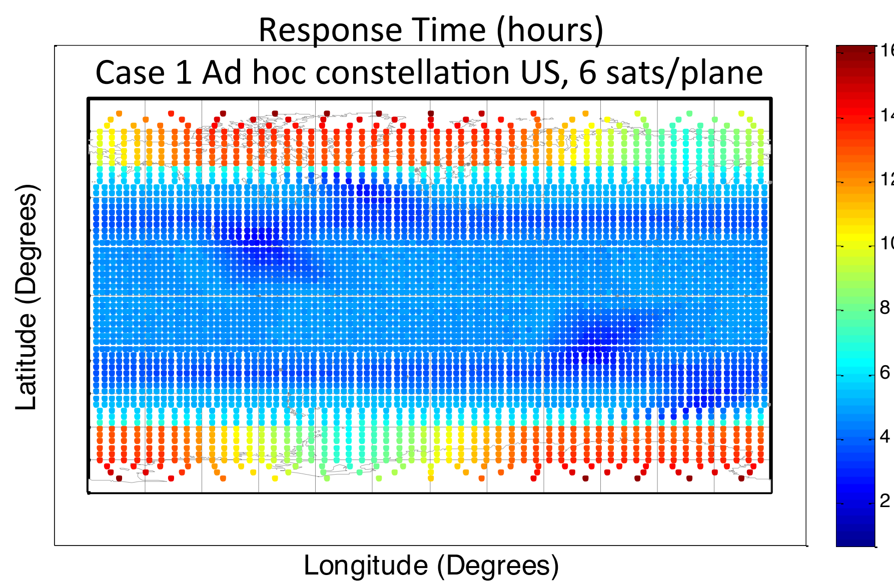
Dnepr fairing
2013 cluster launch

Why are more satellites better?

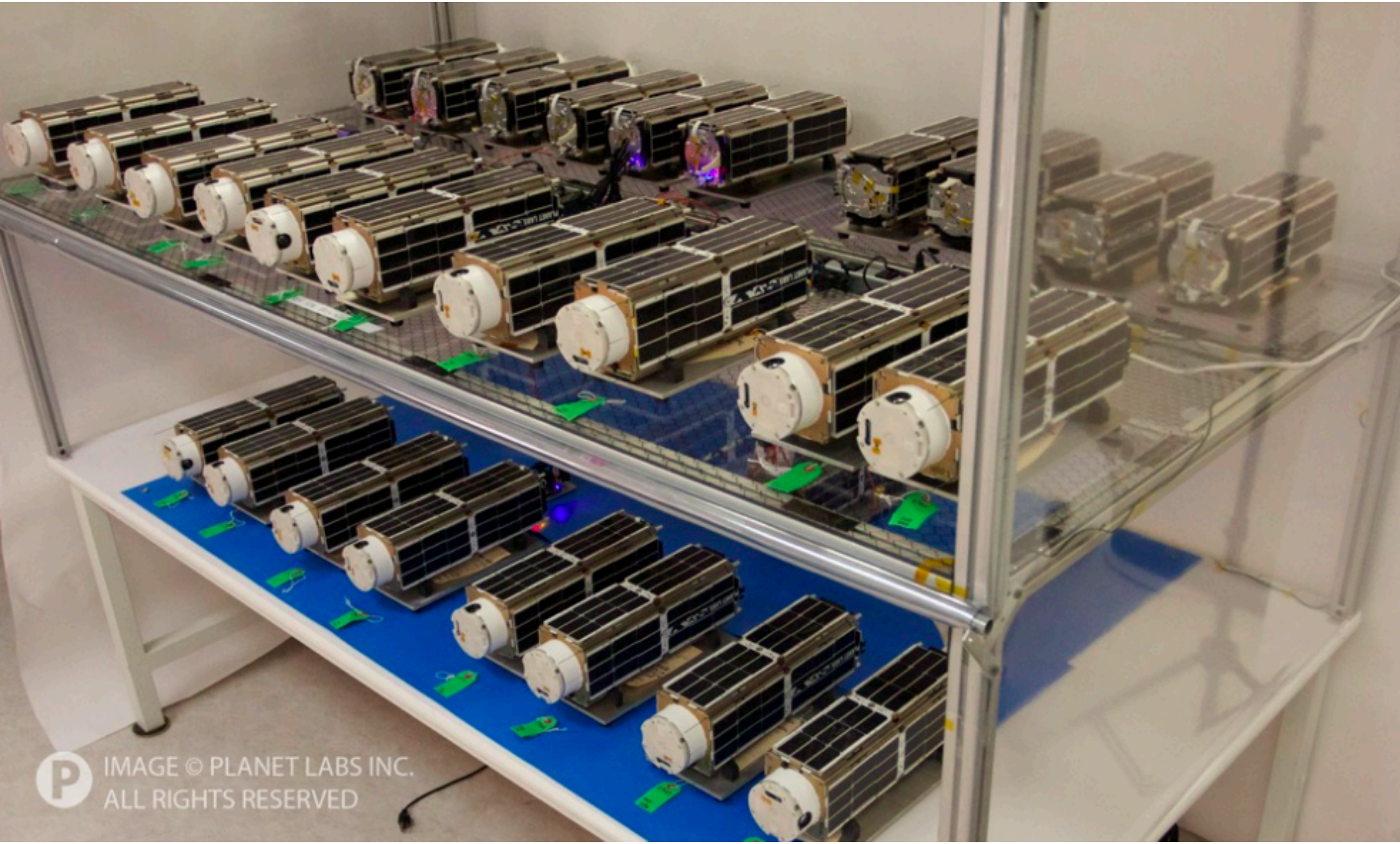
- Temporal coverage (revisit time)
- Spatial coverage (global)
- Redundancy
- Distributed sensors/function
- Lower cost
- Easier access to space, replenishment and technology advancement



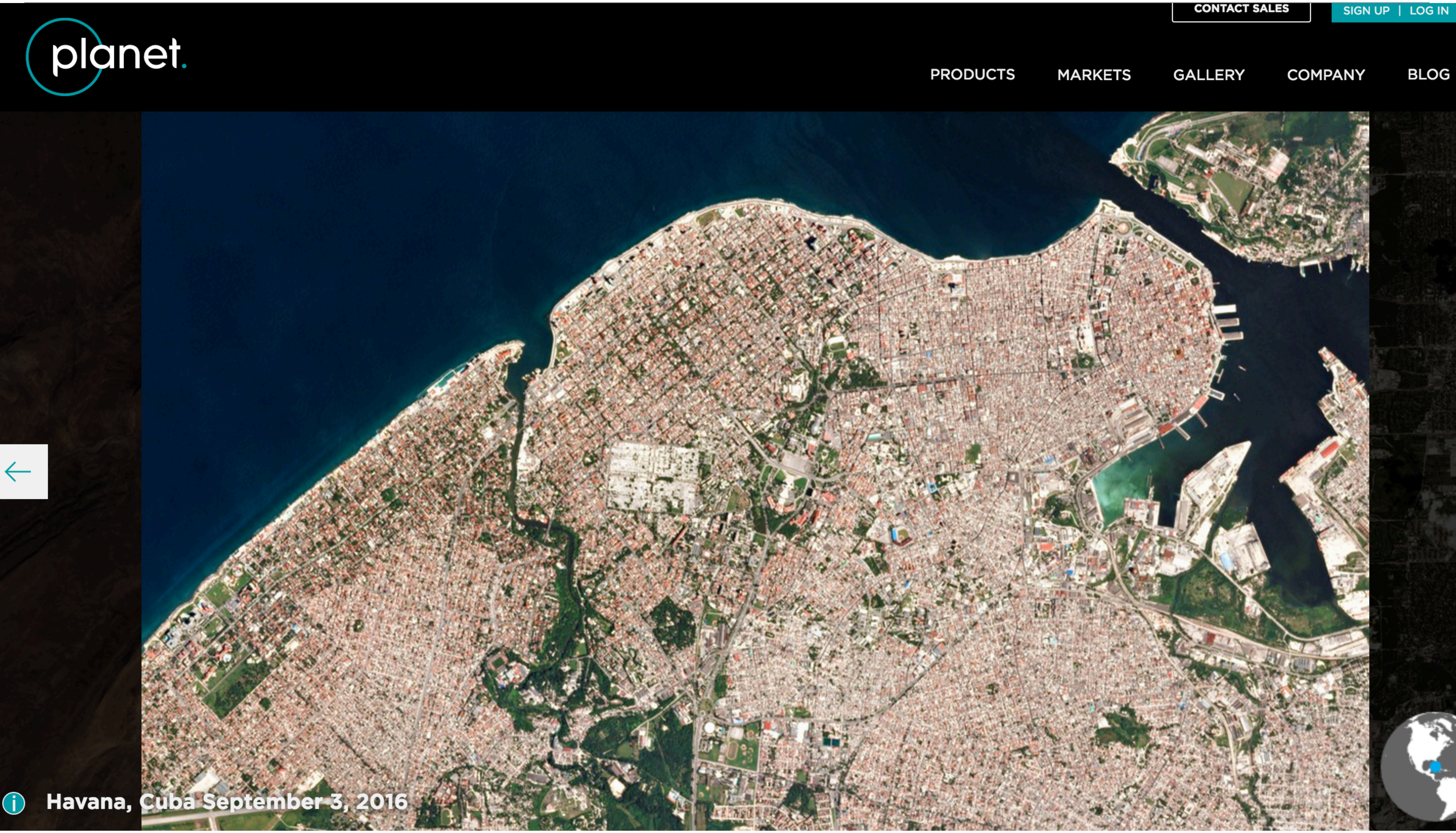




Can launch *many* CubeSats easily



Commercial Constellation Example: Planet

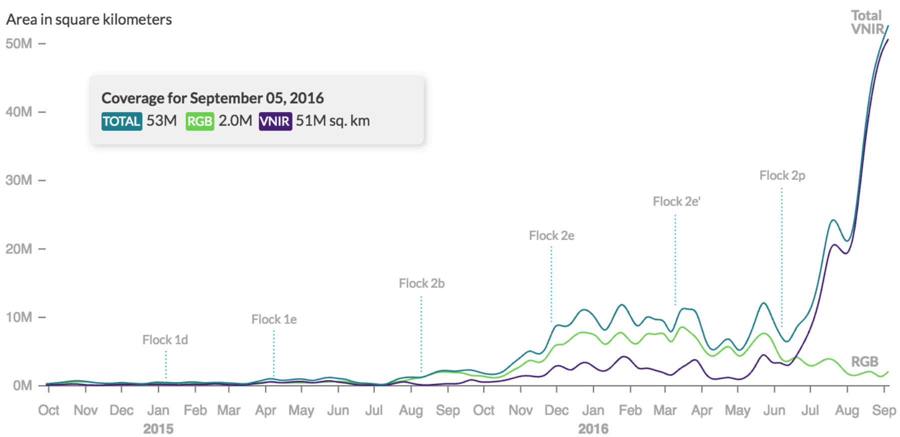


Planet CubeSat Image of Havana, Cuba, 9/3/2016 (3-5 m resolution)

Planet CubeSat Constellation

Land Surface Area Imaged Daily

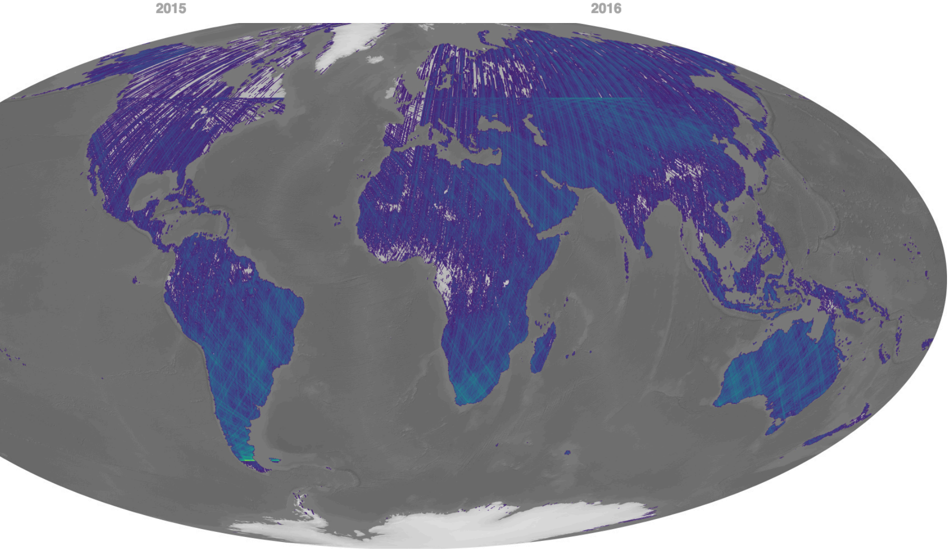
Launches ranging from four to a couple dozen Doves at a time, our aptly named 'flocks' dramatically increase our imagery cadence with each deployment.



63 ACTIVE SATELLITES

30+ DOWNLINK GROUND STATIONS

1.6 TERABYTES PER DAY

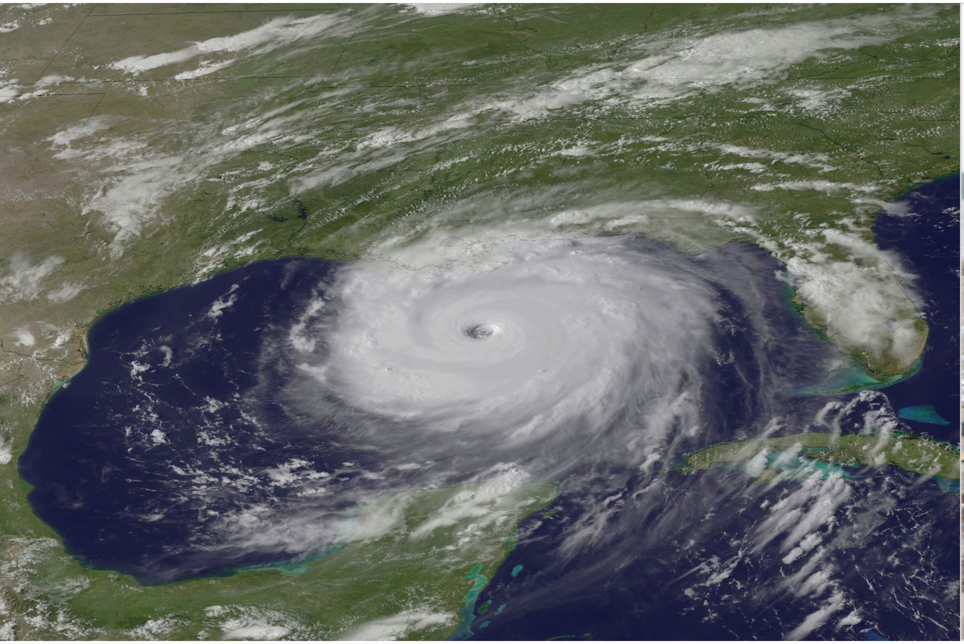


IMAGES COLLECTED DURING SEPTEMBER 2016

Doves	Builds 1-5	Builds 6-10	Builds 11-13
Operational Period	2011-2012	2013-2014	2015-2016
Optics	Off-the-shelf optics, narrow field of view	Custom telescope, focus mechanism	Second generation telescope with twice the field of view
Communications	Off-the-shelf S-band radio downlink	Custom X-brand radio downlink	Optimized comms system to gain – 500% increase in download rate, new antennas
Power	Lithium ion 7/5 AA cells, limited-efficiency solar cells	Custom pack with fuel gauge, solar charge controller, silicon solar cells	100% battery capacity increase, high efficiency solar cells
Spectral Bands	Red, Green, Blue	Red, Green, Blue	Red, Green, Blue, NIR
Image Quality	Image vignetting, low SNR, suboptimal optical quality	Improved optical quality	Vignetting removed, good SNR, quality optical alignment
Capacity (km2/sat/day)	3,000	500,000	2,500,000

https://www.planet.com/pulse/firehose/#more-2603

Research constellation example: weather prediction



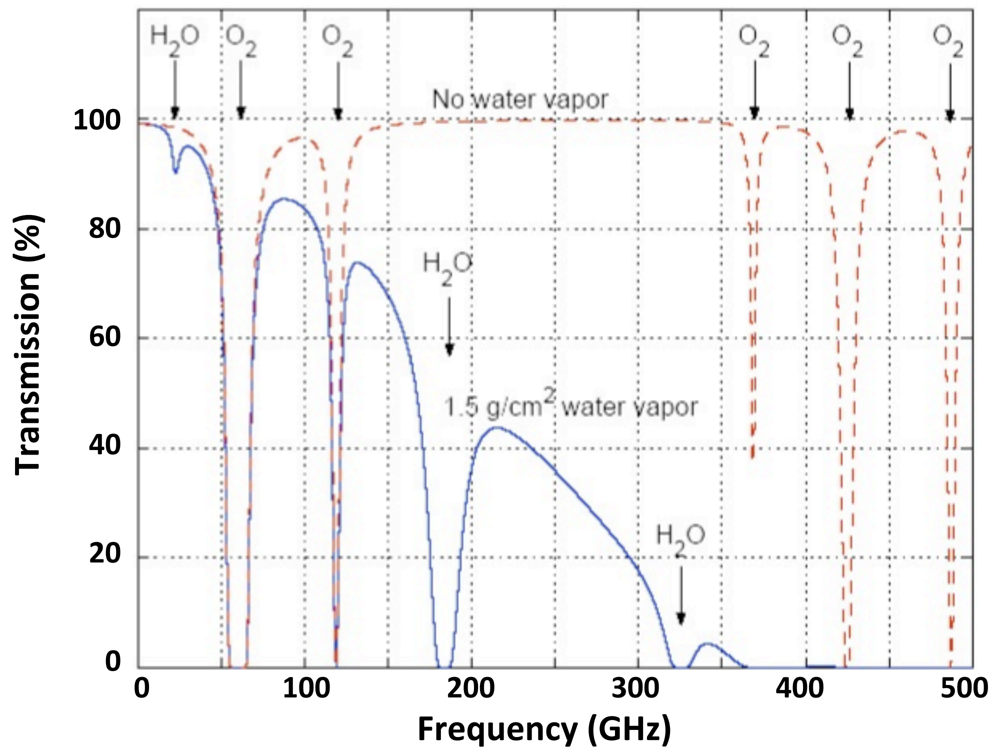
- The US derives $32 B of value from weather forecasts annually[1]
- Earth observing satellites drive the forecasts
- Eternal quest for resolution: Spatial (vertical and horizontal), temporal, and radiometric

[1]*University Center for Atmospheric Research*

Microwave Atmospheric Sensing

Wavelength (meters)	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma Ray
	10^3	10^{-2}	10^{-5}	$.5 \times 10^{-6}$	10^{-8}	10^{-10}	10^{-12}

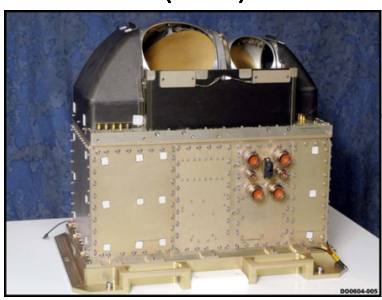
Cloud Penetration; Highest Forecast Impact



The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines

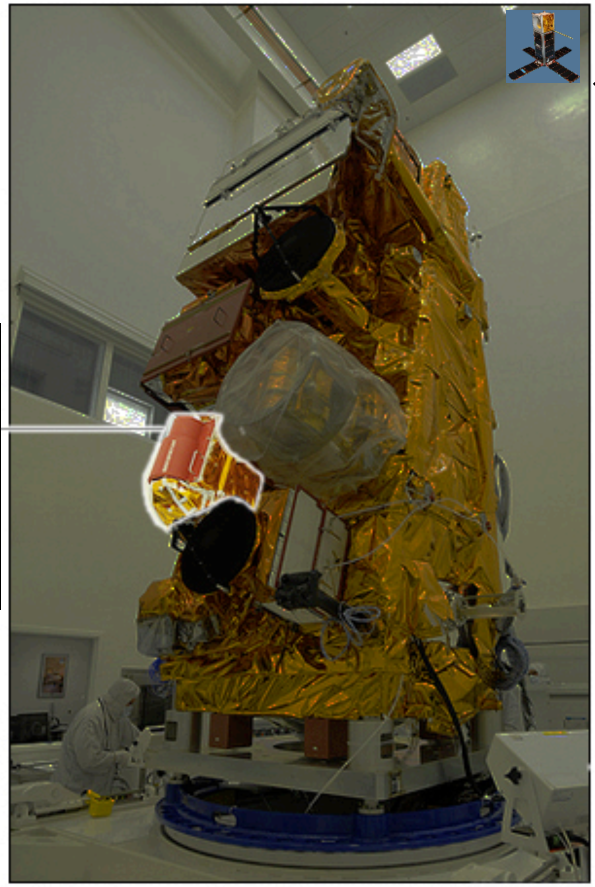
SmallSat Microwave Sounding Approach

Advanced Technology Microwave Sounder (ATMS)



100 kg, 100 W

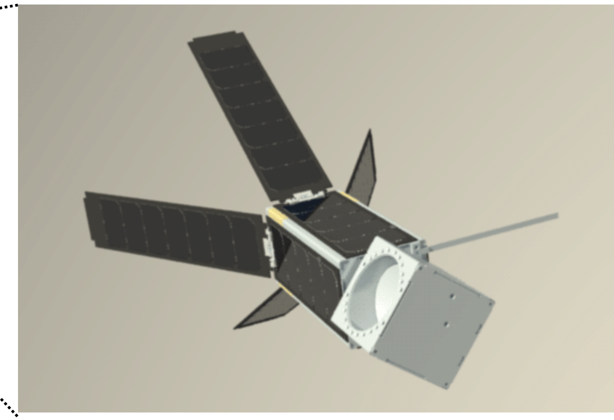
Suomi NPP Satellite (Launched Oct. 2011)



2100 kg NASA/GSFC

NPP: National Polar-orbiting Partnership

MicroMAS Satellite



4.2 kg, 10W, 34 x 10 x 10 cm

- Microwave sensor amenable to miniaturization (10 cm aperture)
- Broad footprints (~50 km)
- Modest pointing requirements
- Relatively low data rate

Weather Prediction Constellation

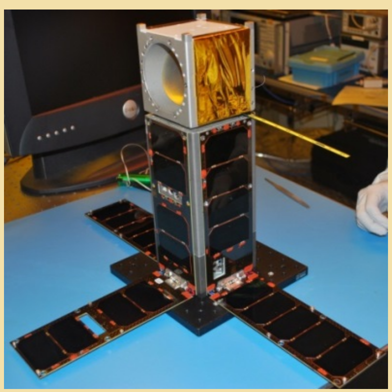
MicroMAS = Microsized Microwave Atmospheric Satellite
MiRaTA = Microwave Radiometer Technology Acceleration
Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)

MicroMAS-1

3U cubesat with 118-GHz radiometer

8 channels for temperature measurements

July 2014 launch, March 2015 release; validation of spacecraft systems; eventual transmitter failure

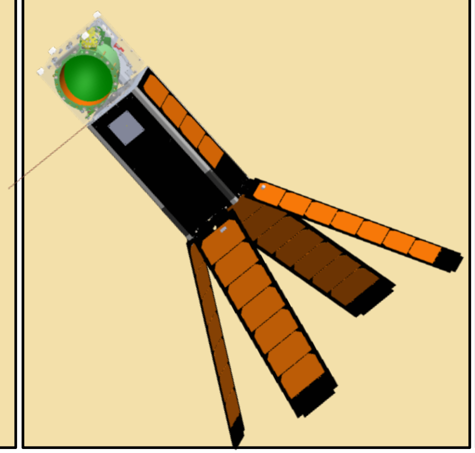


MicroMAS-2

3U cubesat scanning radiometer with channels near 90, 118, 183, and 206 GHz

12 channels for moisture and temperature profiling and precipitation imaging

Two launches in 2017

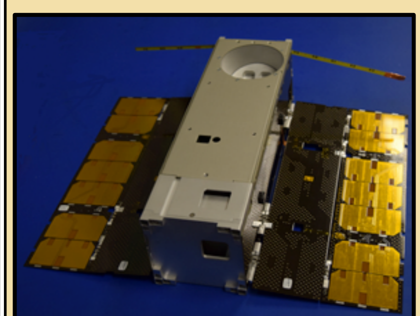


MiRaTA

3U cubesat with 60, 183, and 206 GHz radiometers and GPS radio occultation

10 channels for temperature, moisture, and cloud ice measurements

Early 2017 launch on JP



TROPICS

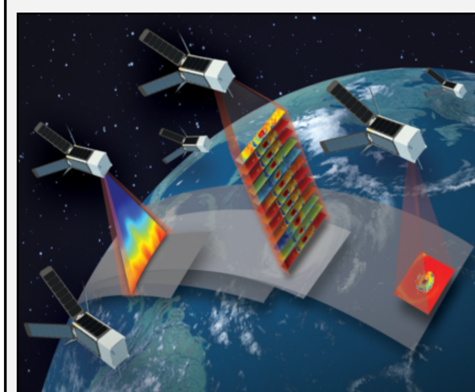
Selected for EVI-3

12 CubeSats (3U) in three orbital planes (600km/30°)

Temperature and moisture profiling and cloud ice measurements

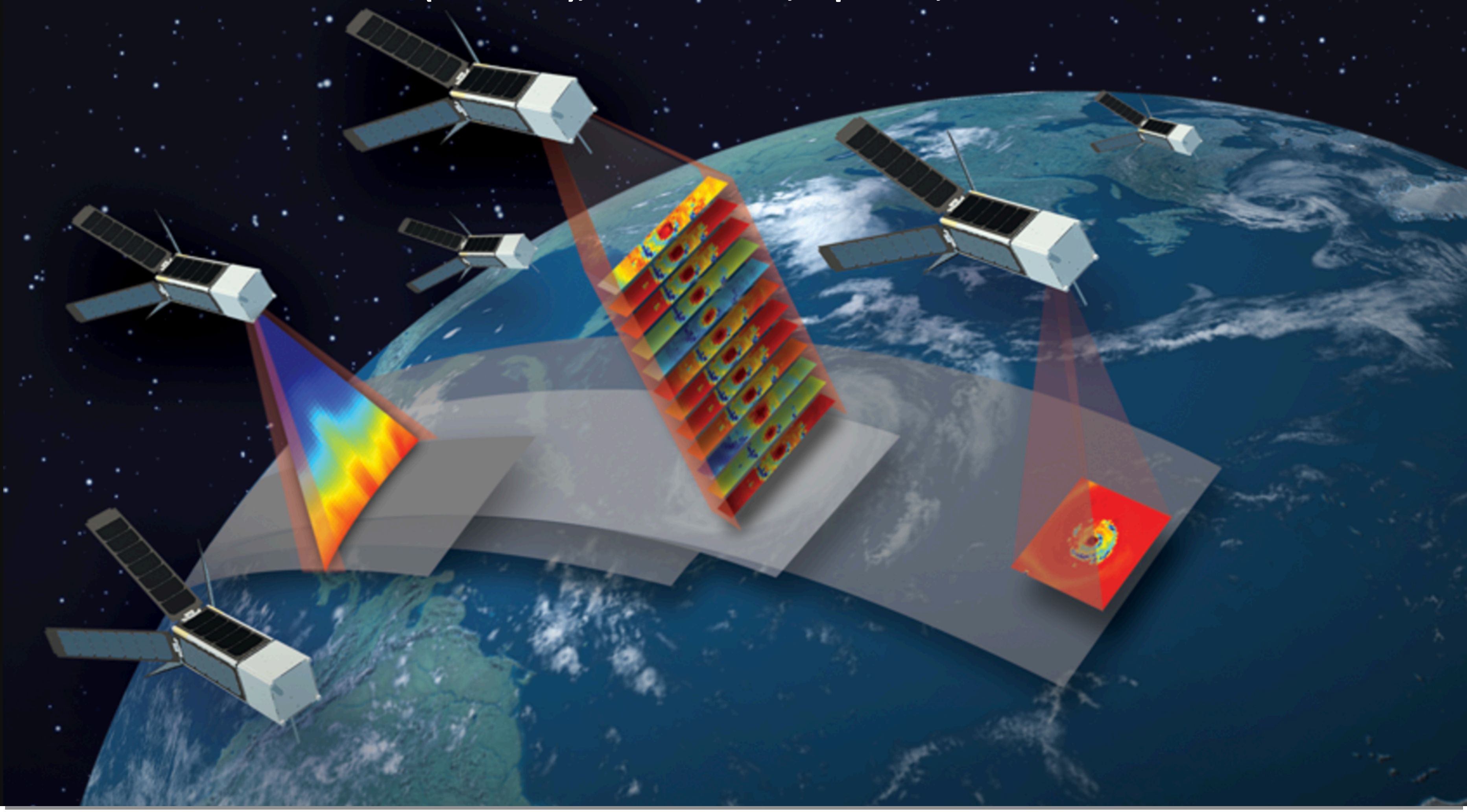
30-minute revisit

2019/2020 launch



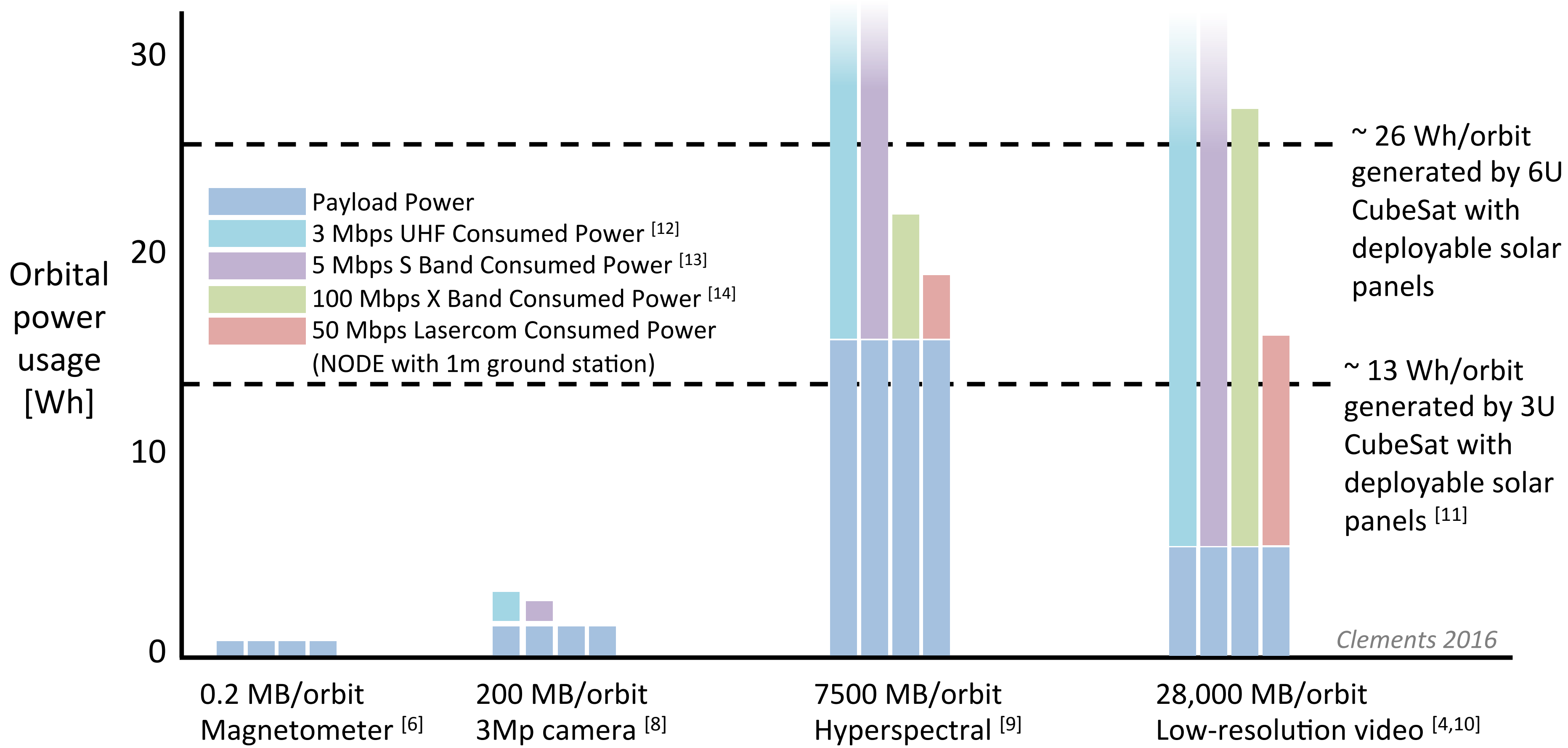
TROPICS weather prediction constellation

Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS), 12 CubeSats, 3 planes, ~30 min revisit time



https://tropics.ll.mit.edu/CMS/tropics/

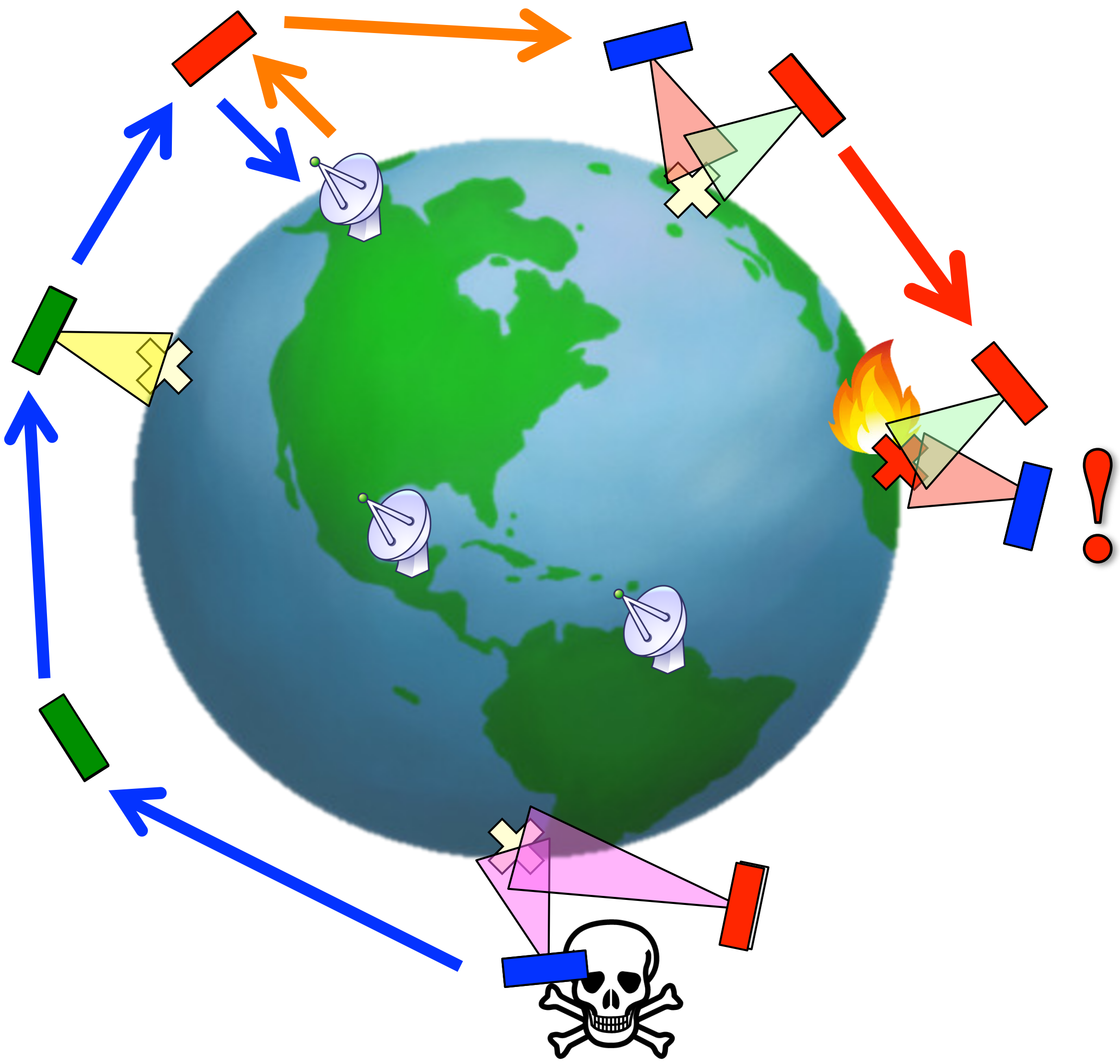
Small Satellite Challenge: Resources



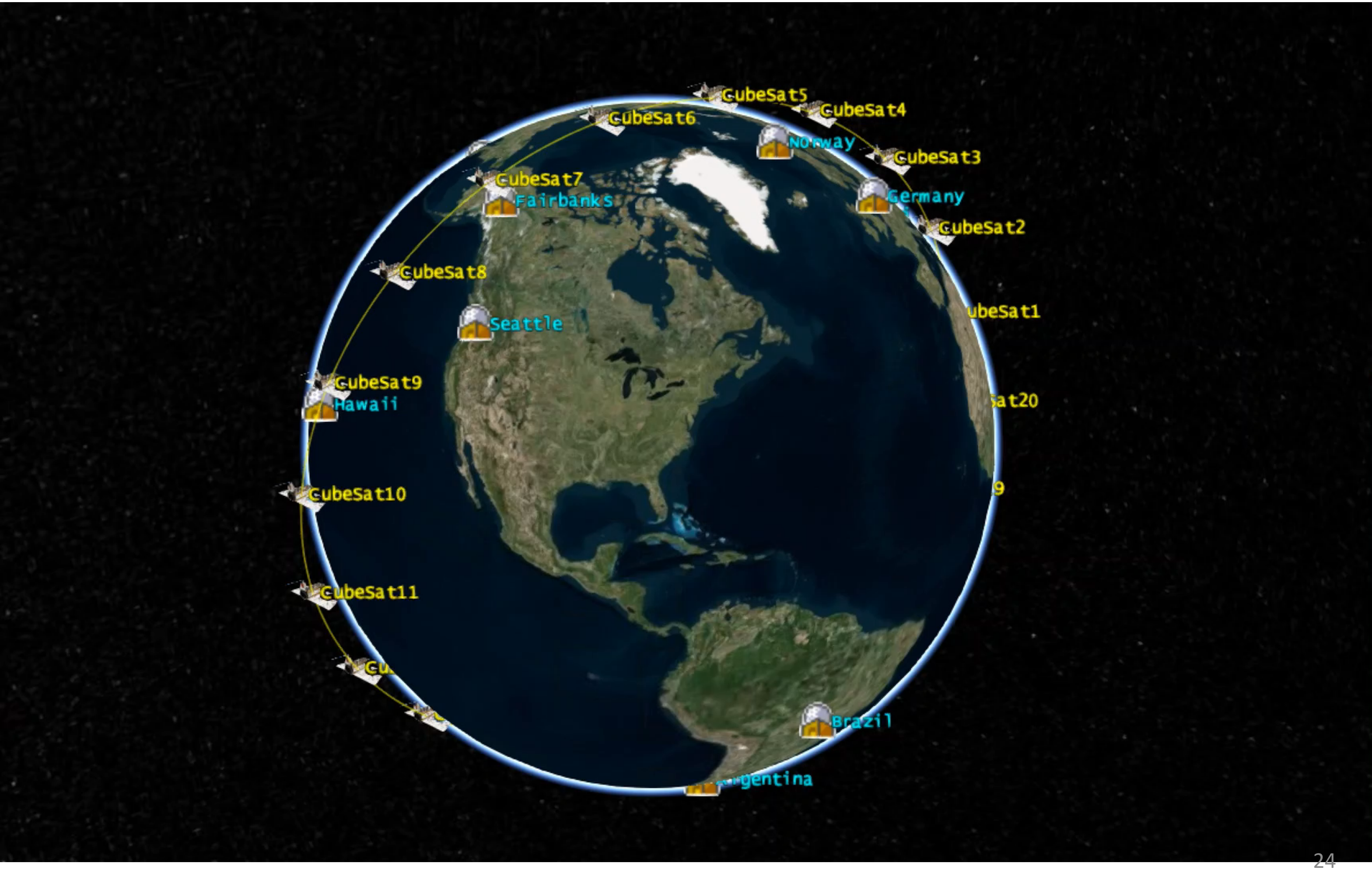
Clements, et al., Optical Engineering, 2016

Benefits of Coordination

1. Remote sensing science applications
2. Spontaneous observation opportunities
3. More effective downlink and uplink with ground stations
4. Robustness to faults on individual satellites
5. Federated operations

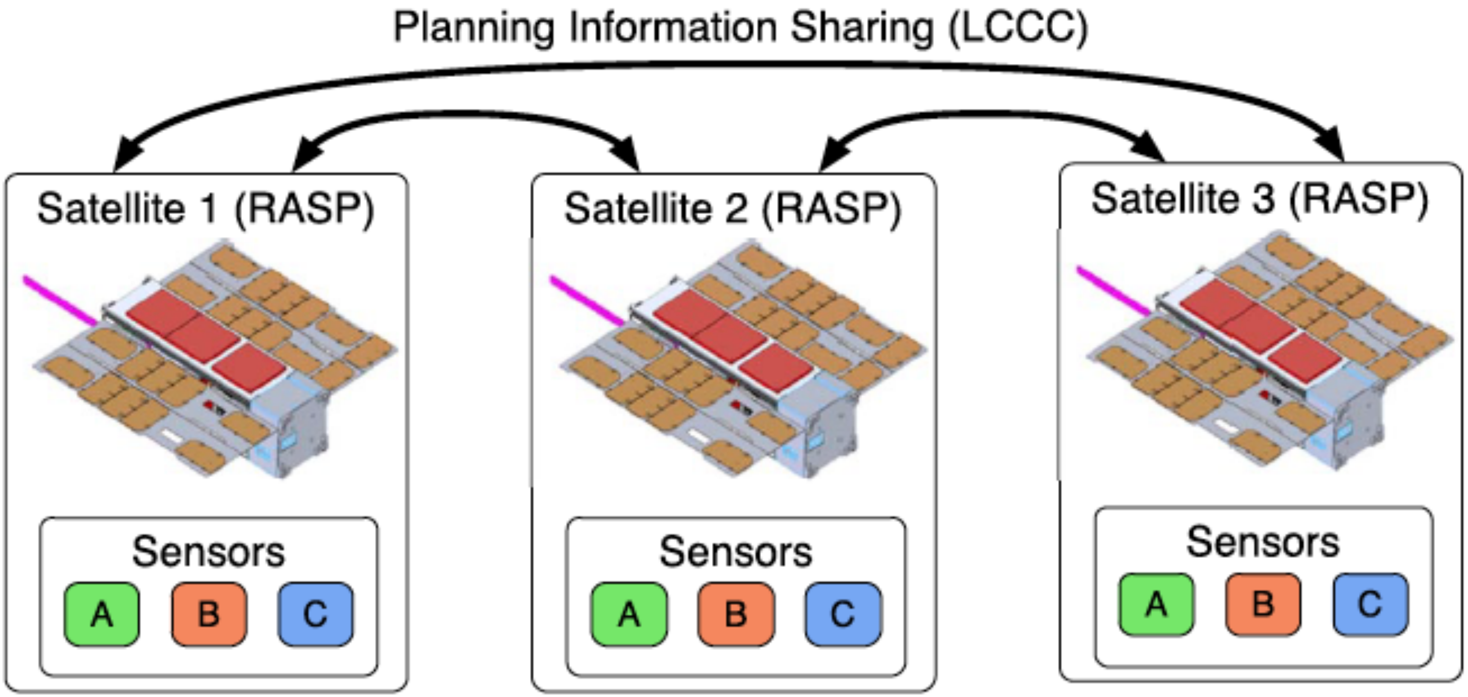


Smart Small Satellites Approach

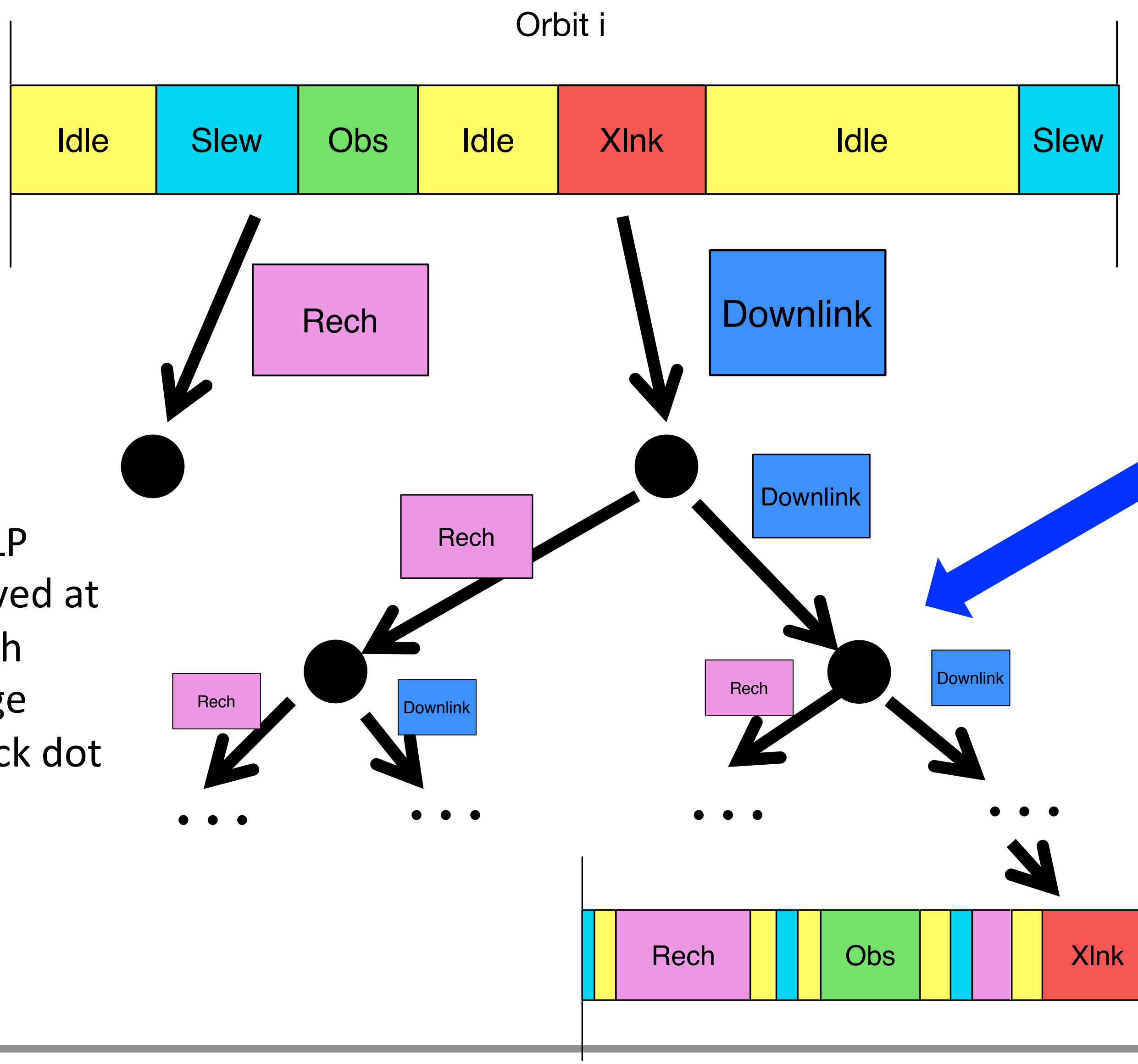


Approach

- Resource-Aware SmallSat Planner (RASP):
  - Plans activities and manages resources for a single sat
- Limited Communication Constellation Coordinator (LCCC):
  - Coordinates observations across constellation through planning info sharing



RASP: Depth First Search



Initial sequence with Obs, XInk, Slew, and Idle

RASP attempts to schedule the activities of each child through a MILP formulation

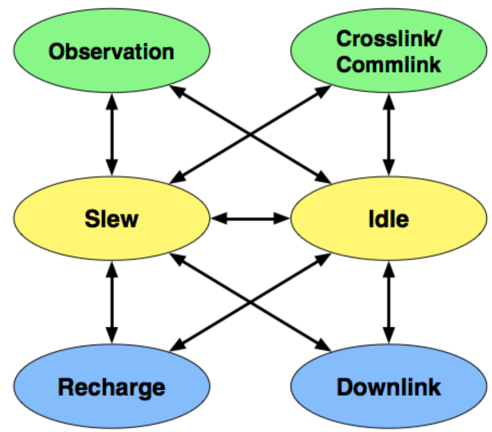
MILP solved at each large black dot

After a while…

Example Satellite Planner Steps

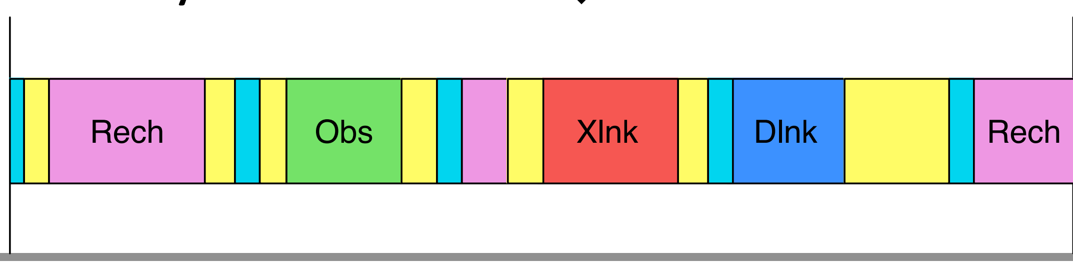
1. Orbital Geometry

2. CubeSat Ops Model

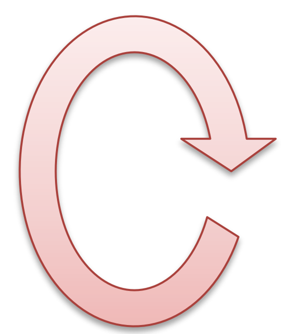


3. Planning Algorithm (e.g. RASP)

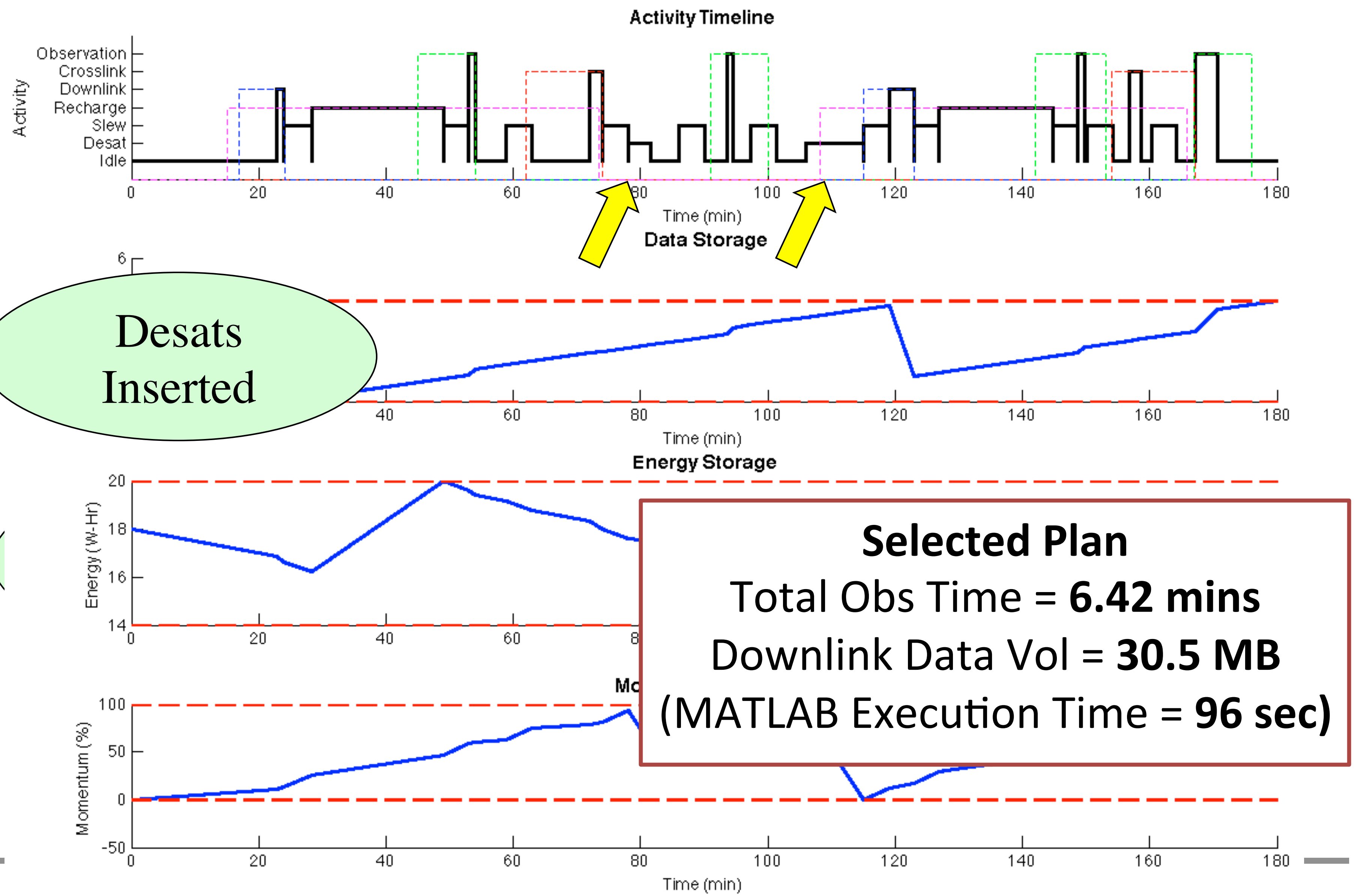
4. Activity Timeline



5. Execution and Replanning

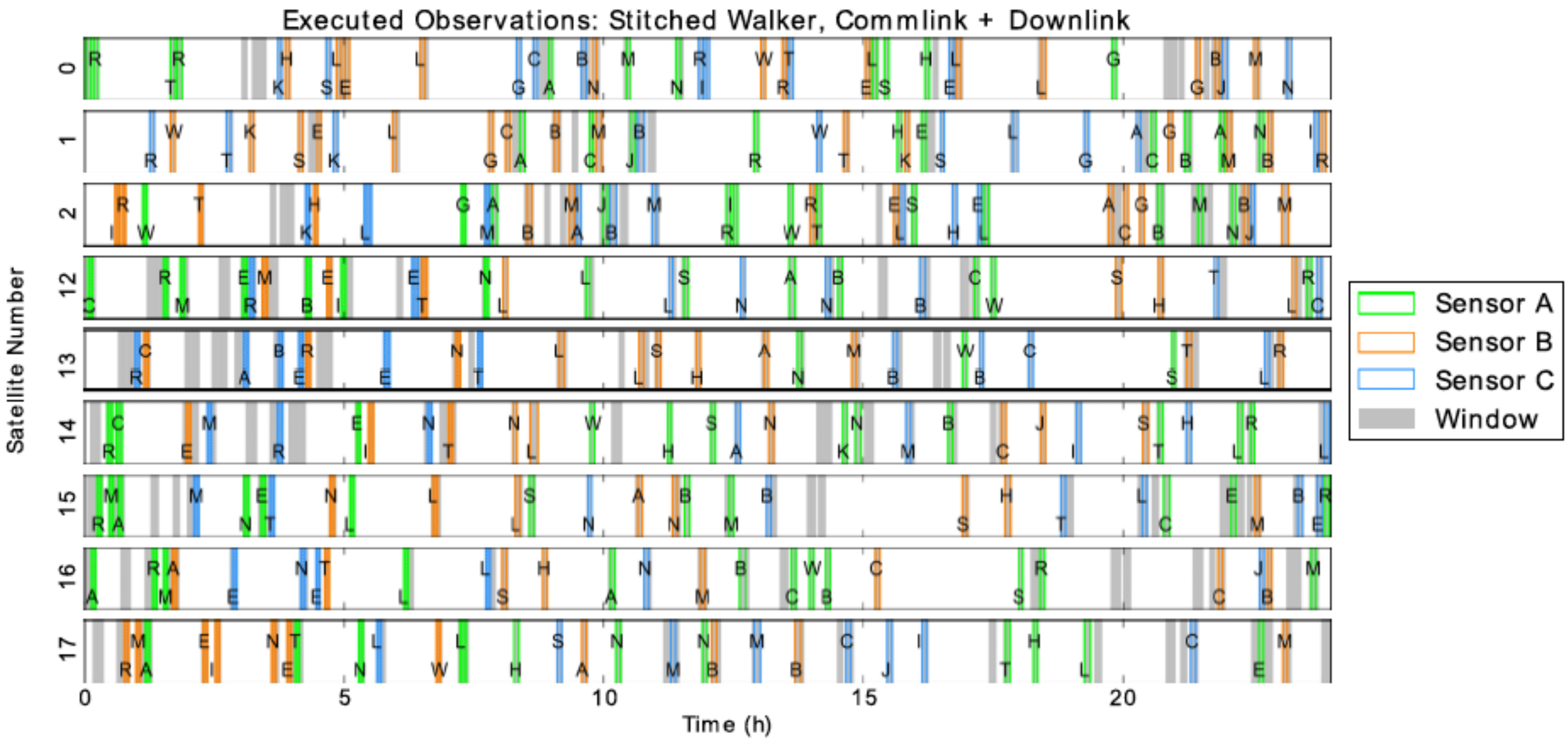


Activity Plan Creation



Selected Plan
Total Obs Time = **6.42 mins**
Downlink Data Vol = **30.5 MB**
(MATLAB Execution Time = **96 sec)**

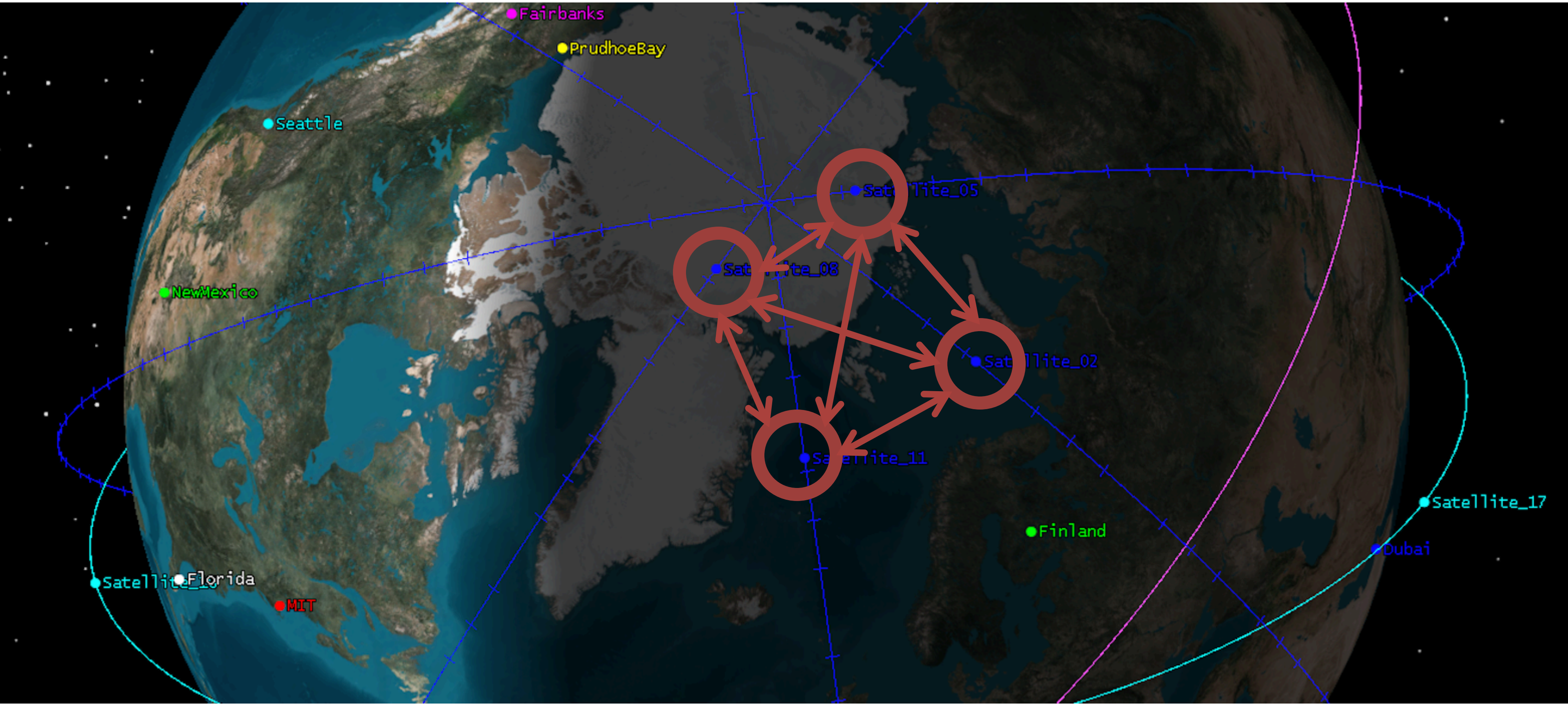
Constellation planning



Kennedy and Cahoy, JAIS 2016

Crosslink Example

- Assumed possible with inter-sat distances up to 2400km
- Multi-hop crosslinks possible



Autonomous Constellations: Enabling Technologies

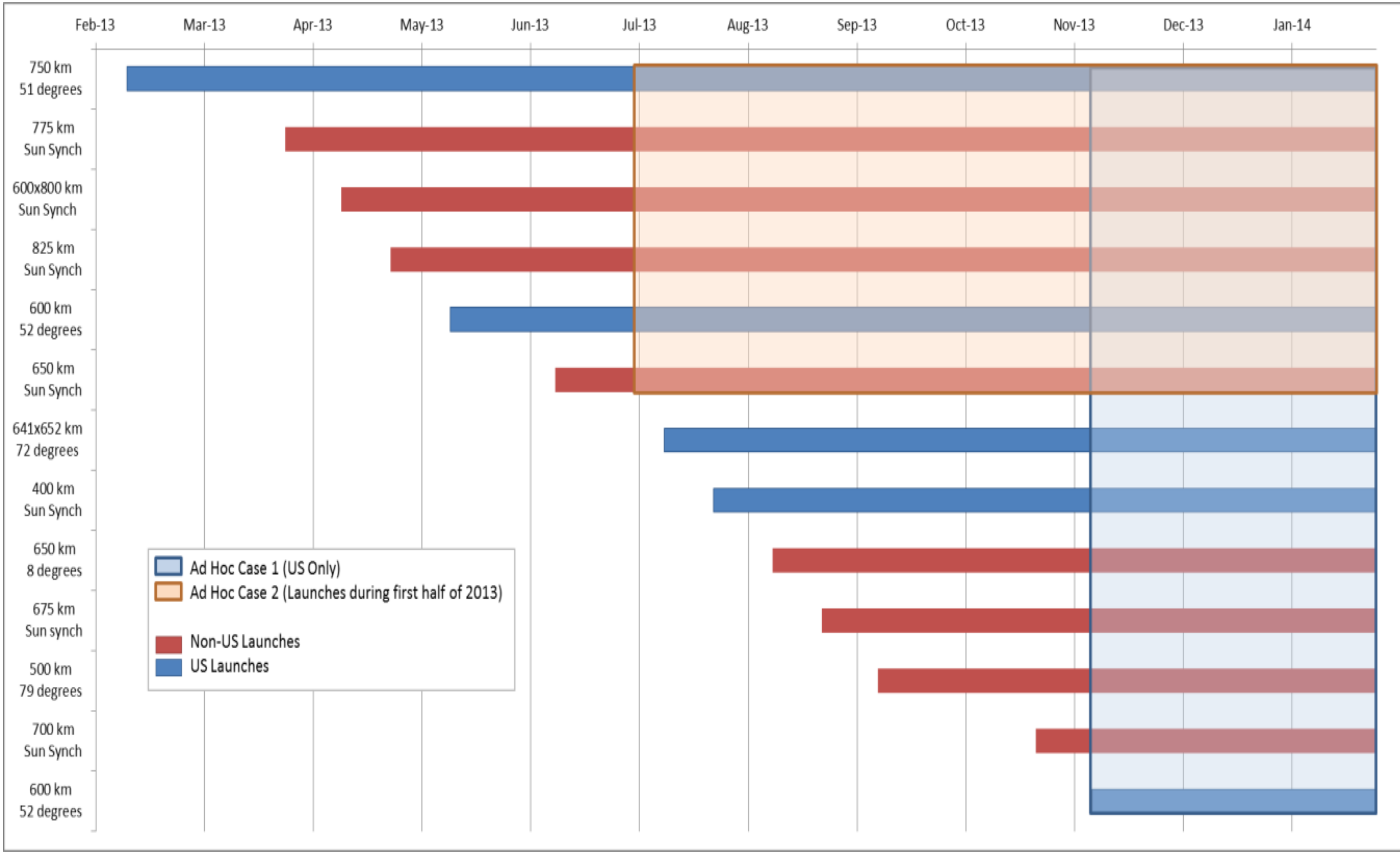
- "Hardware"
  - Diversity of orbital planes; availability of launch vehicles
  - Propulsion capability
  - Crosslink capability; bandwidth
  - Processing capability; firmware implementations
  - Instrument performance
- "Software"
  - Constraint-aware resource management
    - Both space segment and ground segment; resource sharing; scheduling multiple activities at the same time
  - Global observation planning algorithms
    - Sensitivity analyses; performance metric assessment (AoI, revisit)
    - Data quality self-assessment
    - Combined space and ground segment coordination; high priority data; preferred routing
  - Cross-platform interfaces, API

Backup Slides

Thank you!

Questions?

Future (Ongoing) Work



Mixed Integer Linear Programming

- http://acl.mit.edu/milp/MILP_for_Control.pdf
  - Mixed-integer Linear Program (MILP)

$$\begin{aligned} \min_{\mathbf{x},\mathbf{z}} \quad & \mathbf{f}_1^T \mathbf{x} + \mathbf{f}_2^T \mathbf{z} \\ \text{subject to} \quad & \mathbf{A}_1 \mathbf{x} + \mathbf{A}_2 \mathbf{z} \leq \mathbf{b} \\ & \boxed{\mathbf{z} \text{ integer}} \end{aligned}$$

  - Inherently non-convex
  - NP-complete

BUT with good software, can find global-optimum in many useful instances