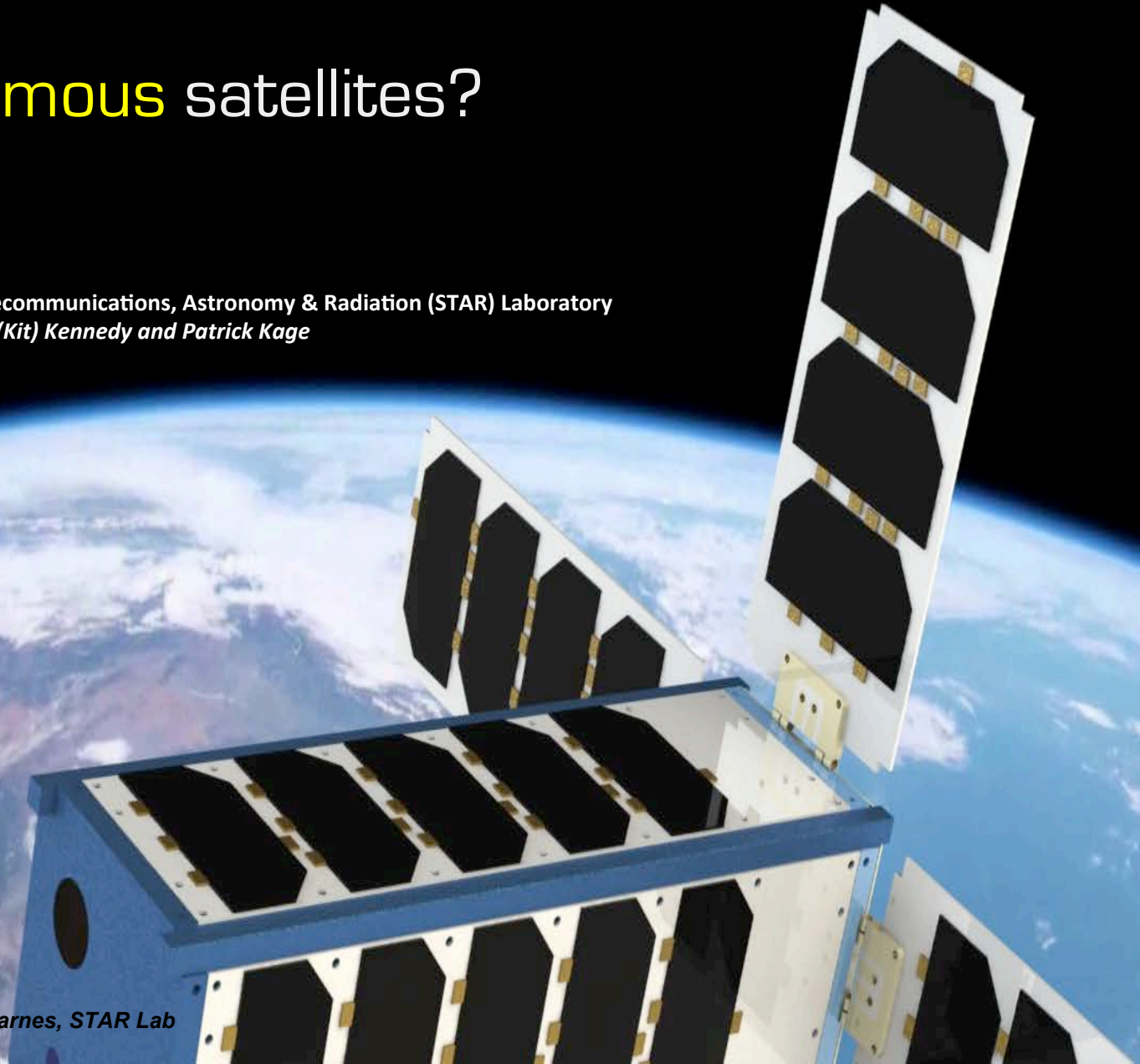


Can we be **everywhere**,
all the time,
with **autonomous** satellites?

Prof. Kerri Cahoy, MIT Space Telecommunications, Astronomy & Radiation (STAR) Laboratory
with contributions from Andrew (Kit) Kennedy and Patrick Kage

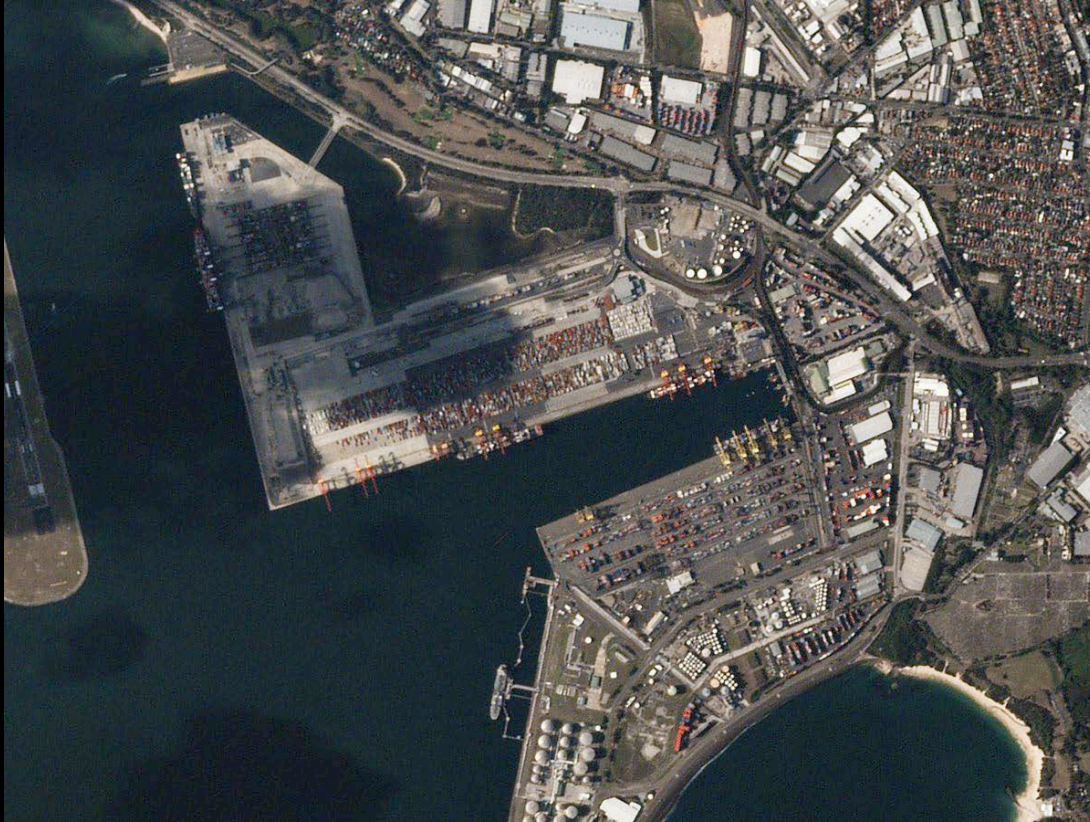
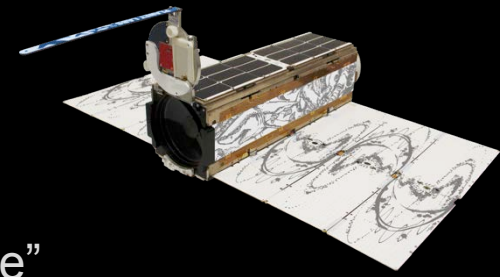


Derek Barnes, STAR Lab



A small satellite took these images

with minimal human involvement

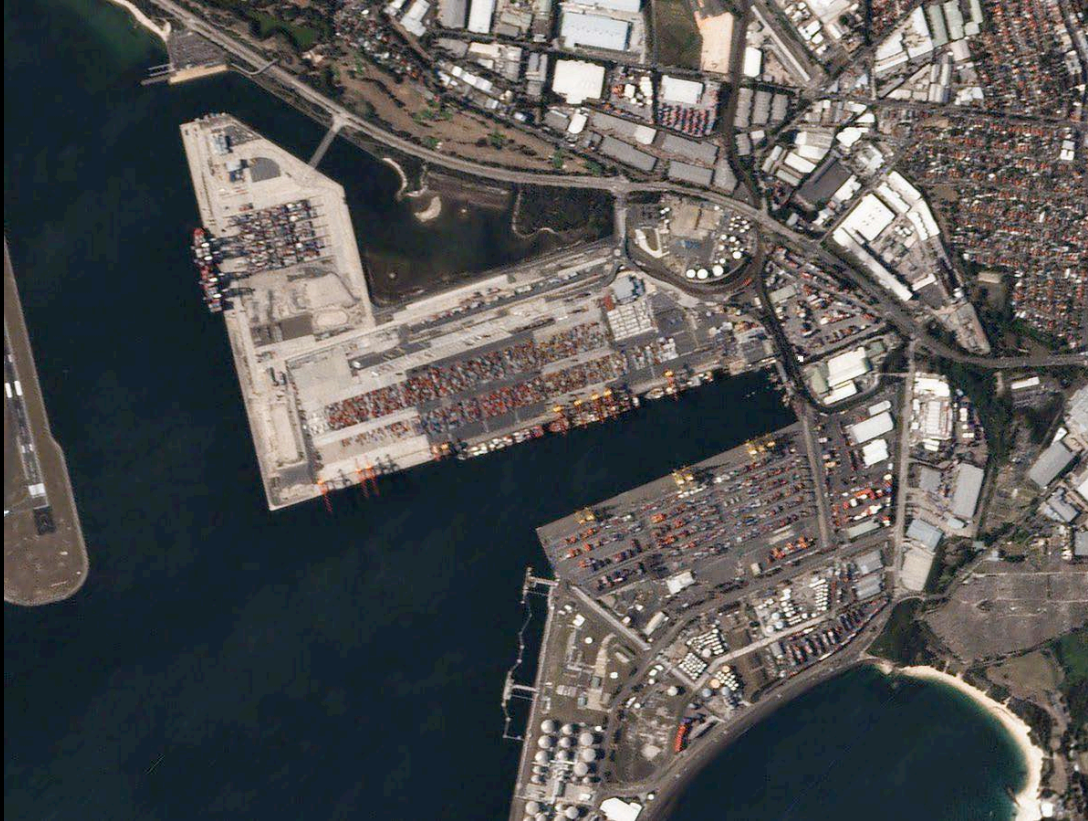
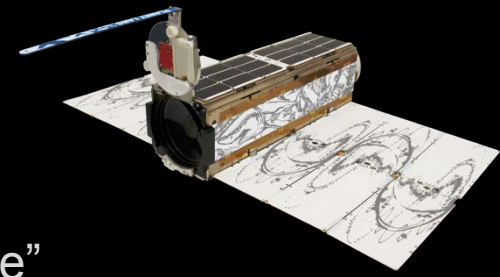


Planet "Dove"

- Sydney, Australia [4]
- 21-23 January 2017
- Daily images of ships in Botany Bay
- Track tankers and container ships with automated image processing software
- 34 cm x 10 cm x 10 cm, 5 kg
- Downlink rates >200 Mbps
- Lifetime 1-3 years per satellite
- >200 launched since 2014
- >100 on-orbit currently
- 88 went up 15 Feb 2017
- Maps Earth's land mass daily

A small satellite took these images

with minimal human involvement

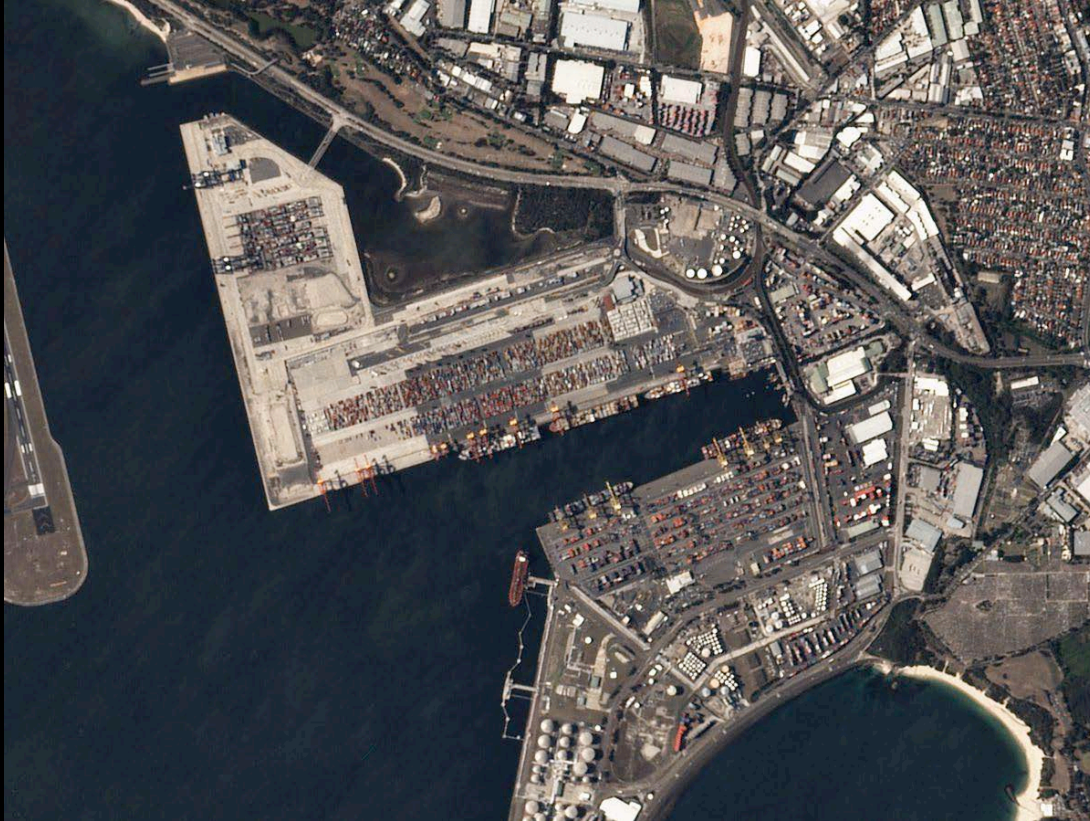
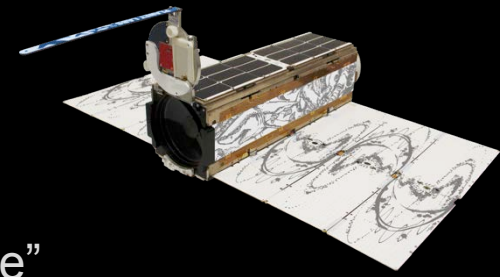


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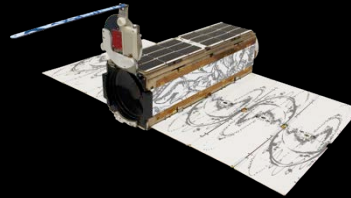


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What are “CubeSats”?

- Invented in 1999 by Jordi Puig-Suari and Bob Twiggs
- Standardized the CubeSat unit (1U)
 - Volume: 10 x 10 x 10 cm
 - Mass: < 1.33 kg
 - Can combine them: 1U, 1.5U, 2U, 3U
 - Now 6U, 12U
- Low cost, commercial parts
- “Hitch a ride” on a rocket
- BUT, because of their small size, CubeSats have very limited resources

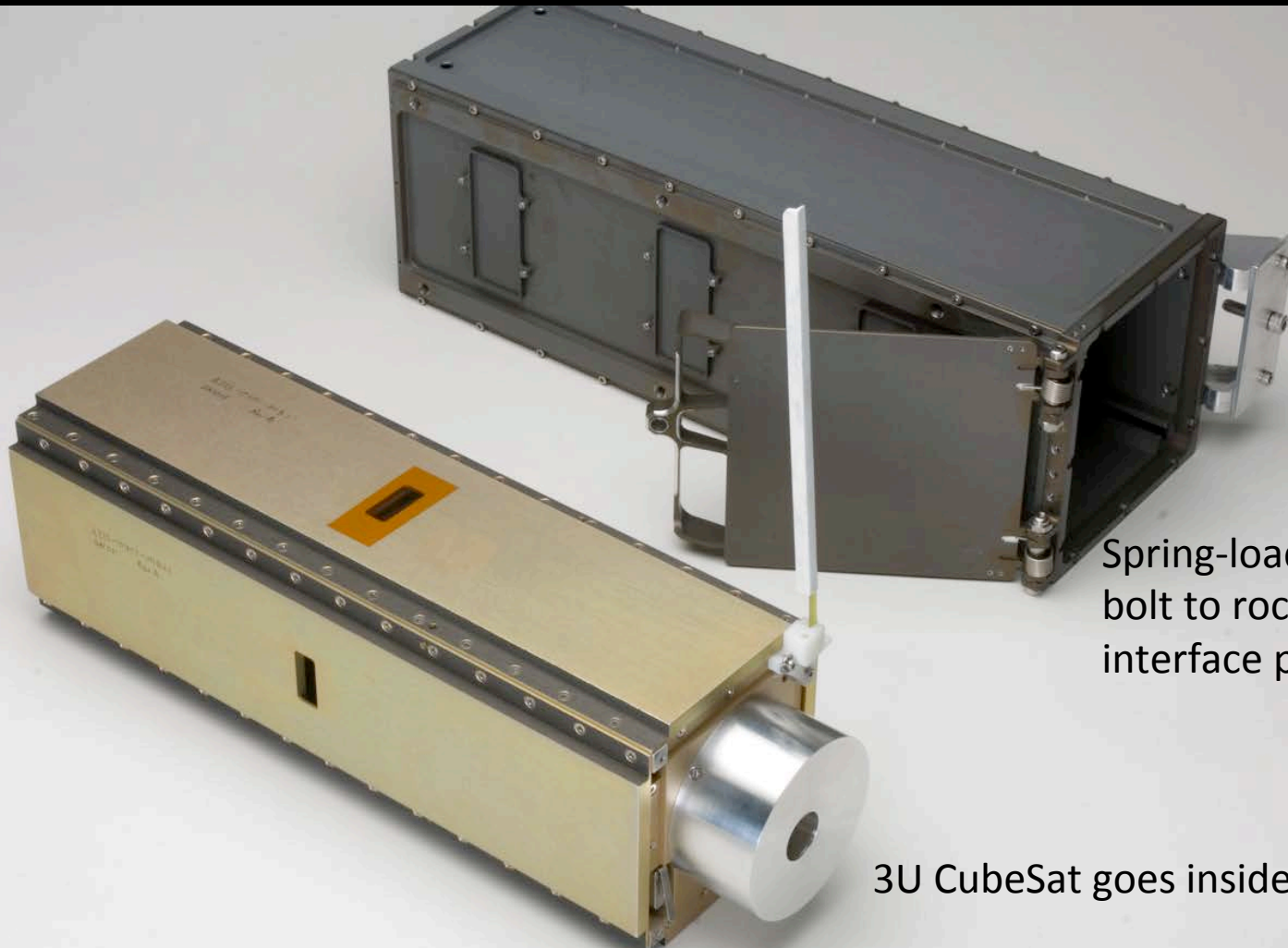


[4]



The Game-changer

Poly-picosatellite orbital deployer (P-POD)



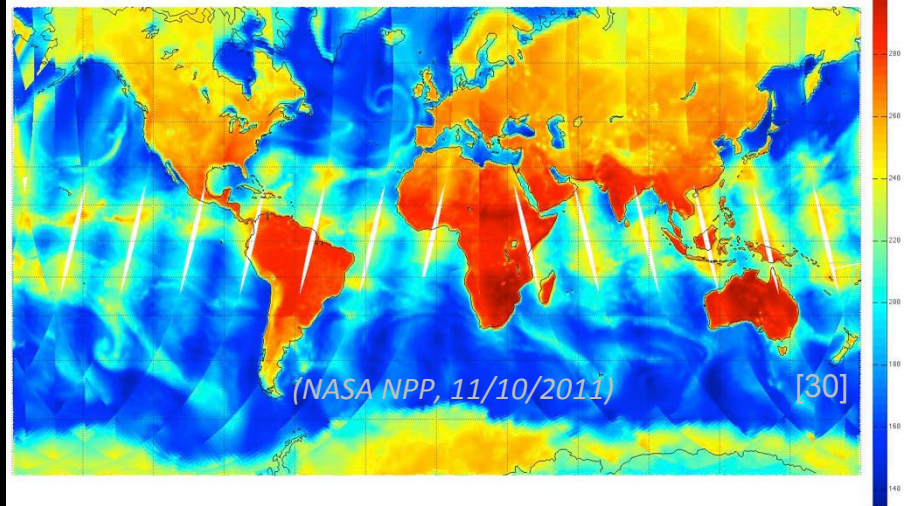
Spring-loaded box,
bolt to rocket
interface plate

3U CubeSat goes inside

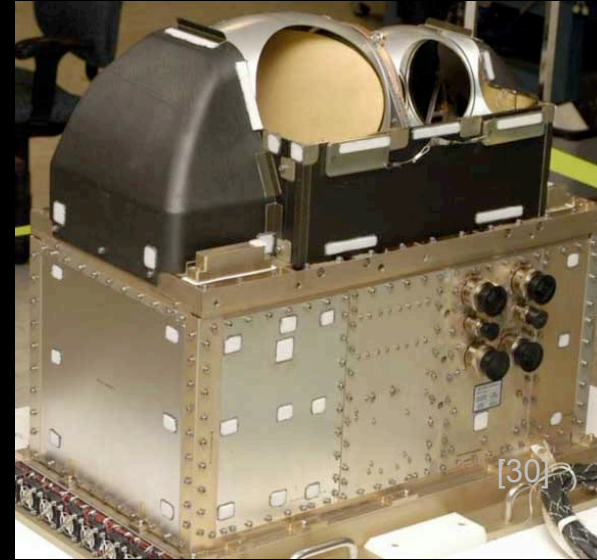
[20]

Tech advances shrink sensors to fit in the box

Temperature map from Advanced Technology Microwave Sounder



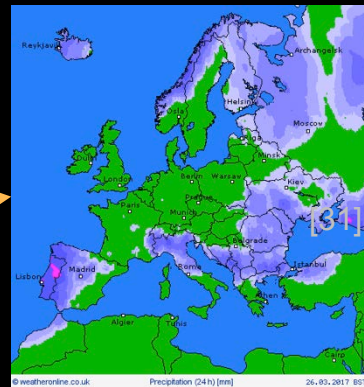
23.8-GHz Brightness Temperature (K)



Advanced
Technology
Microwave
Sounder on
Suomi NPP

75 kg
130 W

Temperature
radiometry map
feeds into forecast
models



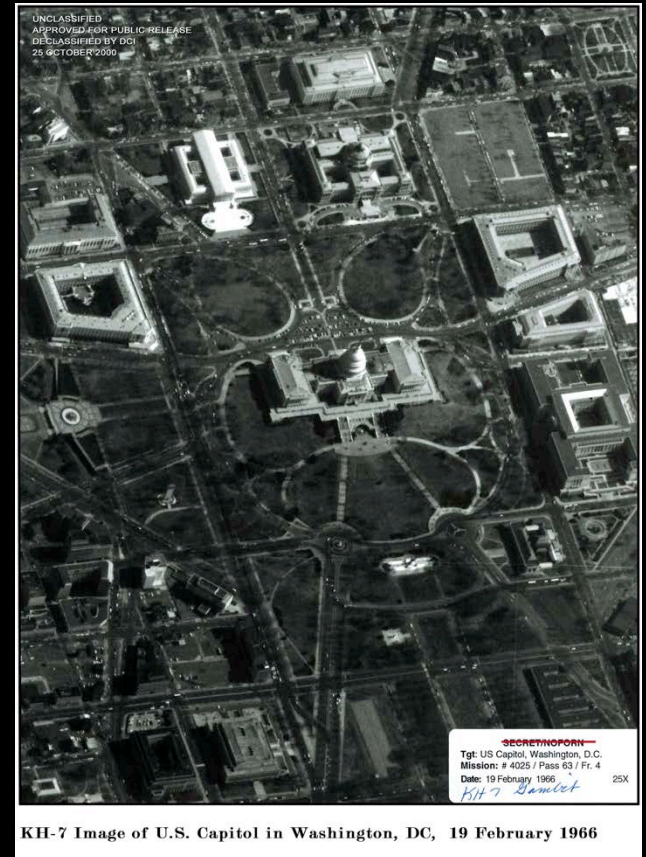
Shrink it by
~100x mass
and ~50x
power for
MicroMAS-1



MicroMAS 3U CubeSat (MIT LL / MIT) [30]

Cost comparison

- US Government Hexagon program
- 20 satellites total FY1966 to FY1986
- **US \$3.262 Billion** in respective year dollars [2]
(also compare with Iridium, \$6B in mid-1990s)
- Commercial Planet “Doves”
- >140+ on orbit currently
- 3U CubeSat launch ~US \$200k each
- Can buy a 3U CubeSat for < US \$1M each
- Estimate in bulk:
< US \$500k each for both launch + CubeSat
- So, ~20 CubeSats in orbit < US \$10M



Traditional: 1 big rocket, 1 big satellite



[5]



[6]

Landsat-8 LDCM launched Feb 2013 on an Atlas V rocket from Vandenberg. The total cost of spacecraft, rocket, launch, and on-orbit checkout was \$855M. Atlas V rockets can cost \$110M-\$150M [7, 8, 9].

New: 2 small rockets, 2 small satellites



[10]



[11]

ESA's pair of Sentinel-2 spacecraft cost a combined 350M euros.
Sentinel-2A launched 23 June 2015 on a Vega launch vehicle (cost ~32M euros).
Sentinel-2B launched 7 March 2017, also aboard a Vega rocket.

New: 1 airplane, 1 tiny rocket, 8 micro satellites



[12]



[13]

Eight 28-kg CYGNSS (Cyclone Global Navigation System Satellites) launched from a single Pegasus XL air-launched rocket. The rocket was deployed from a customized Lockheed L-1011 aircraft, Stargazer on December 15, 2016. The total mission cost was \$152M; Pegasus launch cost was ~\$55M [14].

Making history: 101 CubeSats ride with 1 big satellite



[15]



[16]



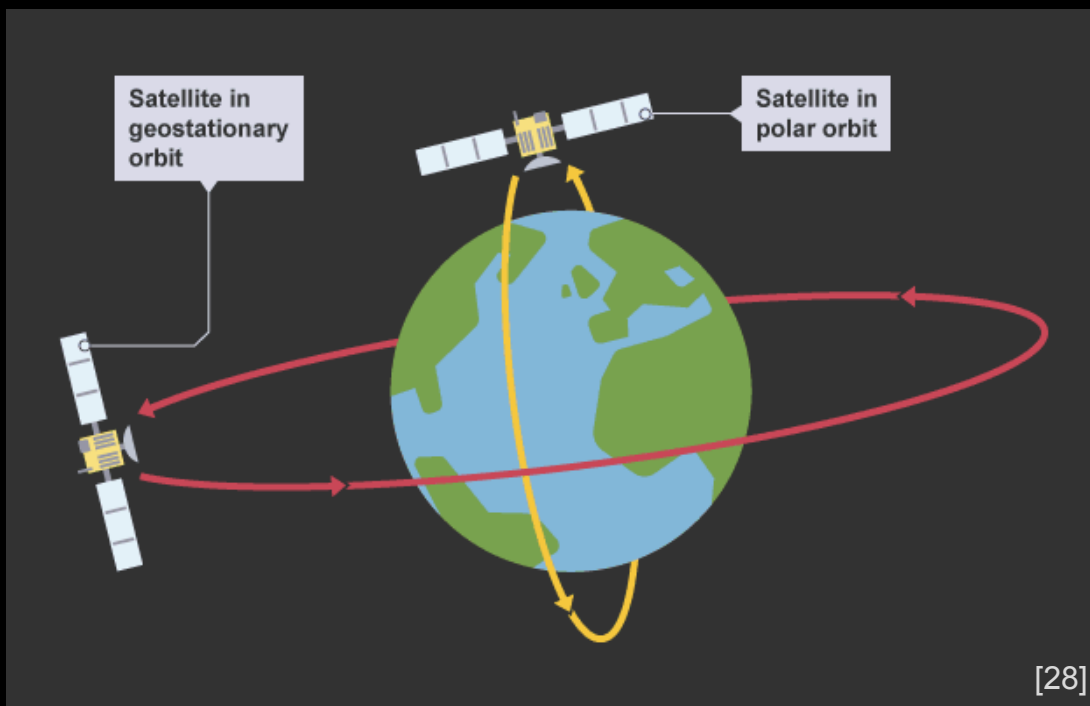
[17]



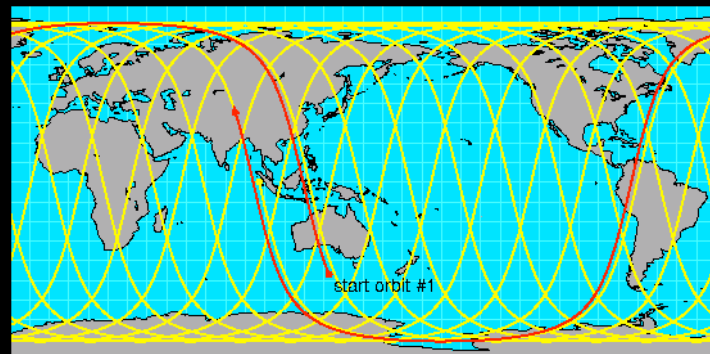
[18]

15 February 2017, 88 Planet CubeSats were deployed from a PSLV with primary payload Cartosat-2D (714 kg, 70 cm diameter aperture imager). Planet's > 140 CubeSat constellation now images Earth's entire landmass daily during the daytime (150M sq km, 58M sq mi).

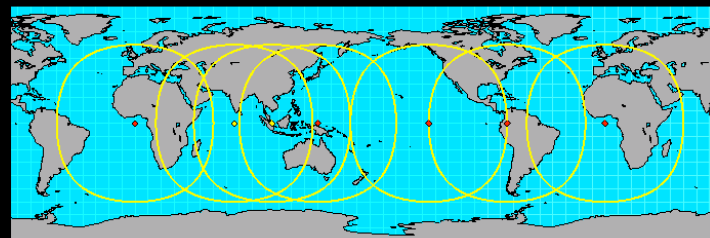
Why is it better to have more satellites?



Daily Polar Satellite Coverage - takes 14+ days to repeat over a spot



Geostationary satellites are always overhead, but far away, miss high lat



[29]

- Because better coverage (temporal, spatial) and redundancy
- Smaller satellites need to work like the big ones, but with smaller sensors
- But, large satellites and rockets cost a lot

Rides to space



Ways to get CubeSats into orbit...



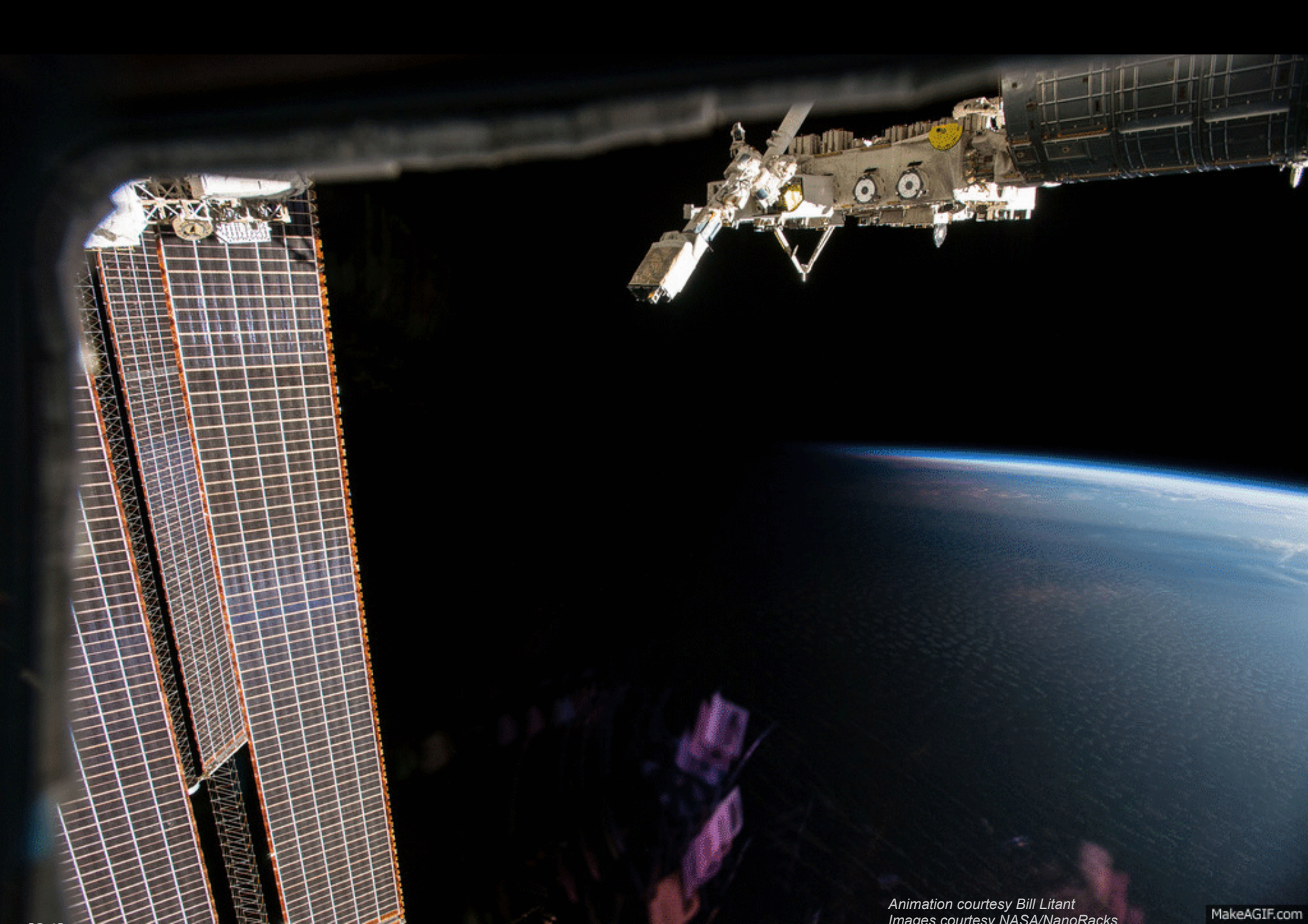
[25,27]

Cosmonaut Oleg Artemyev throws Peruvian CubeSat Chasqui 1 into orbit 18 August 2014



[26]

Cygnus cargo spacecraft unberths from Harmony module



[24]

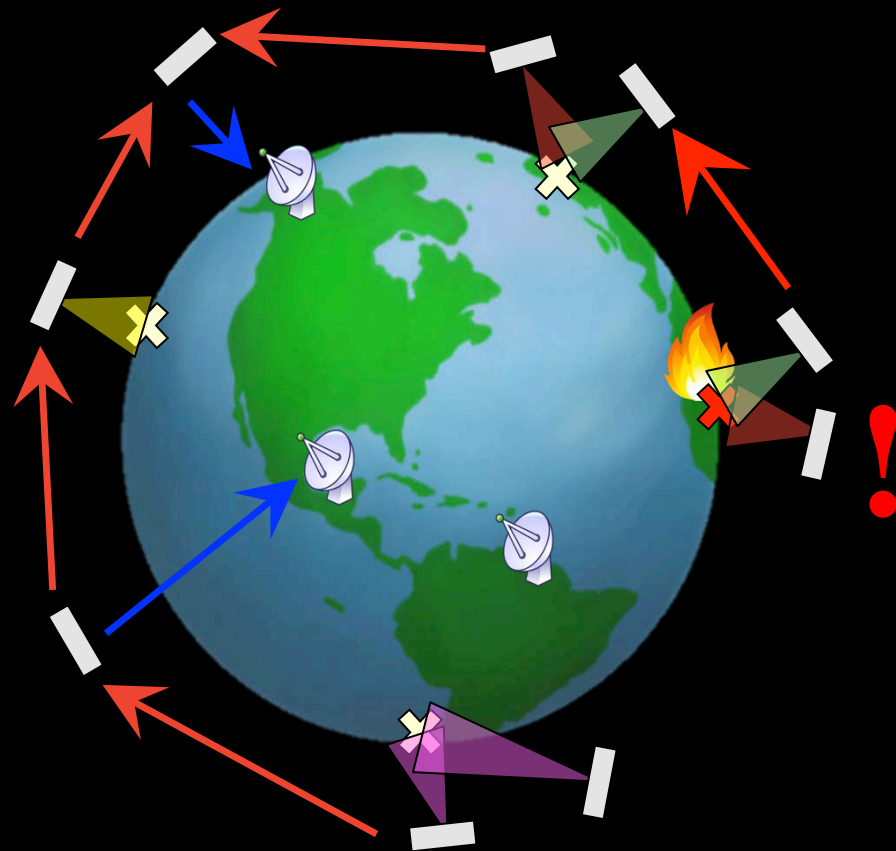
Animation courtesy Bill Litant
Images courtesy NASA/NanoRacks

MakeAGIF.com



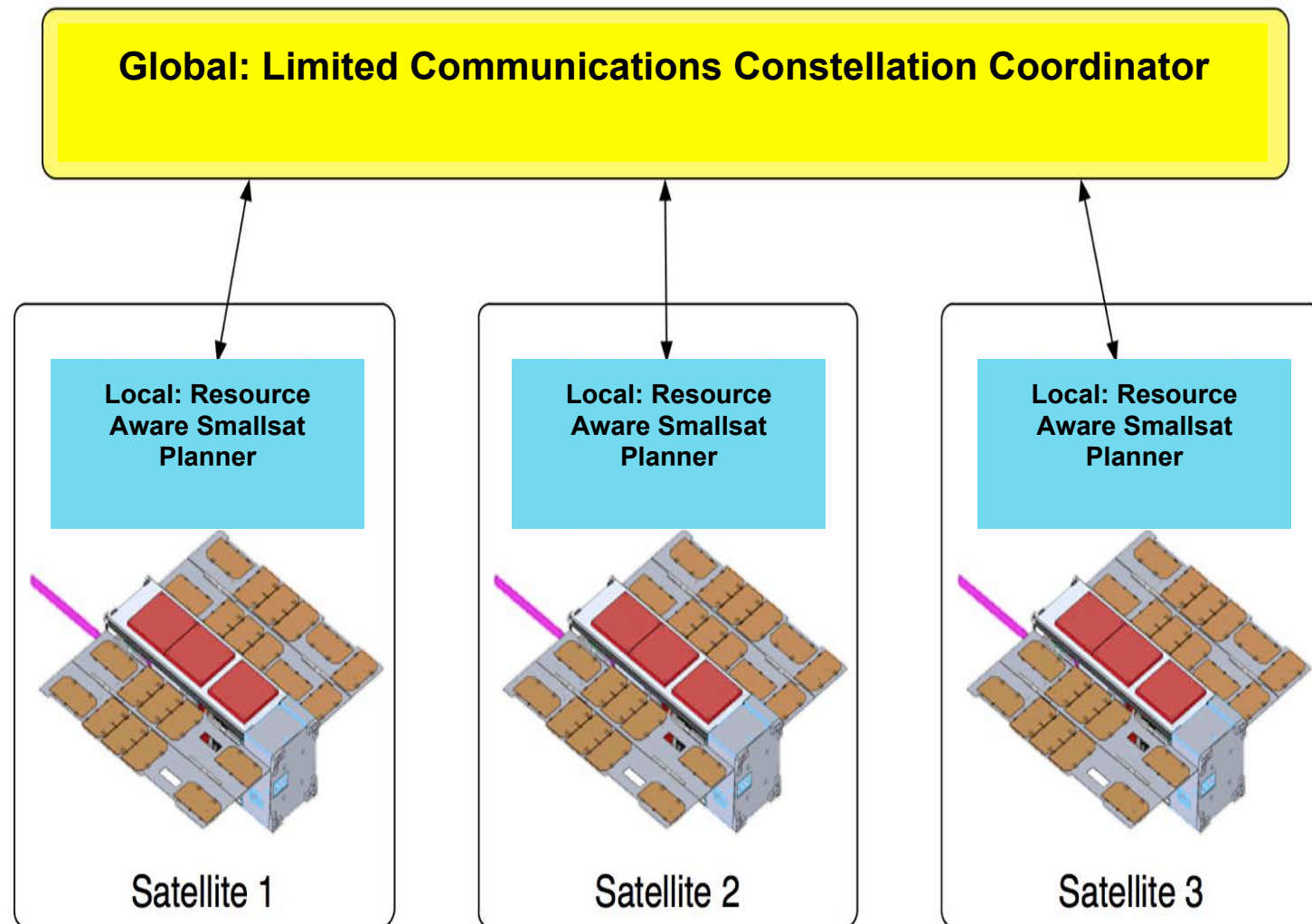
Coordination is key

- Satellites talk to ground (blue)
- Intersatellite links (red)
- Task coordination
- Covering faults/anomalies
- Dynamic prioritization of observations





Autonomy: schedule & optimize limited resources



A. Kennedy

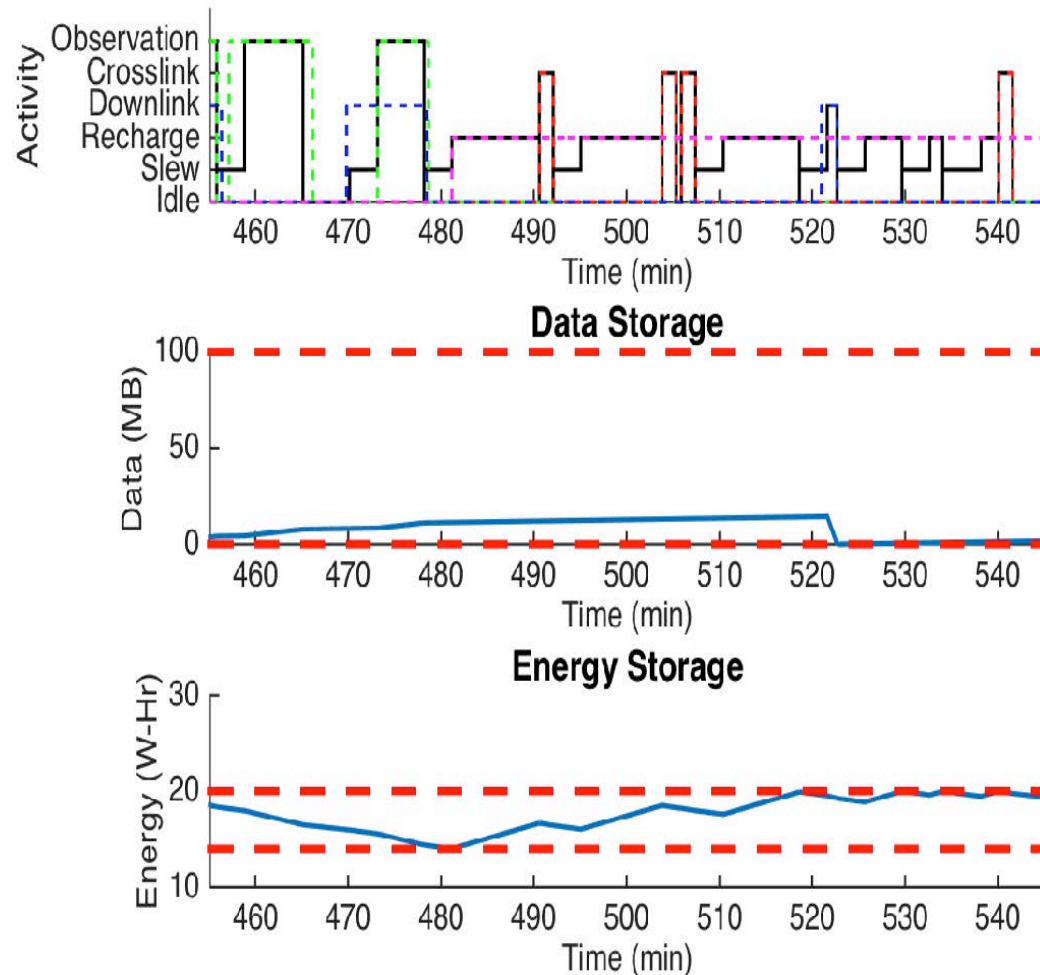
Both local and global optimizations can use mixed-integer linear programming

Local Resource Monitoring and Activity Scheduling

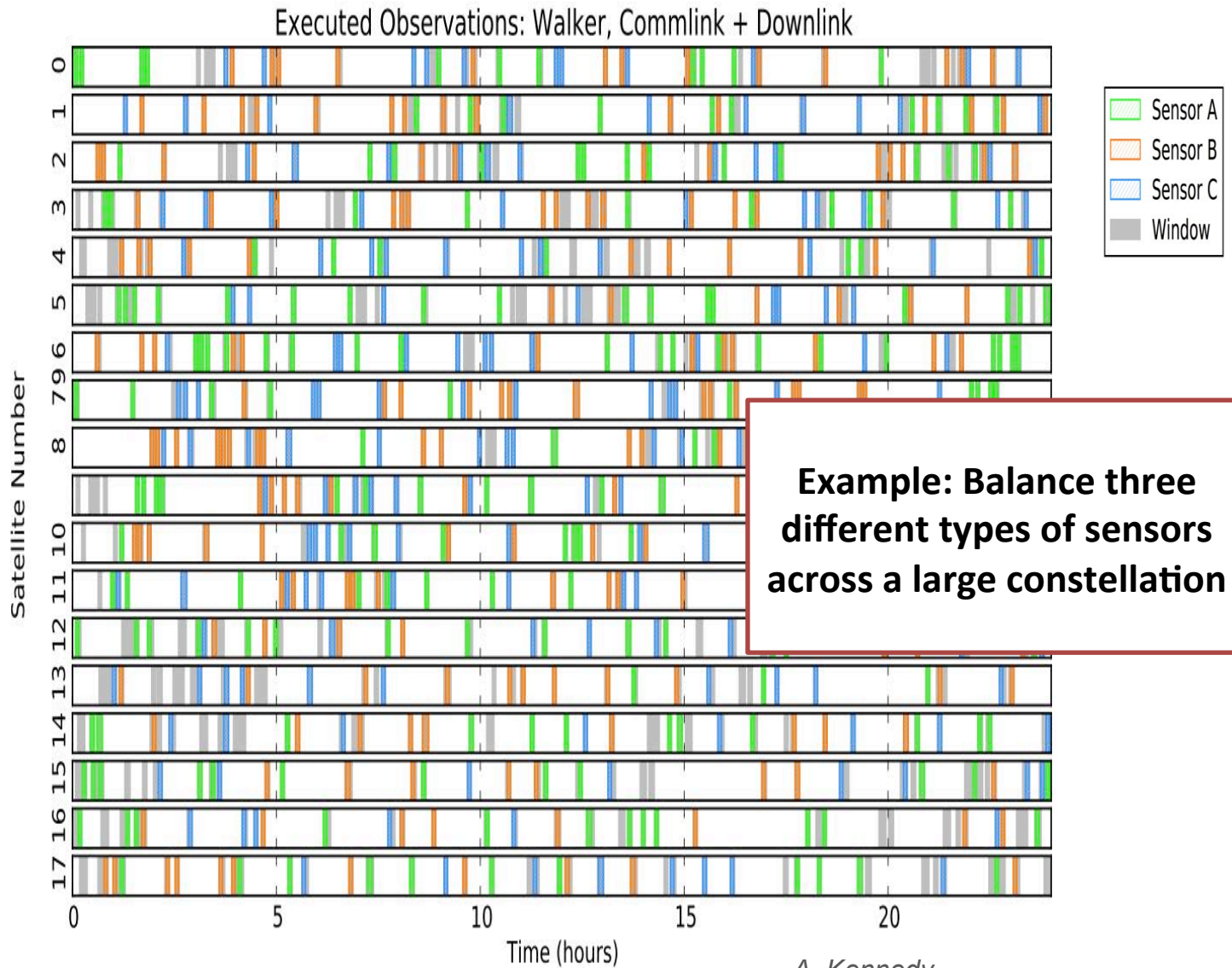
The local planner runs independently on each satellite

It sets a detailed time schedule of activity based on latest observation priorities

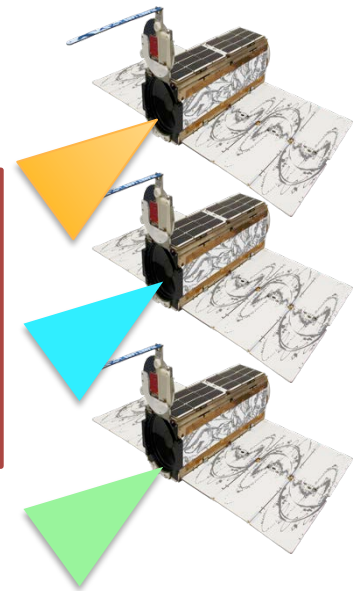
It also optimizes data storage and routing



Global Coordination of satellites, each with different sensors



A. Kennedy



Autonomy Enablers

- High-performance hardware and efficient software to implement satellite and ground coordination
- Frequent and fast ground and intersatellite links (e.g., lasercom)
- Many inexpensive ground stations
- Propulsion to enable mobility and chasing targets



Ion electro spray propulsion; MIT Space Propulsion Lab (Fernando Mier Hicks)



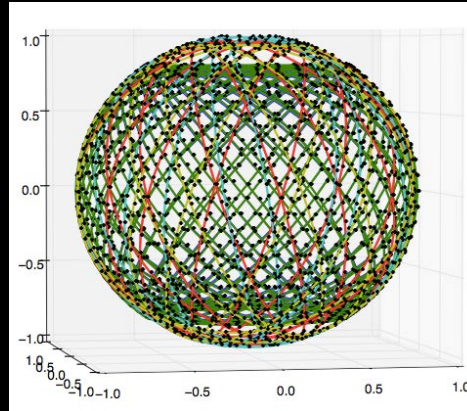
Simulated Disturbance

Precision pointing for lasercom crosslinks, MIT STAR lab (Hyosang Yoon)

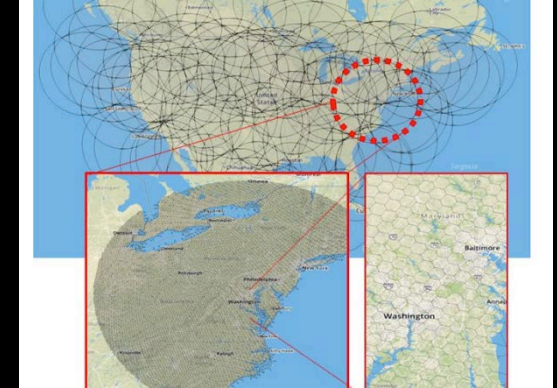
“New” LEO Comm Constellations need autonomy



OneWeb 648+ satellites



SpaceX 4,425 proposed

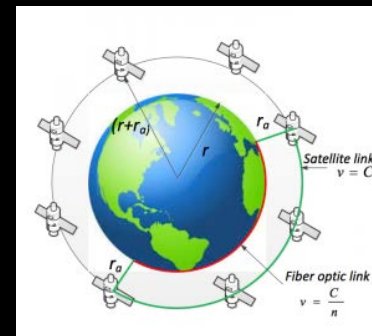


Boeing 1,396 proposed



[32, 33, 34, 35, 36]

Telesat 117 satellites



Samsung 4,600 proposed

Coming soon: imaging data at your fingertips

- Imagine being able to use a web browser on your phone to look at places on Earth as they update in real time.

Planet Explorer Beta [37]



- Tracking cargo (or pirates)
- Monitor construction
- Watch competitors
- Crop yield estimates
- Disaster recovery
- Forest management
- Water management

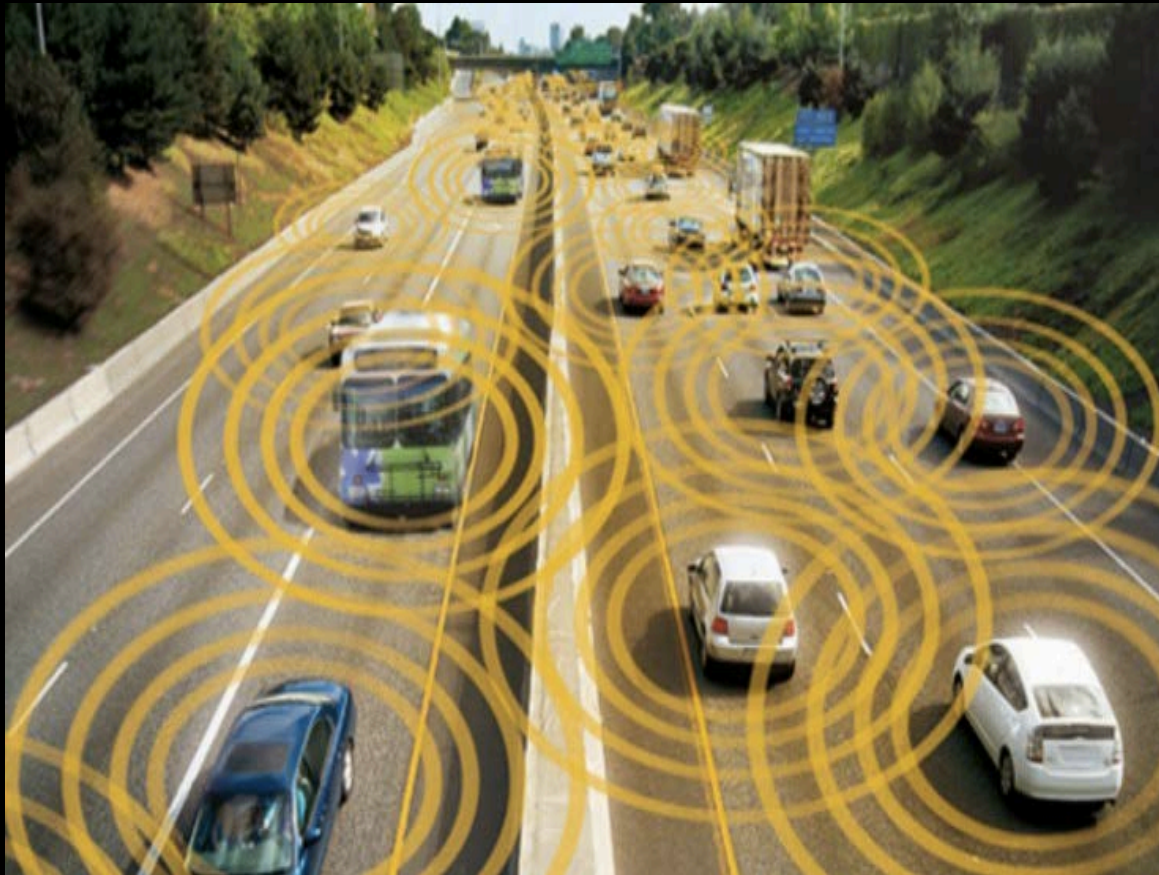
Coming soon: meteors on-demand

- Imagine being able to order online a colorful smallsat-enabled meteor shower over your next party
- It's a fun idea, but there are also research applications for space-based beacons



Coming soon: truly global 5G+

- Imagine broadband anywhere – cars, countryside, ships, planes



Thank you. Questions?

References 1/2

All accessed between 3/20/2017 and 3/28/2017

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- [2] https://en.wikipedia.org/wiki/KH-9_Hexagon
- [3] Botany Bay image from: <https://www.planet.com/gallery/>
- [4] <https://www.planet.com/company/approach/>
- [5] Atlas V LDCM <https://www.youtube.com/watch?v=nglvXmxJQlw>
- [6] https://www.nasa.gov/sites/default/files/images/722423main_2013-1-23-1_full.jpg
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- [20] http://www.nasa.gov/centers/ames/images/content/152693main_genebox-015.jpg
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[23] <https://directory.eoportal.org/web/eoportal/satellite-missions/d/dubaisat-2>

[24] Images of MicroMAS-1 launch and deployment courtesy NanoRacks and NASA

[25] <https://www.youtube.com/watch?v=DSqDoDqQVQo>

[26] <http://www.flickr.com/photos/nasa2explore/12644390754/>

[27] <http://www.space.com/26841-spacewalking-cosmonaut-launches-peru-satellite-video.html>

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[29] https://www.rap.ucar.edu/~djohnson/satellite/about_illustrations.html

[30] MiRaTA and MicroMAS slides from Cahoy et al., "Development of the Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat for all-weather atmospheric sounding" presented at URSI NRSJ January 2017

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<http://www.weatheronline.co.uk/weather/maps/forecastmaps?LANG=en&CONT=euro&MAPS=vtn&LOOP=0&LAND=OS&MORE=1&UP=0&R=0&DAY=0>

[32] <https://airbusdefenceandspace.com/newsroom/news-and-features/airbus-defence-and-space-selected-to-partner-in-production-of-oneweb-satellite-constellation/>

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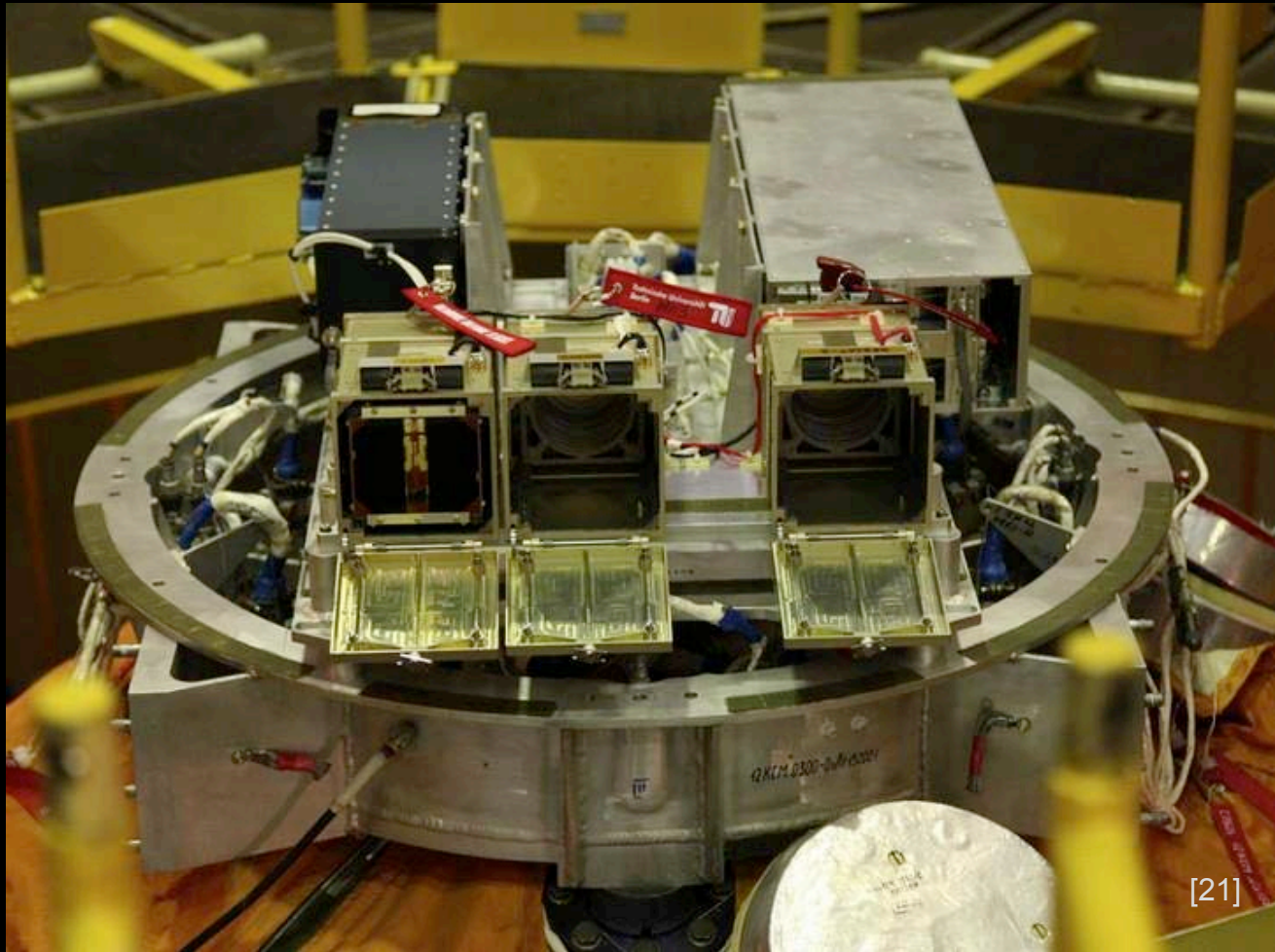
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[36] <http://spacenews.com/boeing-proposes-big-satellite-constellations-in-v-and-c-bands/>

[37] <https://www.planet.com/explorer/>

Backup

Safe containers bolt in “spare” corners of rocket



[21]

CubeSat deployment pods on top of the Bion-M1 spacecraft on Soyuz-2-1a: BeeSat-2, BeeSat-3 and SOMP in front; OSSI-1 (1U) in a 3U-Pod back left; DOVE-2 (3U) in back right. 19 April 2013 launch.

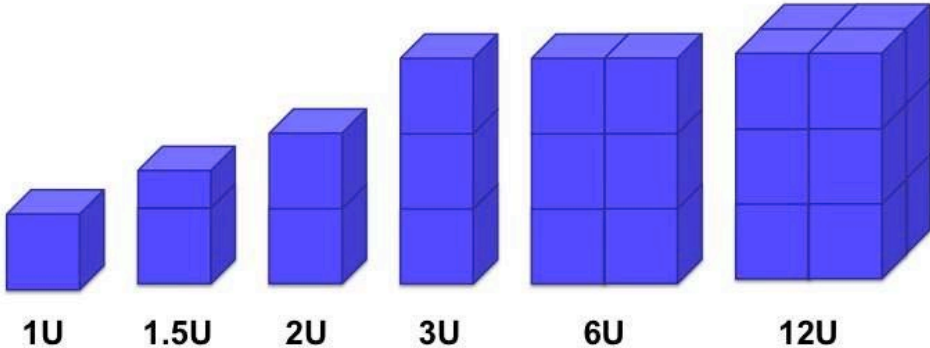
Small satellite types

Small Satellites have total (wet) mass less than 180 kg

About the size of a small refrigerator

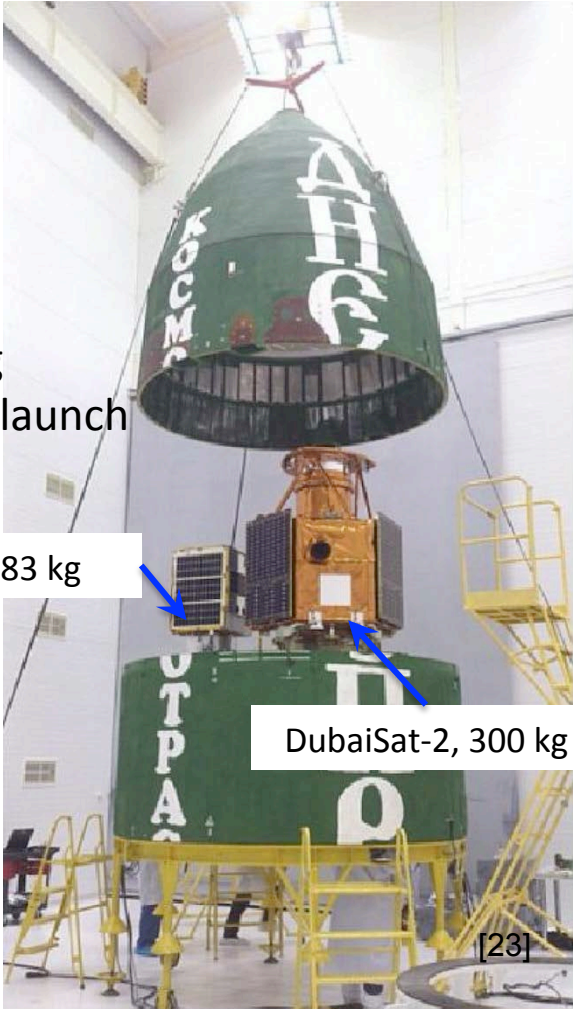
But, they get smaller...

- Minisatellite, 100-180 kg
- Microsatellite, 10-100 kg
- Nanosatellite, 1-10 kg
- Picosatellite, 0.01-1 kg
- Femtosatellite, 0.001-0.01 kg



[22]

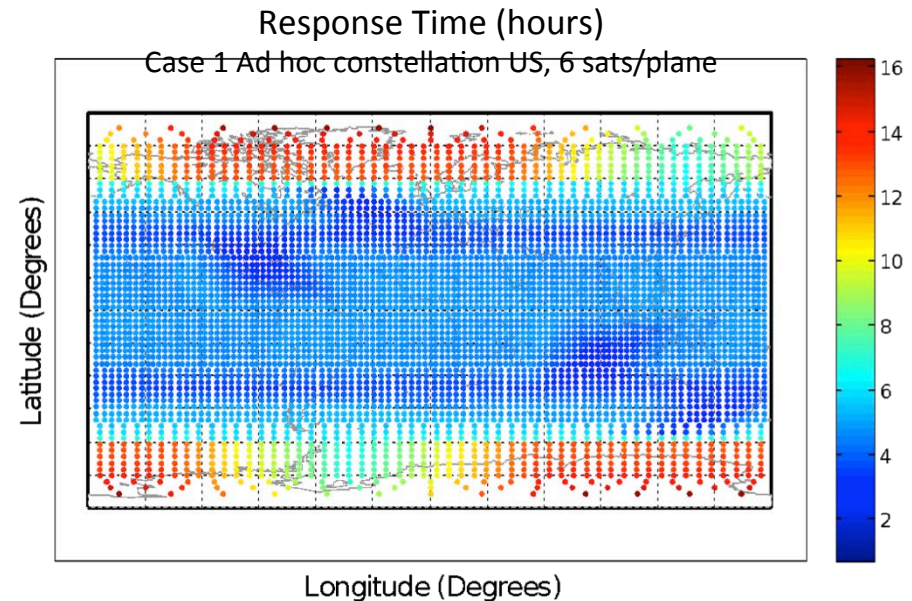
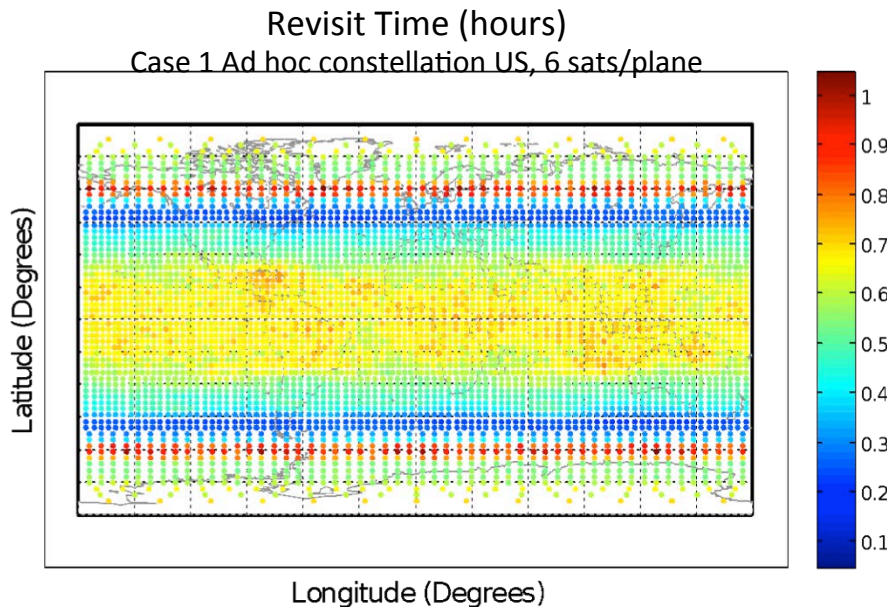
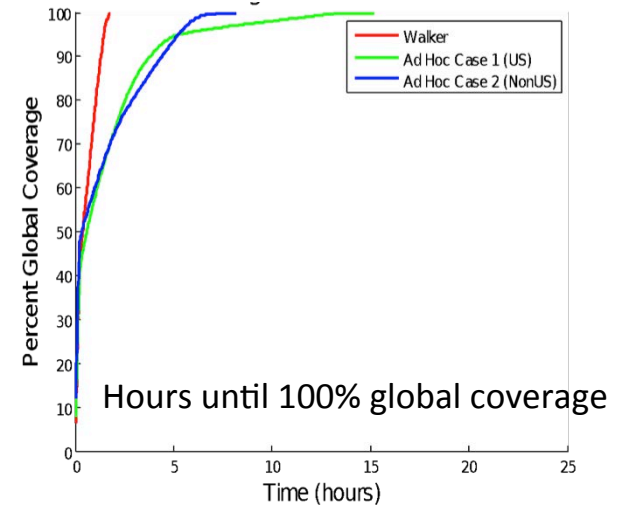
Dnepr fairing
2013 cluster launch



[23]

Why are more satellites better?

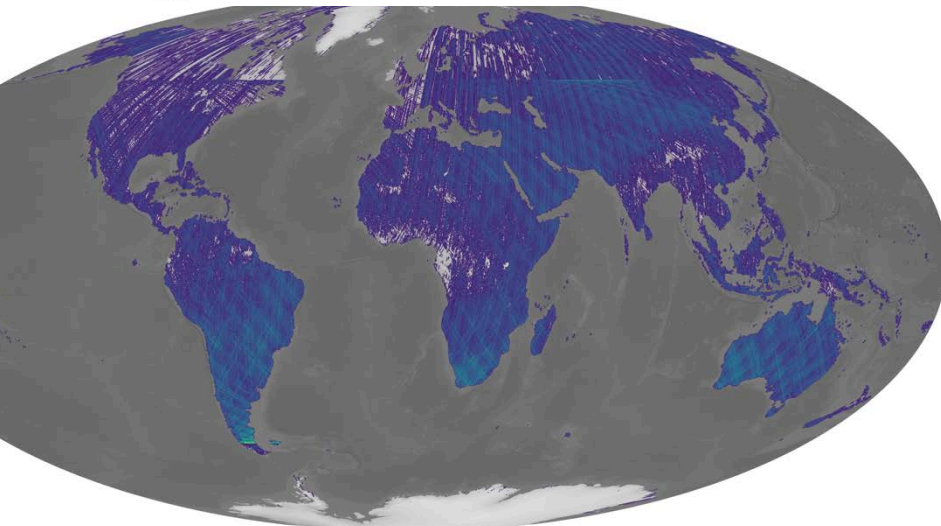
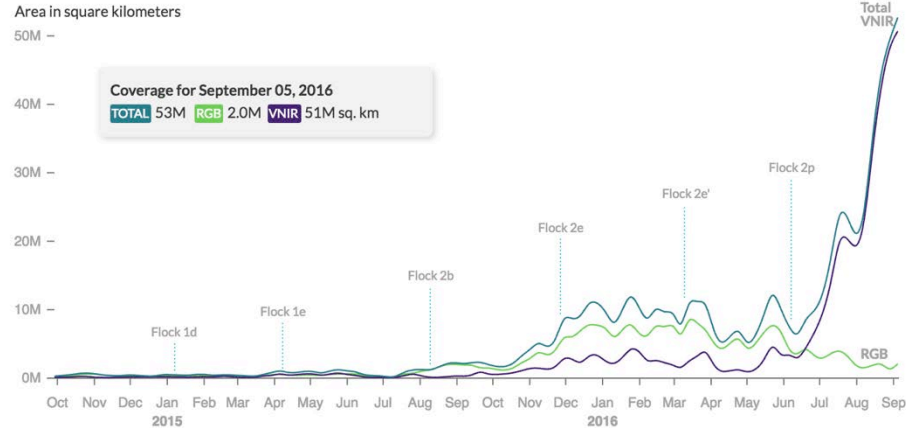
- Temporal coverage (revisit time)
- Spatial coverage (global)
- Redundancy
- Distributed sensors/function
- Lower cost
- Easier access to space, replenishment and technology advancement



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.



IMAGES COLLECTED DURING SEPTEMBER 2016



63 ACTIVE SATELLITES



30+ DOWNLINK GROUND STATIONS

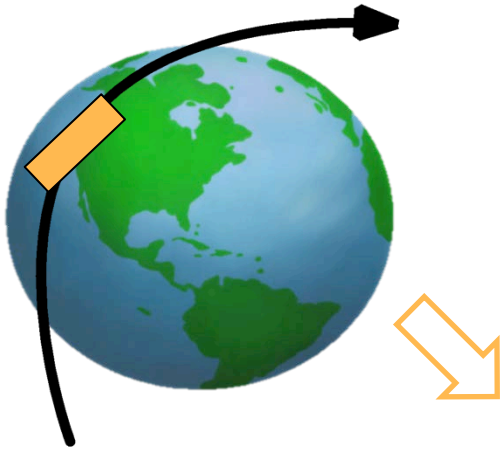


1.6 TERABYTES PER DAY

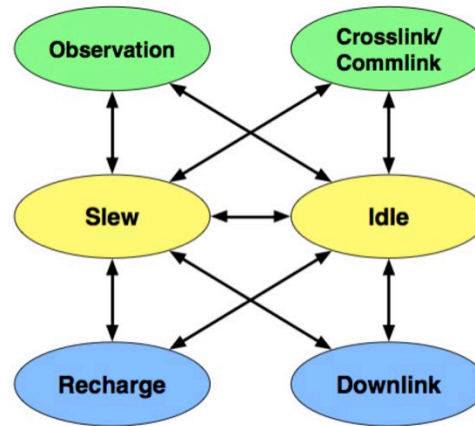
	Doves	Builds 1-5	Builds 6-10	Builds 11-13
Operational Period		2011-2012	2013-2014	2015-2016
Optics		Off-the-shelf optics, Custom telescope, focus narrow field of view mechanism	Second generation telescope with twice the field of view	
Communications		Off-the-shelf S-band radio downlink	Custom X-band 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 (km ² /sat/day)		3,000	500,000	2,500,000

Example Local Planner Steps

1. Orbital Geometry



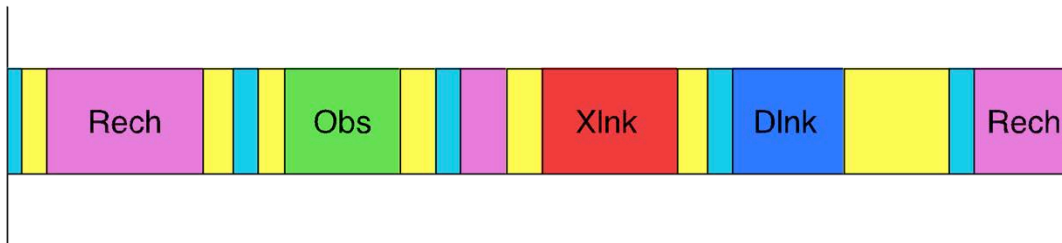
2. CubeSat Ops Model



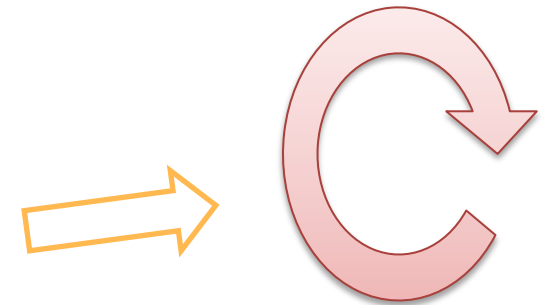
3. Planning Algorithm (e.g. RASP)



4. Activity Timeline



5. Execution and Replanning



Planet image ideas

EAST TAVAPUTS PLATEAU

Utah, USA Nov 13, 2016

Natural Gas well pads dot the sandstone canyons of Utah's East Tavaputs Plateau.

GENOA

Italy Nov 30, 2016

Kilometers-long breakwaters separate the Mediterranean Sea from the port town of Genoa, Italy. The circular Porto Antico (or Old Harbor), once a crucial trading port for goods, now serves as the town's tourism center, complete with an aquarium and a panoramic view tower.

SUGARCANE DEFORESTATION

Bolivia Jan 1, 2017

Amazon forestry researchers observed this rapid deforestation near the Bolivian Andes in Planet data.

[According to Mongabay, over 2000 hectares of forestland were cleared](#) in preparation for the expansion of the San Buenaventura Sugar Mill. See the sugarcane fields expand rapidly over just six months.

NADOR

Morocco Jan 3, 2017

The Moroccan city of Nador is sheltered from the Mediterranean by Mar Chica, a sandy saltwater lagoon. Mar Chica has a shallow maximum depth—only eight meters—allowing us to see the ebb and flow of tides clearly from space.

KEY WEST

Florida, USA Jan 6, 2017