Cubesats

MAE 4160, 4161, 5160

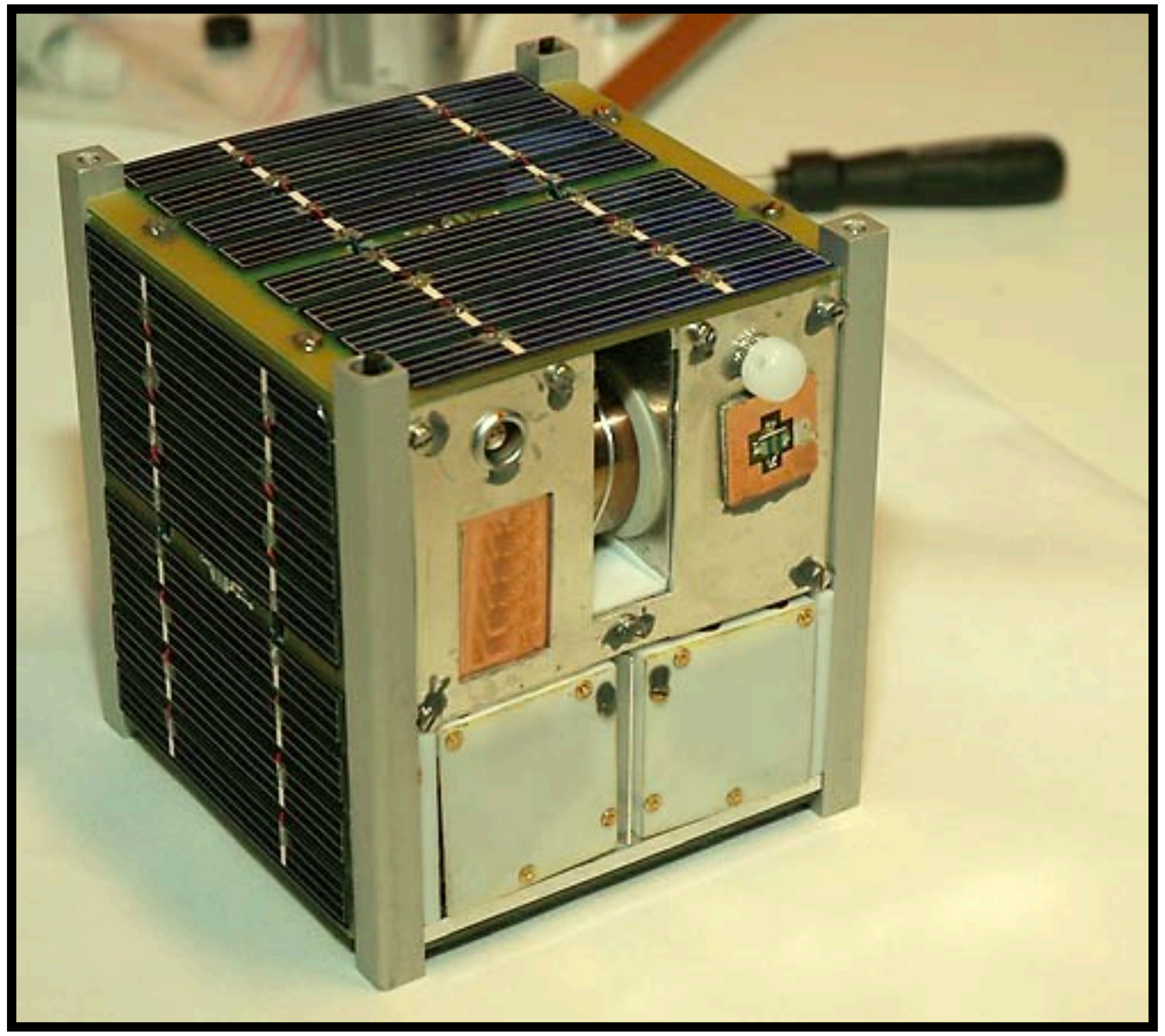
V. Hunter Adams, PhD

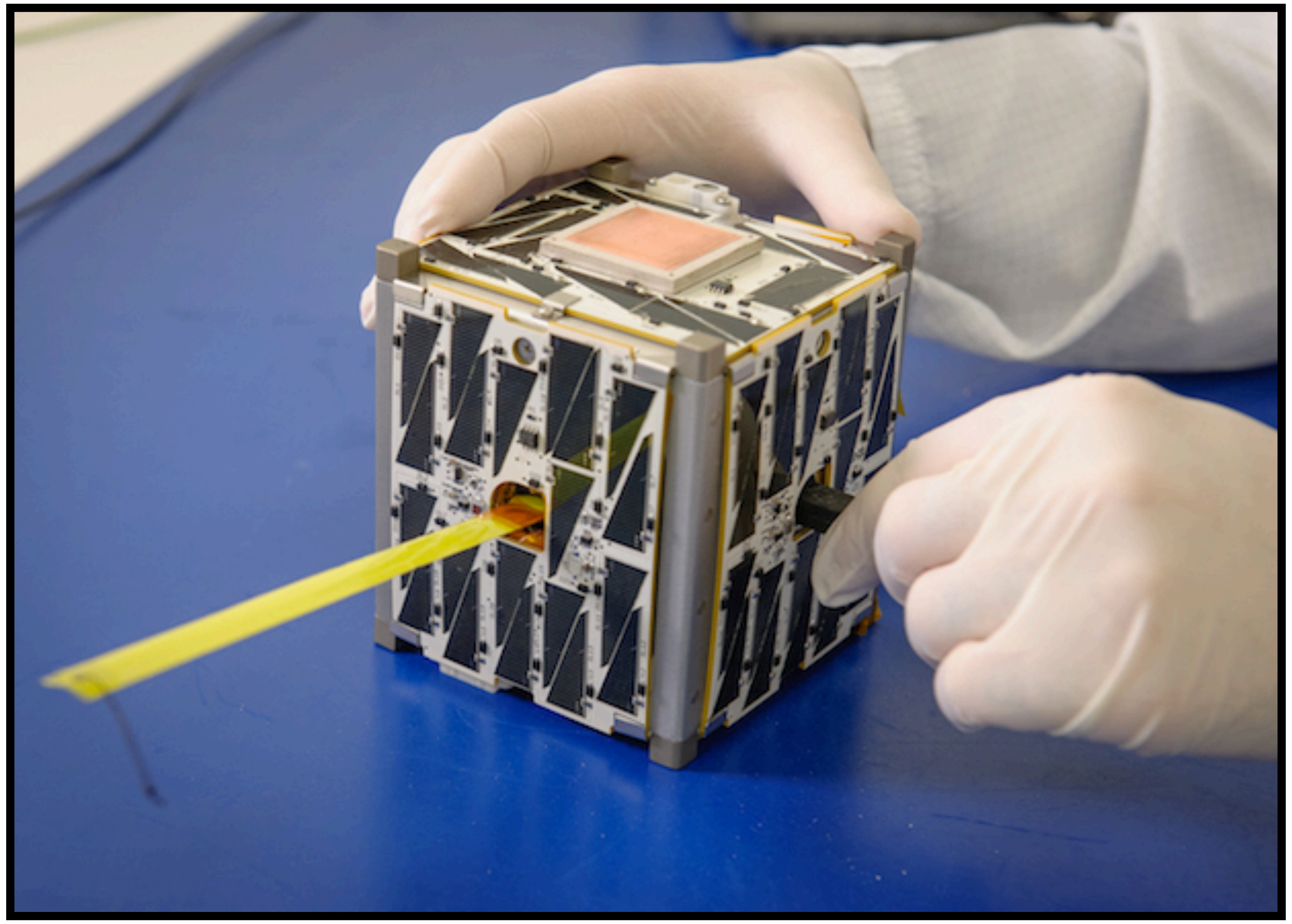
Today’s topics:

- The cubesat standard
- The cubesat revolution
- Cubesat limitations
- Subsystems on a cubesat
- How cubesats create economic and scientific value
- Case study: Pathfinder for Autonomous Navigation (presented by your TA, Stewart Aslan)

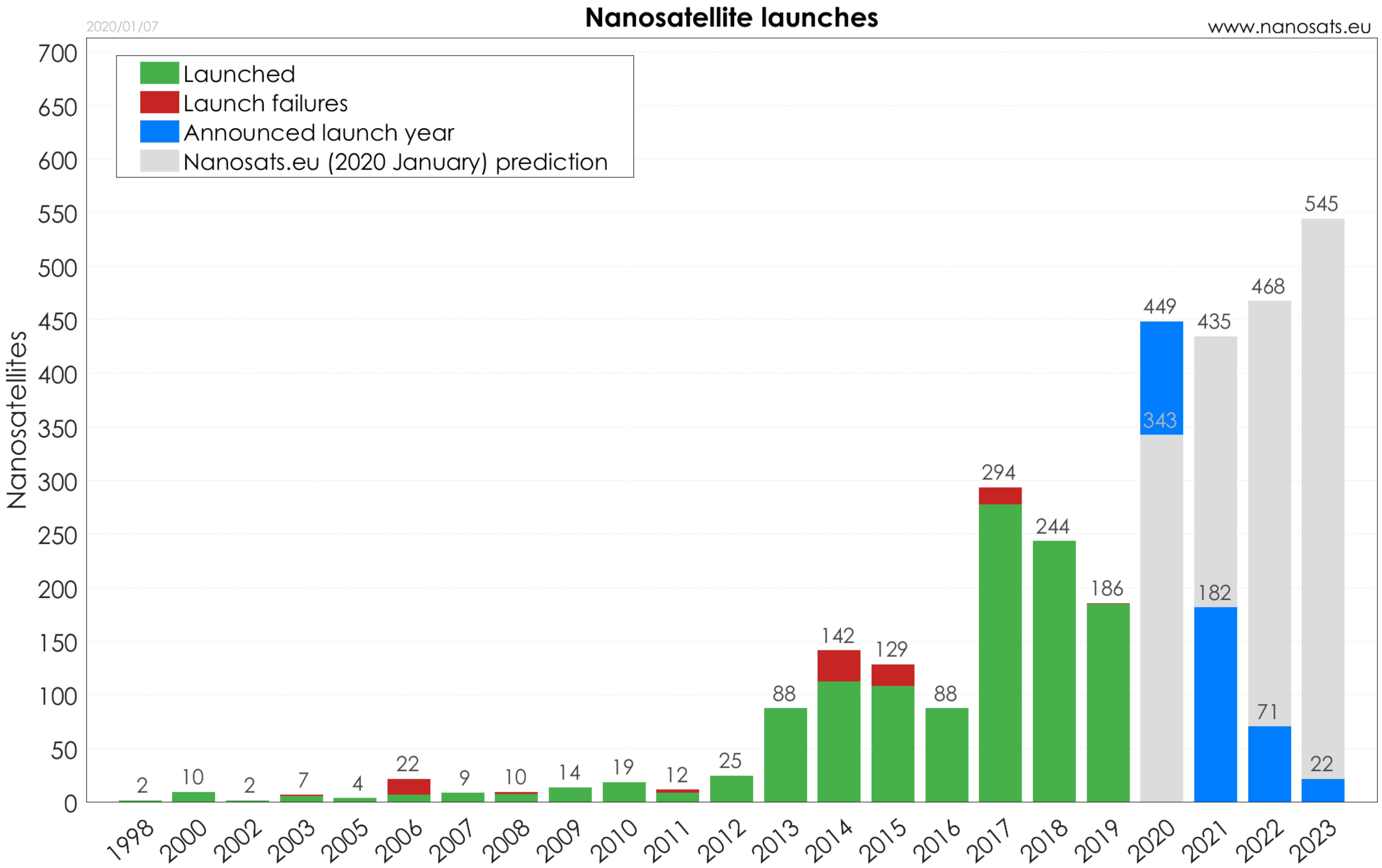
The CubeSat standard

- Size measured in “U’s” — 1U is a 10x10x10 cm cube
- Typical configurations include 1U, 1.5U, 2U, 3U, 6U
- Heavy utilization of commercial-off-the-shelf (COTS) hardware
- Standardized design enables standardized launch interface



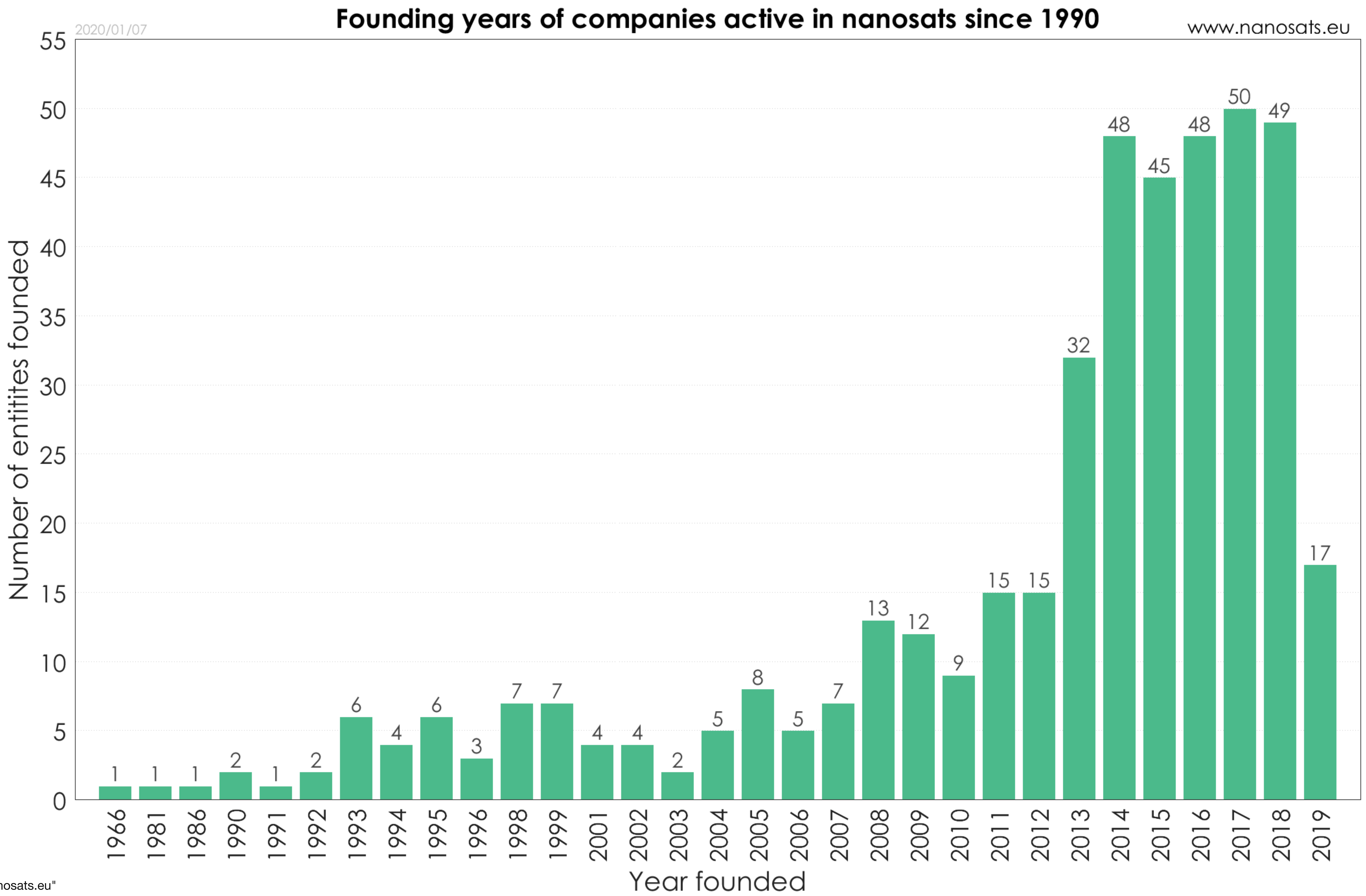


Evidence of the revolution



"Erik Kulu, Nanosats Database, www.nanosats.eu"

Evidence of the revolution



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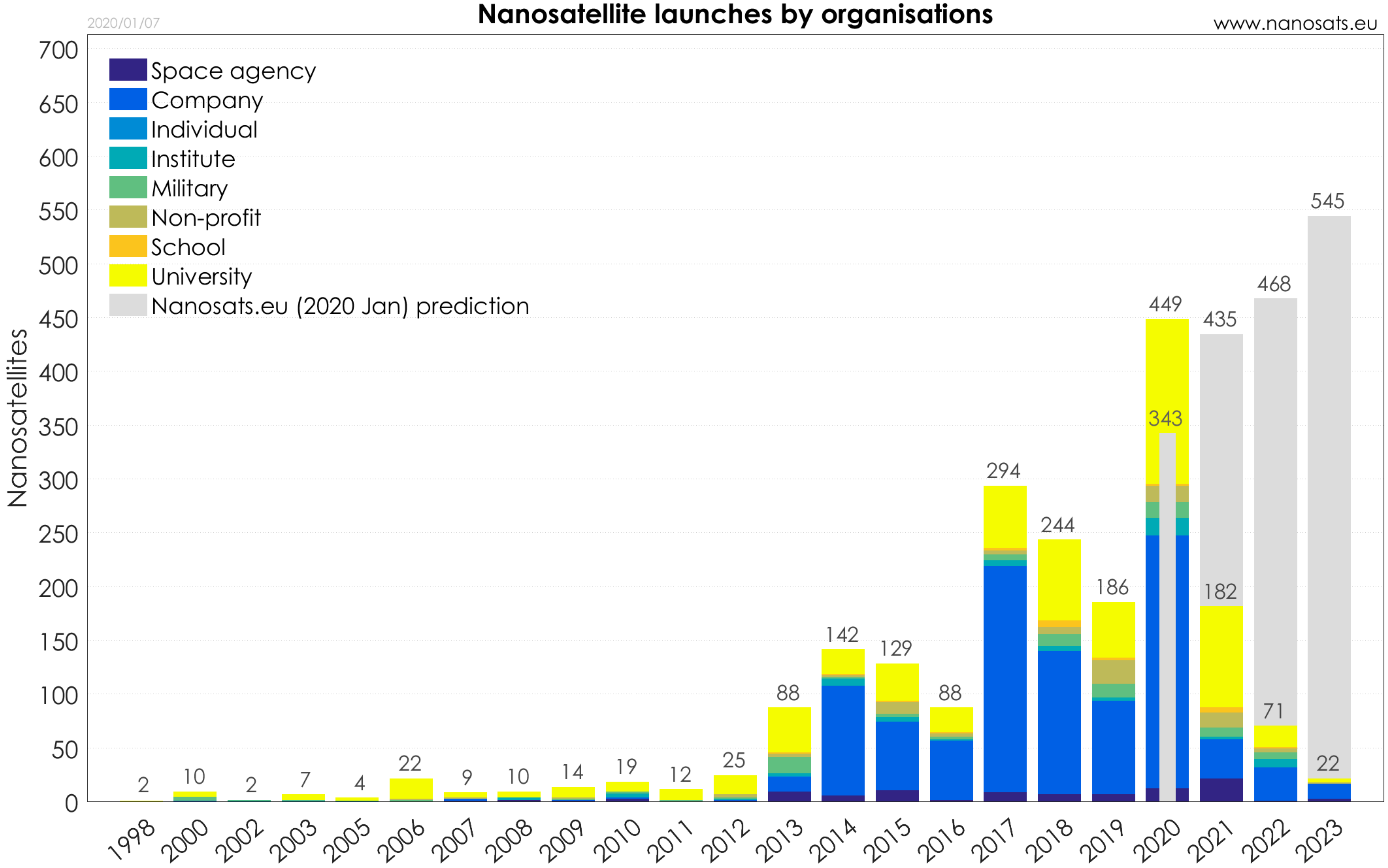

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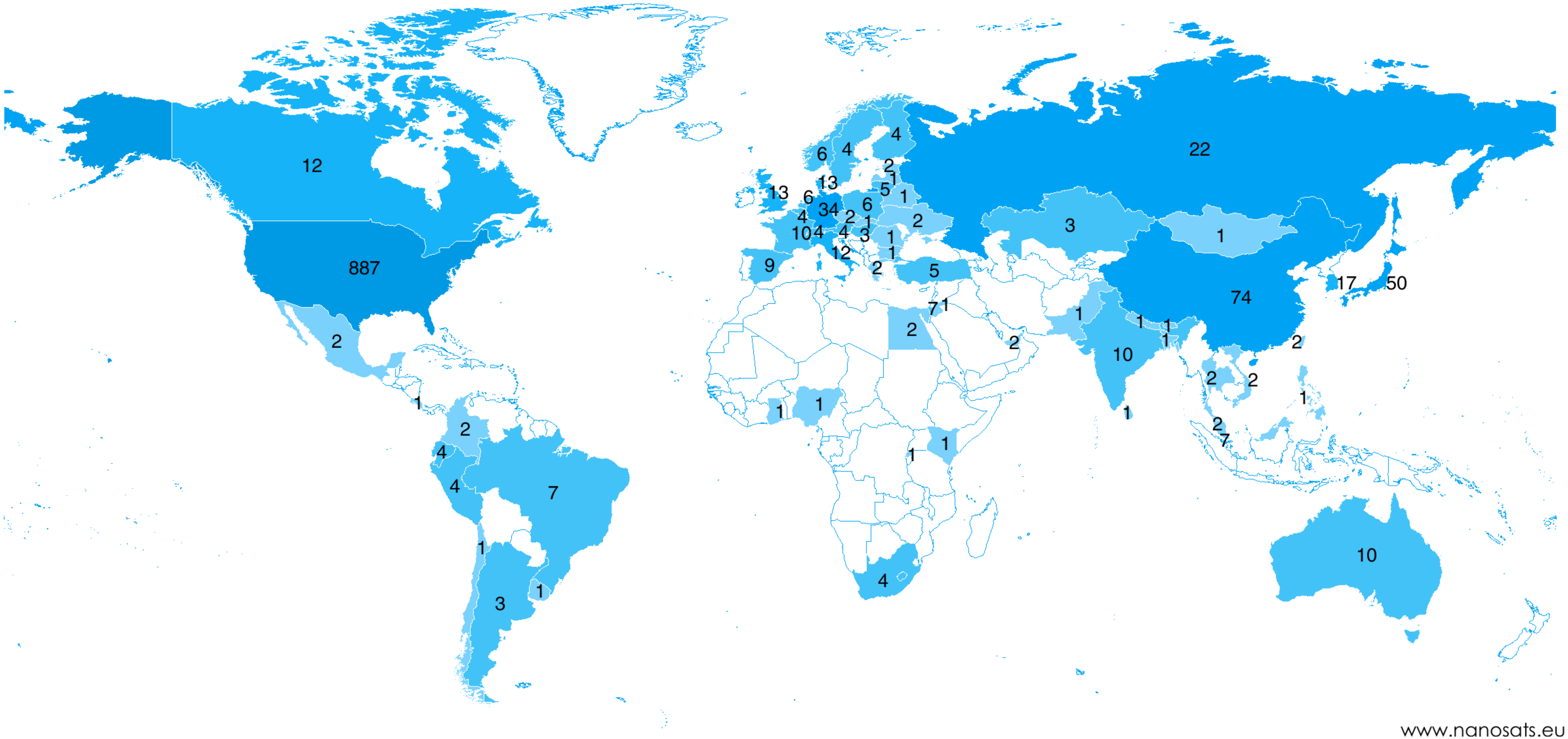
Evidence of the revolution

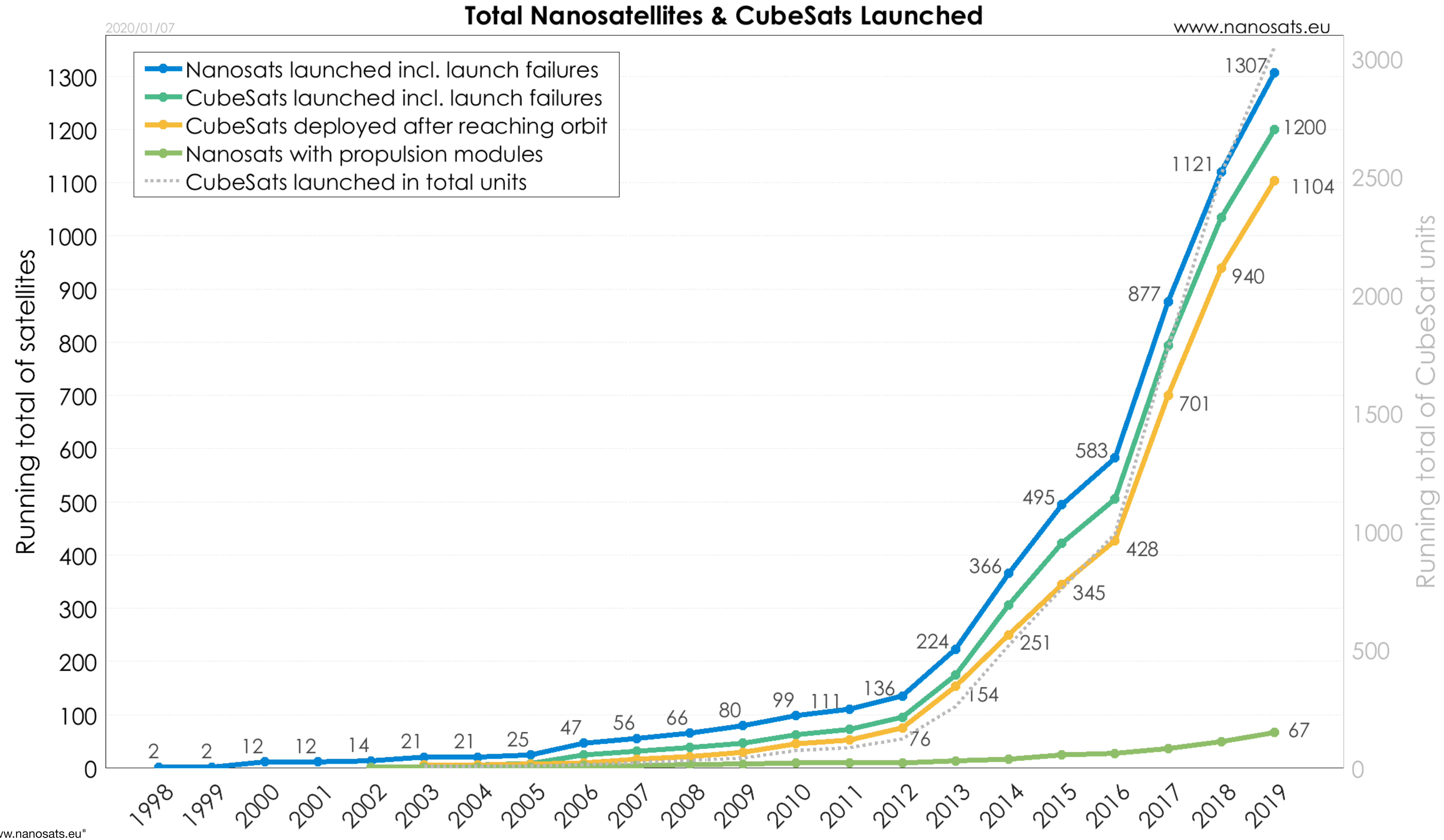
Launched nanosatellites



www.nanosats.eu

"Erik Kulu, Nanosats Database, www.nanosats.eu"

Evidence of the revolution



"Erik Kulu, Nanosats Database, www.nanosats.eu"

Cubesat payloads

Often include . . .

- Low-resolution CCD cameras
- GPS receivers
- Space weather sensors

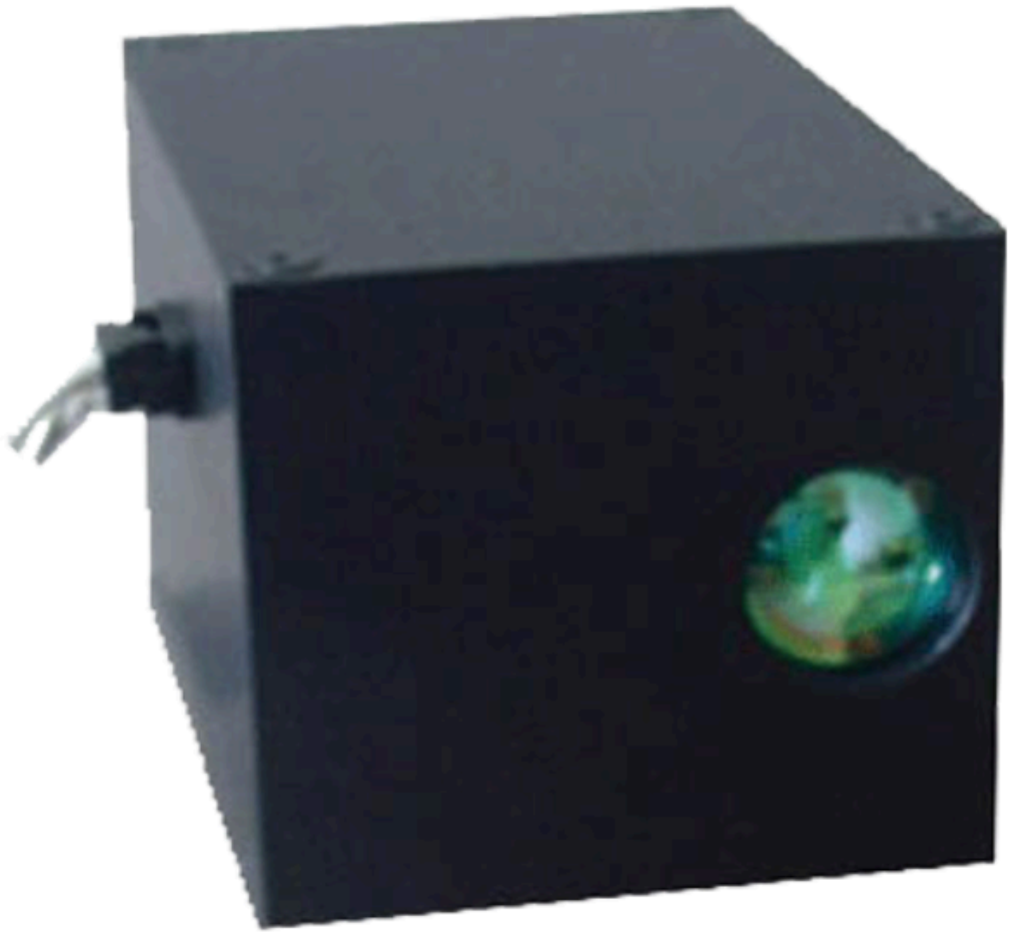
More sophisticated payloads have included . . .

- GPS receivers for radio occultation
- Reflectometry sensors
- Photometers
- Magnetometers
- Atmospheric sounders
- Spectrometers
- Interferometers

Not flown (to my knowledge) . . .

- Active instruments (radar, lidar, etc.) — missions planned
- Instruments in the SWIR/MIR region of the spectrum (cryocooling)

Low-resolution CCD
~10's of dollars



IR spectrometer
~$30,000

Cubesat limitations

Severe technological limitations (on both instruments and bus) introduced by the cubesat standard

- Power issues
- Spatial resolution
- Signal-to-noise ratio
- Communications issues
- Thermal issues
- Data processing issues
- ADCS/propulsion issues
- Launch strategy, lifetime, deorbiting

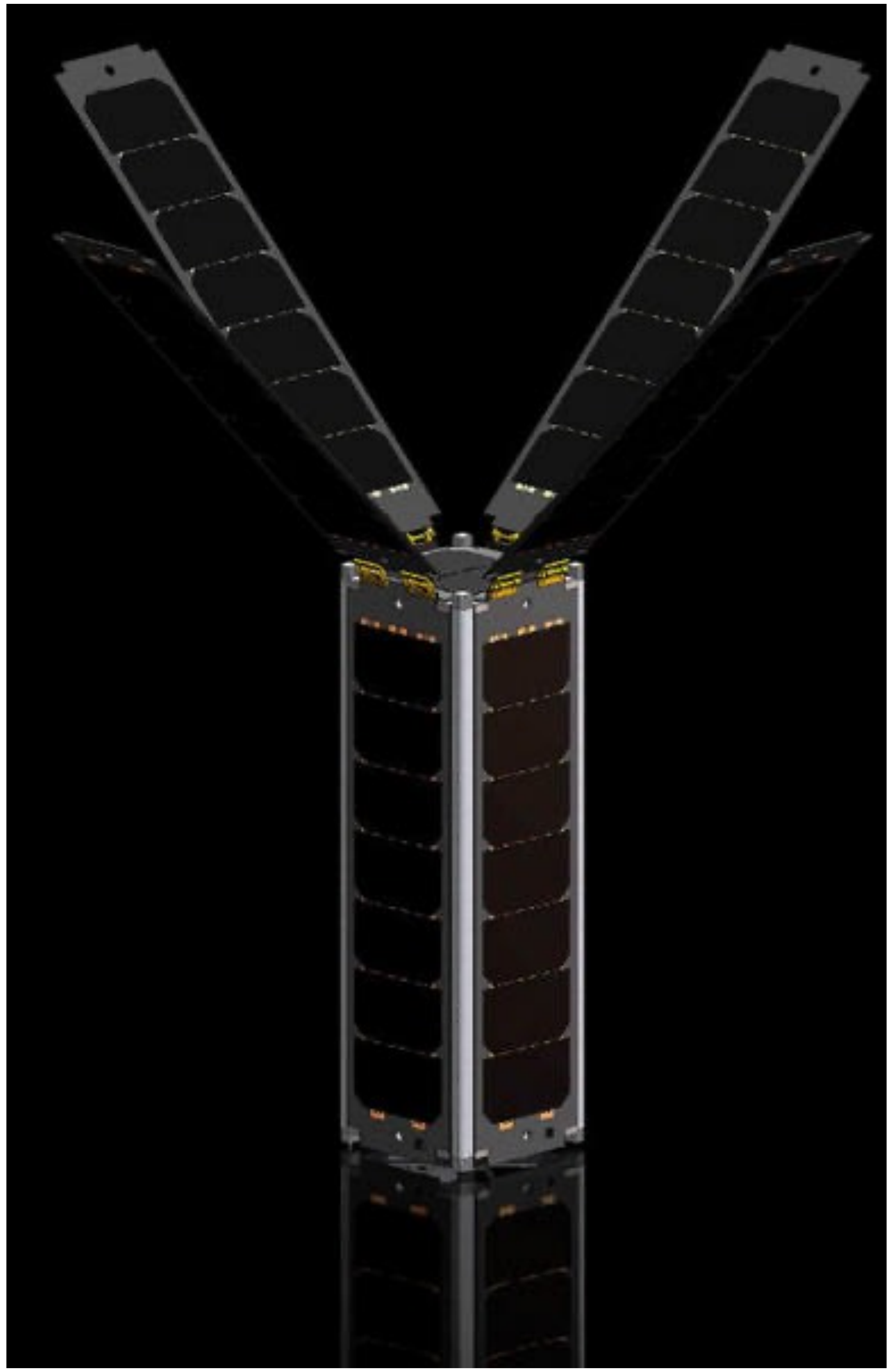
Zac Manchester with KickSat

Power

- Beginning-of-life (BOL) powers provided by solar arrays are on the order of a few Watts for 1U

$$P_{BOL} \approx \left(S_0 \approx \frac{1400W}{m^2} \right) \times (A \approx 0.1m \times 0.1m) \times \left(\eta I_d \approx 0.2 \right) = 2.8W$$

- This places severe limitations on the instruments and bus:
  - No active instruments ⟶ no radar, lidar
  - No active cooling ⟶ No SWIR instruments
  - No moving parts ⟶ No scanning mechanisms
- Ways to overcome this:
  - Body-mounted + deployable solar arrays
  - Up to 50-60W for 3-6U Cubesats
- Typical energy storage is ~10-30Wh
  - sufficient to handle eclipses
  - Eclipse time ~ 1/3 period ~ 30 min



Clyde Space


Best Research-Cell Efficiencies
NREL
Transforming ENERGY
Cell Efficiency (%)
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Perovskite/Si tandem (monolithic)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
(various types)
47.1%
44.4%
39.2%
37.9%
35.5%
32.8%
30.5%
29.1%
28.0%
27.8%
27.6%
26.7%
26.1%
25.2%
23.4%
23.3%
22.3%
22.1%
21.2%
16.6%
16.5%
14.2%
14.0%
12.6%
11.9%
(Rev. 09-16-2019)

Wikipedia

Angular and spatial resolution

- The aperture, D, of an instrument determines its diffraction-limited resolution Δx

$$\Delta x \approx h \cdot \frac{\lambda}{D}$$

- This is **approximately 5-10m for optical remote sensing from 800 km altitude**
- Ways to overcome this:
  - Deployable instruments

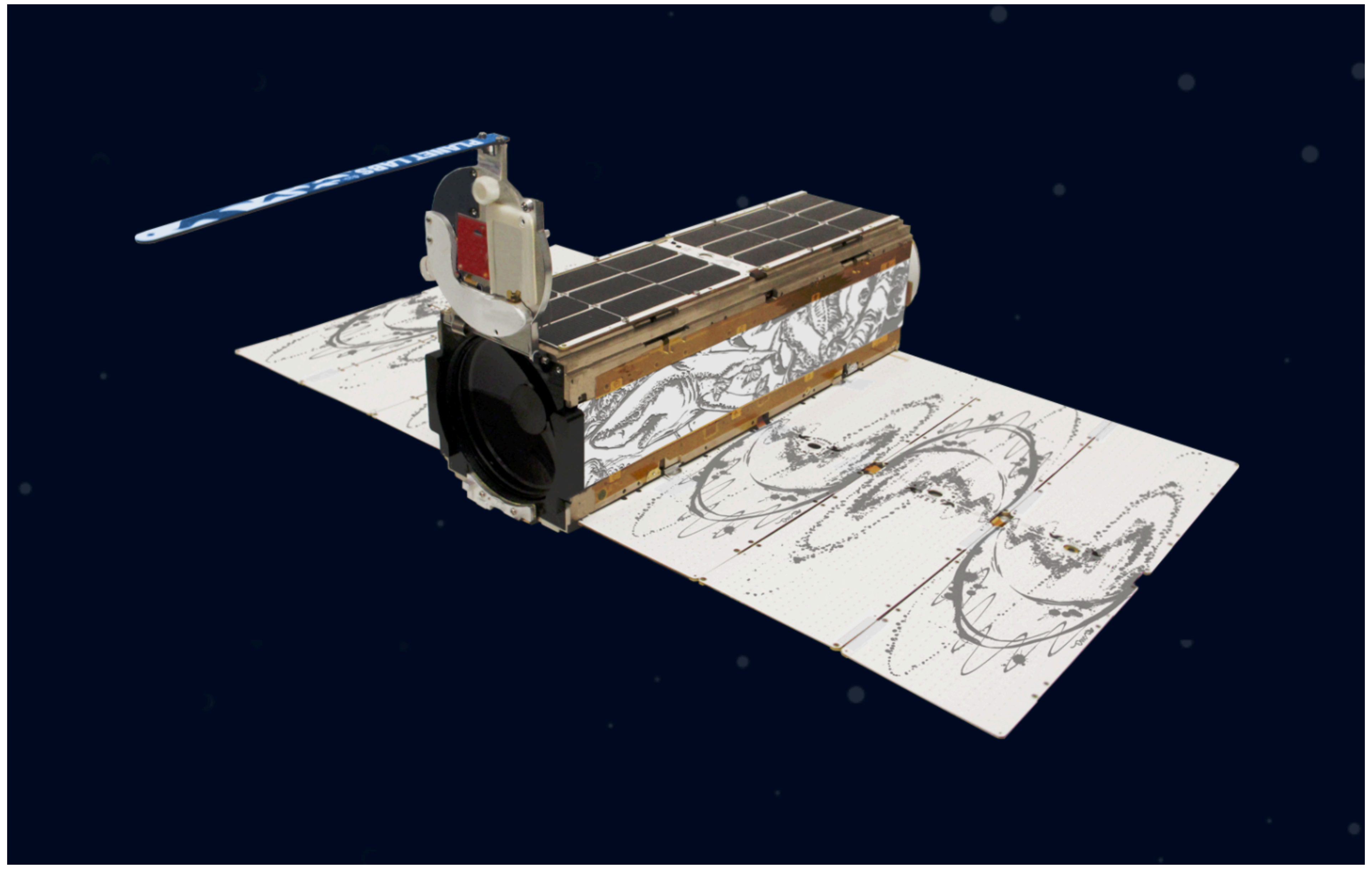
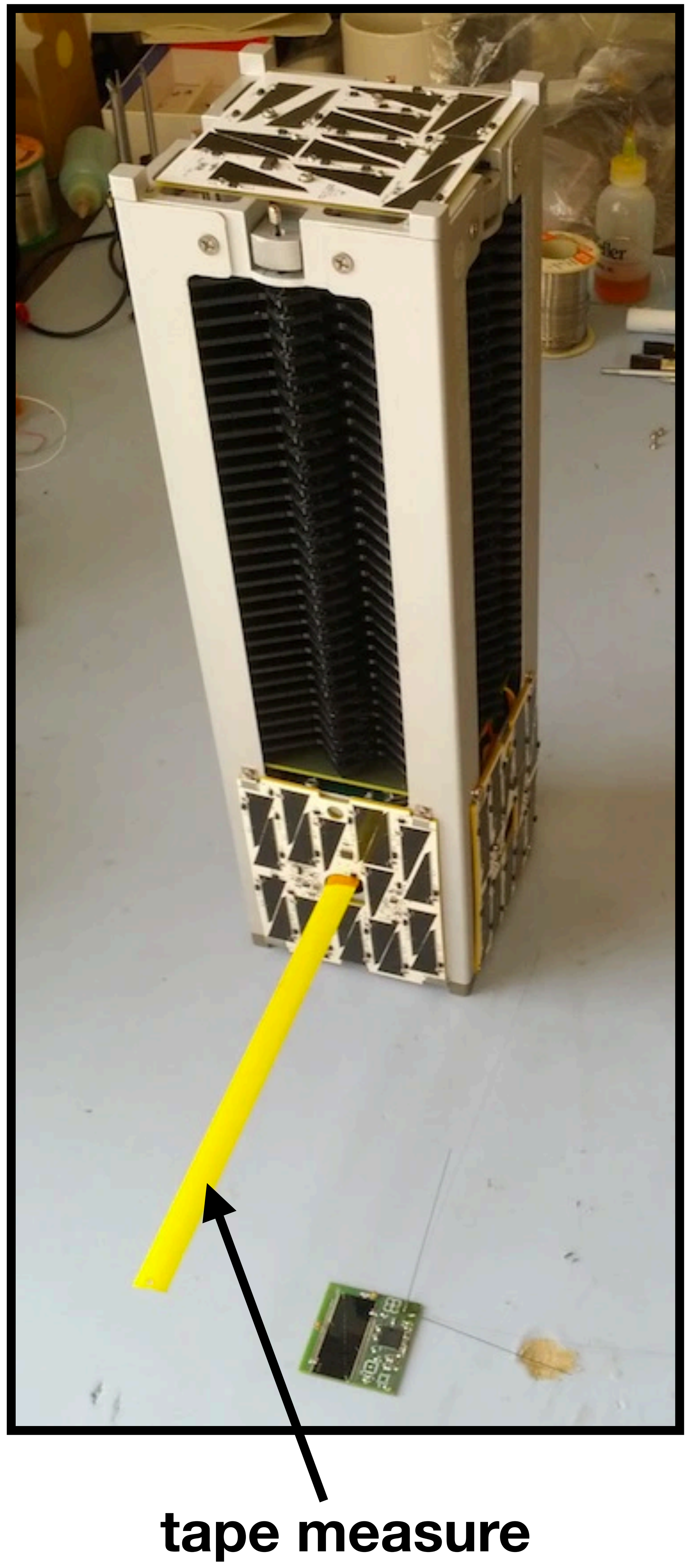
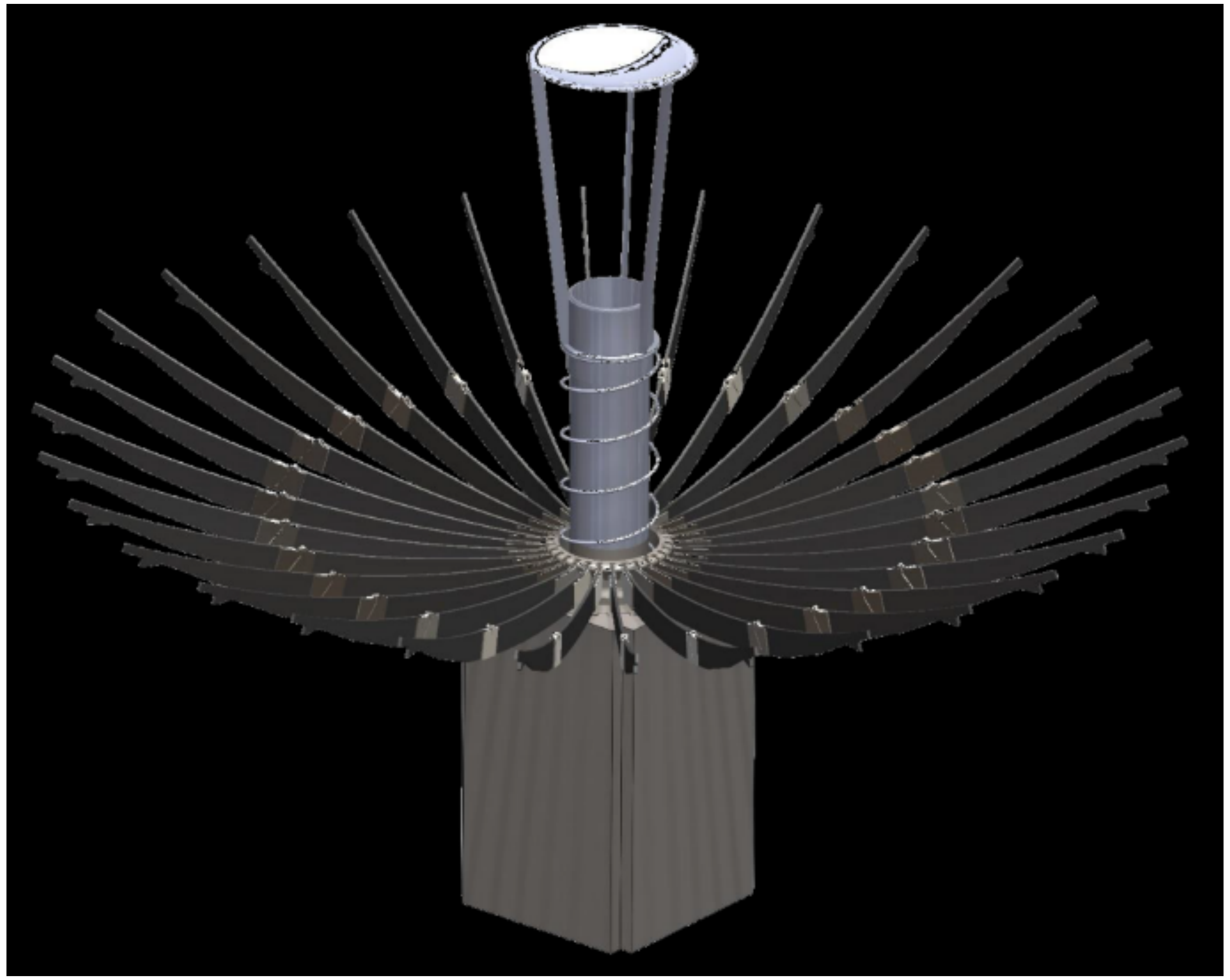


Image credit: Planet

Communications

- Most cubesats communicate on UHF frequencies (300MHz - 3GHz)
  - Often use dipole or monopole antennas built from tape measures, or off-the-shelf omnidirectional antennas
  - RF power typically <1W
  - Usually, for a 1U, data rates on the order of kbps
- Severely limits duty cycle of the instrument due to contact duration
  - Assuming 10 min of contact per day at 1Mbps (high-end of what's achievable), we can download 50 Mb/day, ~50 1Mpixel images/day
  - Alternative: use a service provider (GlobalStar, Iridium, etc.). More time in communication, but greater cost per bit of communication
  - Alternative: deployable high-gain antennas



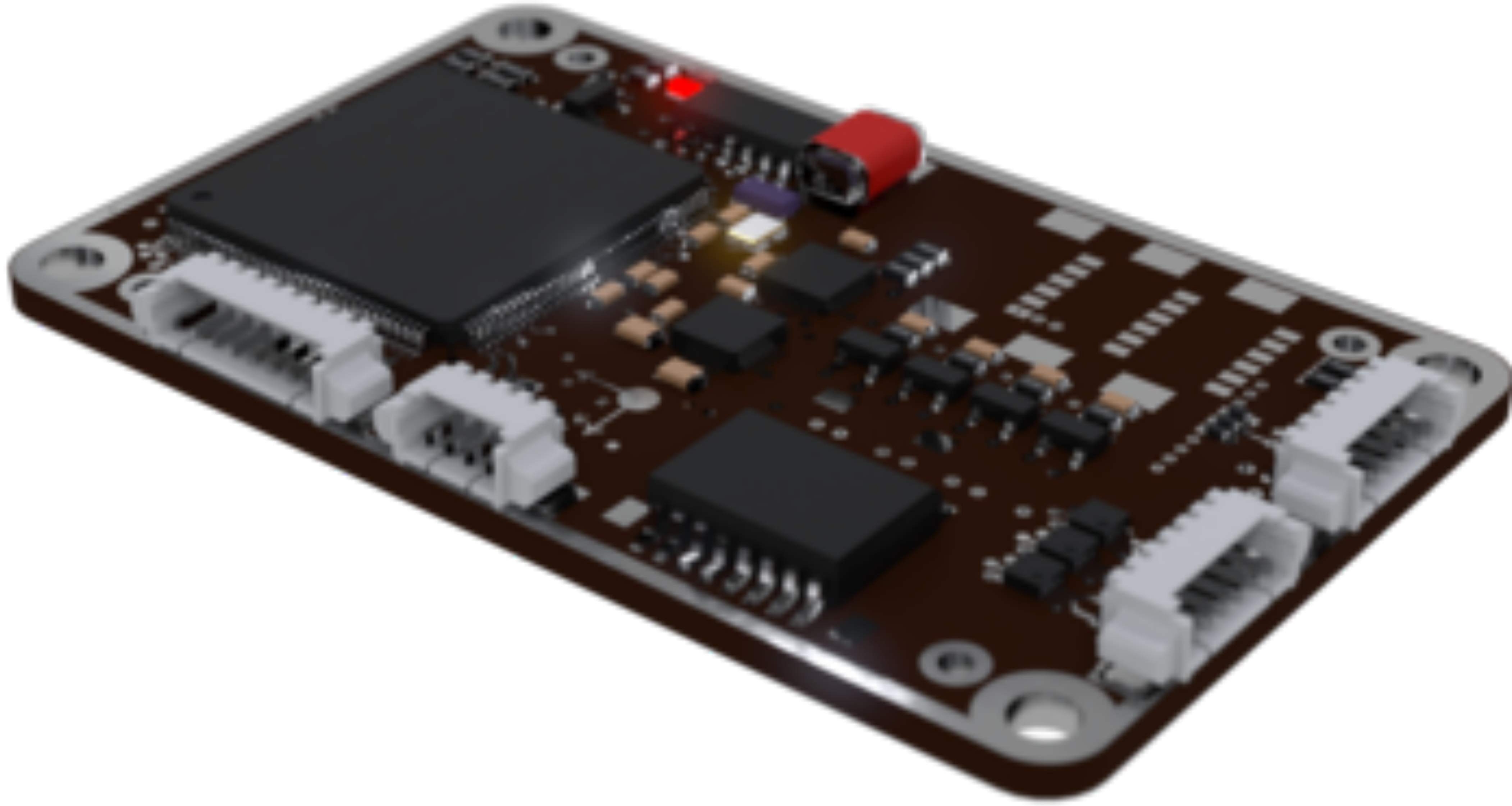


Ka-Band Deployable Antenna (KaPDA)
In development at JPL
~46dbi of gain

KaPDA Stowed

Avionics

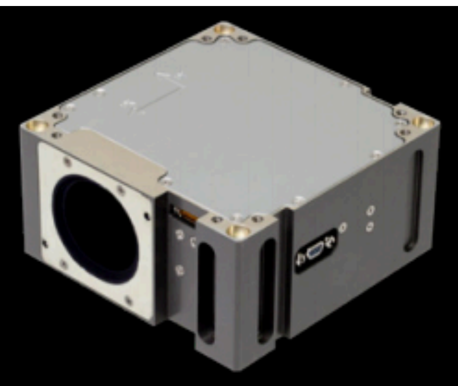
- Command and data handling often based on an **I2C bus** (100kbps - 5Mbps), and uses PIC, MSP, and ARM architectures
- Data storage is typically on the order of a few MB, up to a few GB with the addition of SD cards
- 8GB equivalent to ~3500 640x480 8-bit/pixel single-band images
    - Or 32 multispectral cubes (32 bands, 1Kx1K pixel, 8bit/pixel)
- Storage does not typically limit the duty cycle of an instrument. Downlink capability is usually the bottleneck.

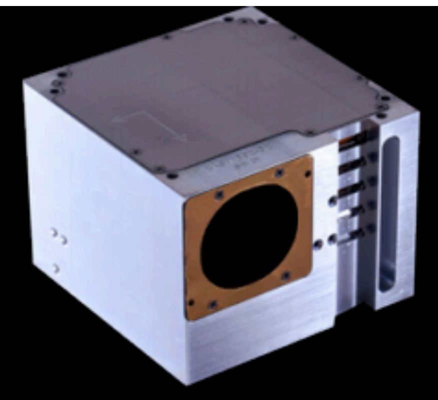


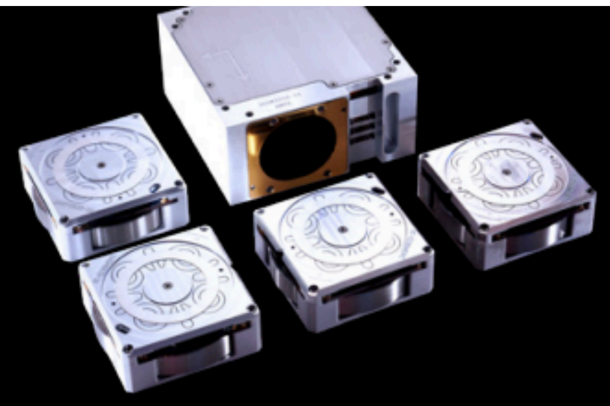
GOMSpace

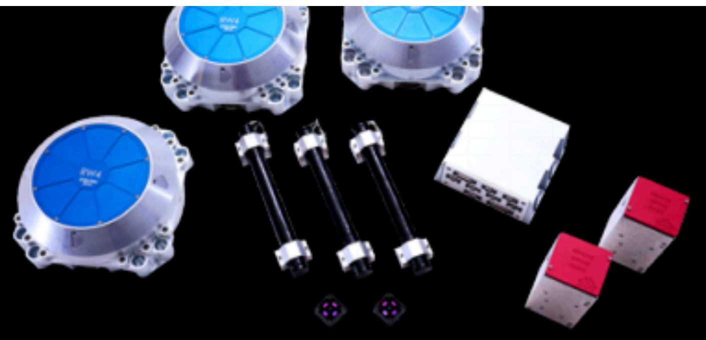
ADCS

- Attitude **determination**
  - Very often includes magnetometers
  - Very often includes sun sensors
  - Accuracies typically on the order of ~0.5 - 1deg
  - Star trackers with accuracy ~10 arcsec are commercially available (BCT)
- Attitude **control**
  - Passive and active magnetic torquers
  - Sometimes reaction wheels
  - Control accuracies typically on the order of 0.5-1 deg
  - Commercially available attitude control systems with accuracy down to 0.003 deg





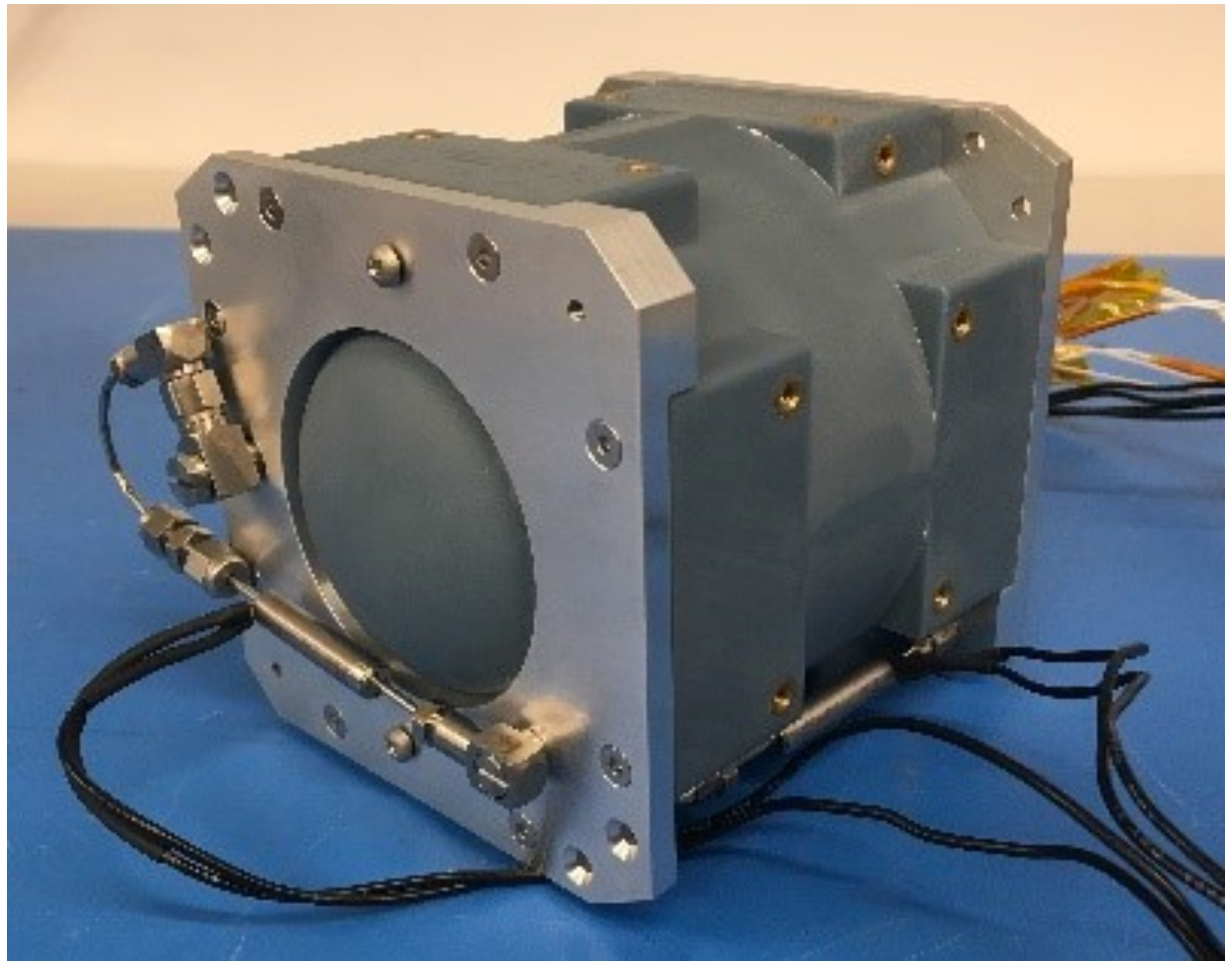




	XACT-15	XACT-50	XACT-100	FLEXCORE
SPACECRAFT POINTING ACCURACY	±0.003 deg (1-sigma) for 2 axes; ±0.007 deg (1-sigma) for 3rd axis	±0.003 deg (1-sigma) for 2 axes; ±0.007 deg (1-sigma) for 3rd axis	±0.003 deg (1-sigma) for 2 axes; ±0.007 deg (1-sigma) for 3rd axis	±0.002 deg (1-sigma), 3 axes; 2 Trackers
MASS	0.885 kg	1.23 kg	0.433 kg + 1.38 kg (wheels + torque rods)	Configuration Dependent
VOLUME	10 x 10 x 5 cm (0.5U)	10 x 10 x 7.54 cm (0.75U)	10 x 10 x 5 cm (0.5U) (not incl. external components)	< 12.1 x 11.4 x 4.9 cm (not incl. external components)
ELECTRONICS INPUT VOLTAGE	12V	12V	12V	5V and 28V
TYPICAL DATA INTERFACE	RS-422			
SLEW RATE	≥10 deg/sec (4kg, 3U CubeSat)	≥10 deg/sec (14kg, 6U CubeSat)	≥10 deg/sec (25kg, 12U CubeSat)	Application Dependent
SPACECRAFT LIFETIME	5 Years (LEO)			
MOMENTUM	15 mNms	50 mNms	100 mNms	Between 0.5 and 8 Nms ***depending on which** wheels are used

Propulsion

- The vast majority of cubesats **do not have propulsion**
  - Cannot do orbit injection
  - Cannot do orbit maintenance
  - Cannot do deorbiting
- Current propulsion systems
  - Cold gas thrusters: $I_{sp} \approx 50 - 100s$, $\Delta V \approx 50 - 100m/s$
  - Electric propulsion: $I_{sp} \approx 1400 - 1500s$, $\Delta V \approx 50 - 500m/s$

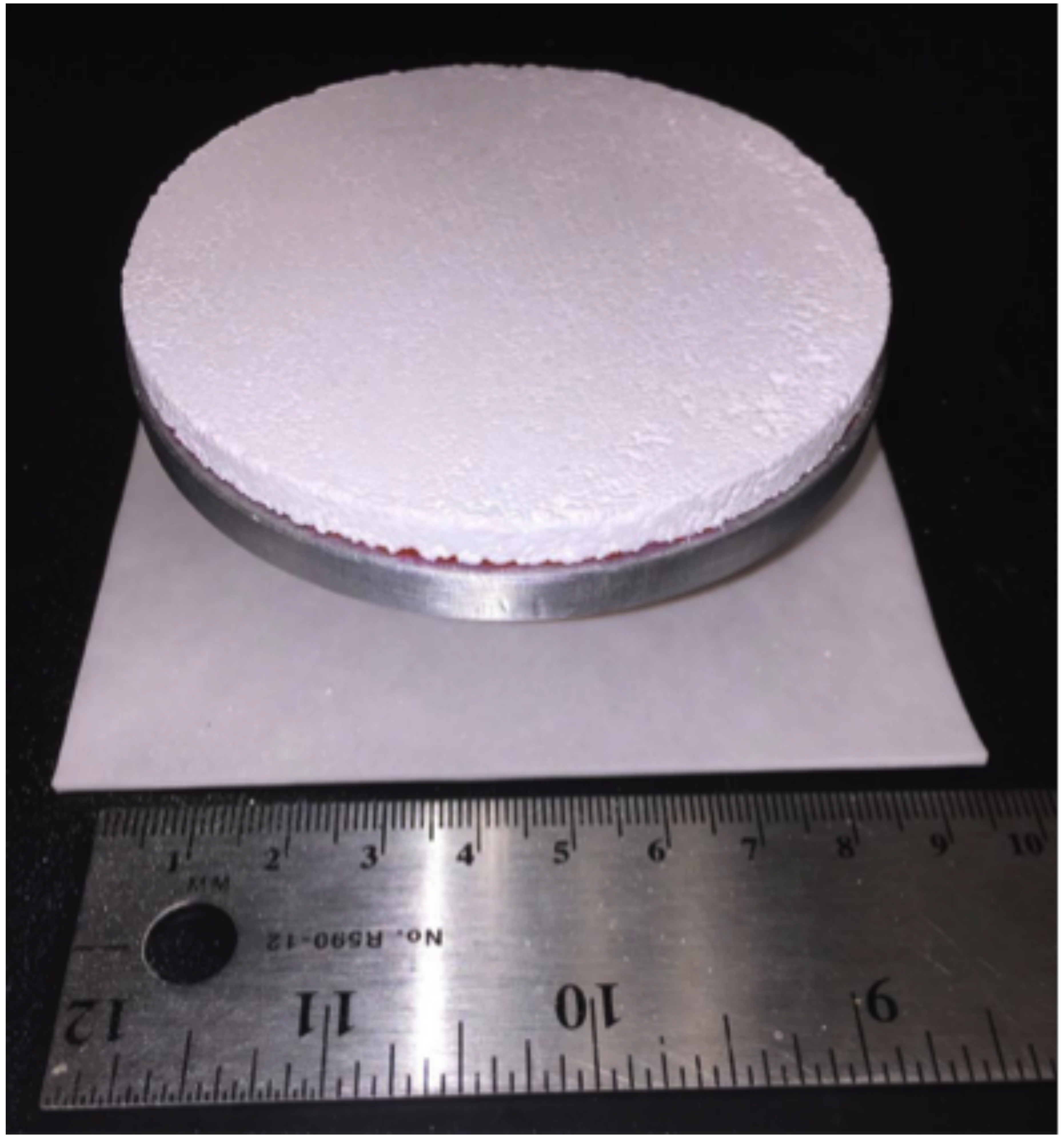


Propulsion module for Cornell's Pathfinder for Autonomous Navigation (PAN)

Thermal

- Usually **passive thermal control**, with heat sinks and optical tape on the outer structure
- Radiators are not very effective due to limited size
  - Heat fluxes typically on the order of Watts to tens of Watts
  - Precludes payloads dissipating hundreds of Watts or more
- Active thermal control for batteries (heaters)
- No cryocooling
  - Sensors in the MIR are discarded due to low SNR (increase in dark noise)
- Various high-performance coolers are in development
  - **Solar white**: Robert Youngquist

https://technology.nasa.gov/features/youngquist.html

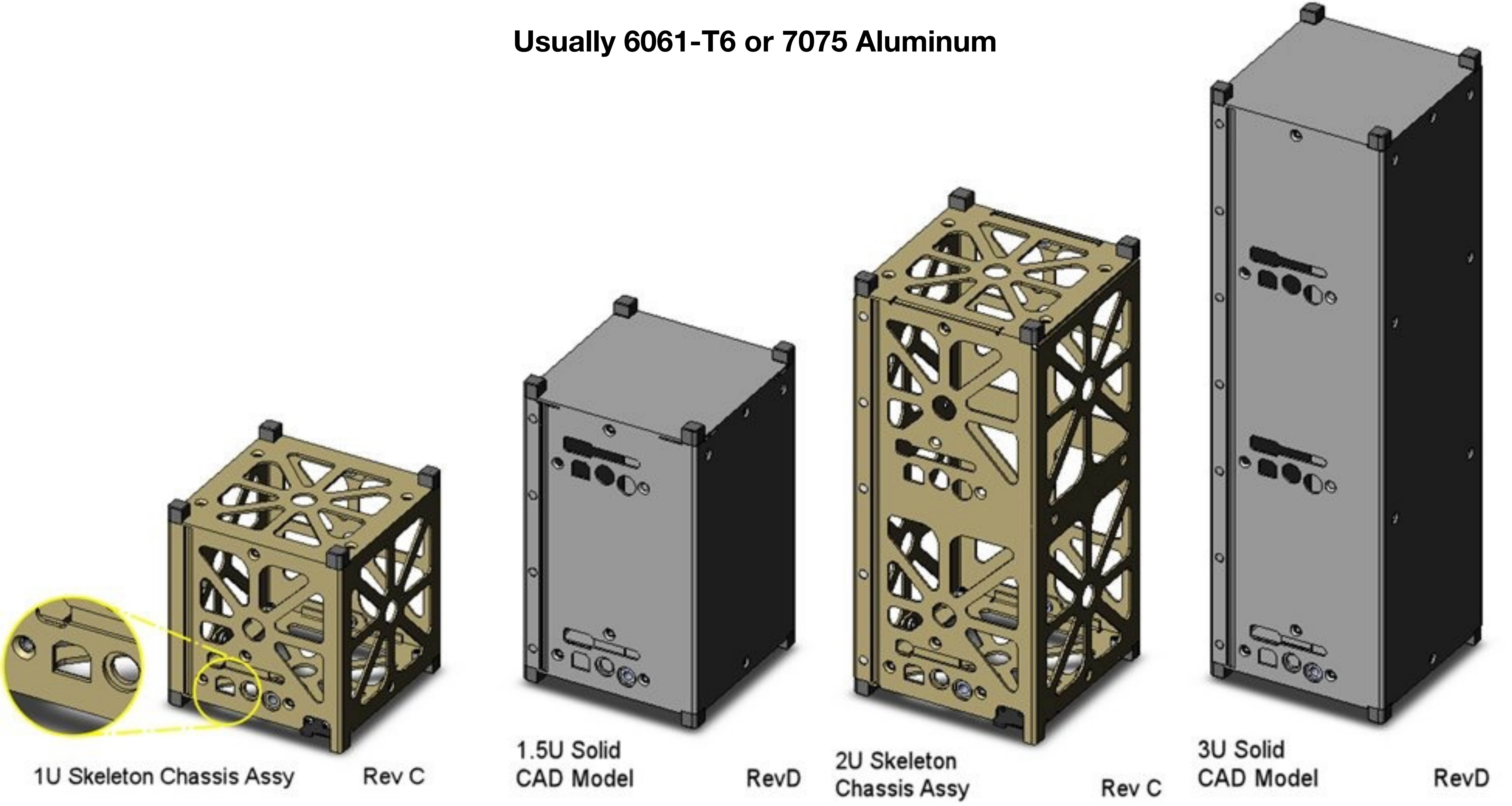


“This technology can lead to a new generation of solar radiation shields that may allow future probes to nearly reach the surface of the Sun.”

-Bob Youngquist

Structures

Usually 6061-T6 or 7075 Aluminum

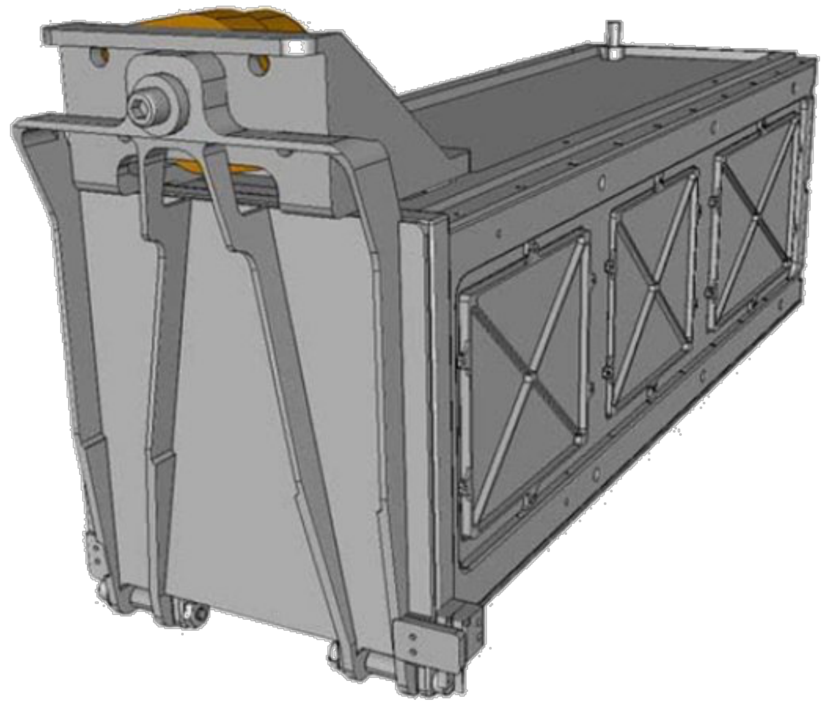


Launch and insertion

- Almost always launched as **secondary payloads**
  - Piggy-back rides with commercial launches
  - Low-cost, but no choice in orbits
  - Most available launches are to ISS orbits
  - Lifetimes on the order of months at these altitudes (due to drag)
- Cubesats are placed inside deployment mechanisms (e.g. P-POD) that generate small $\Delta V \approx 1.5 m/s$
  - Not much, difficult to get optimal spacing between satellites
- Then deployed from ISS
  - Nanoracks uses the ISS mechanical arm

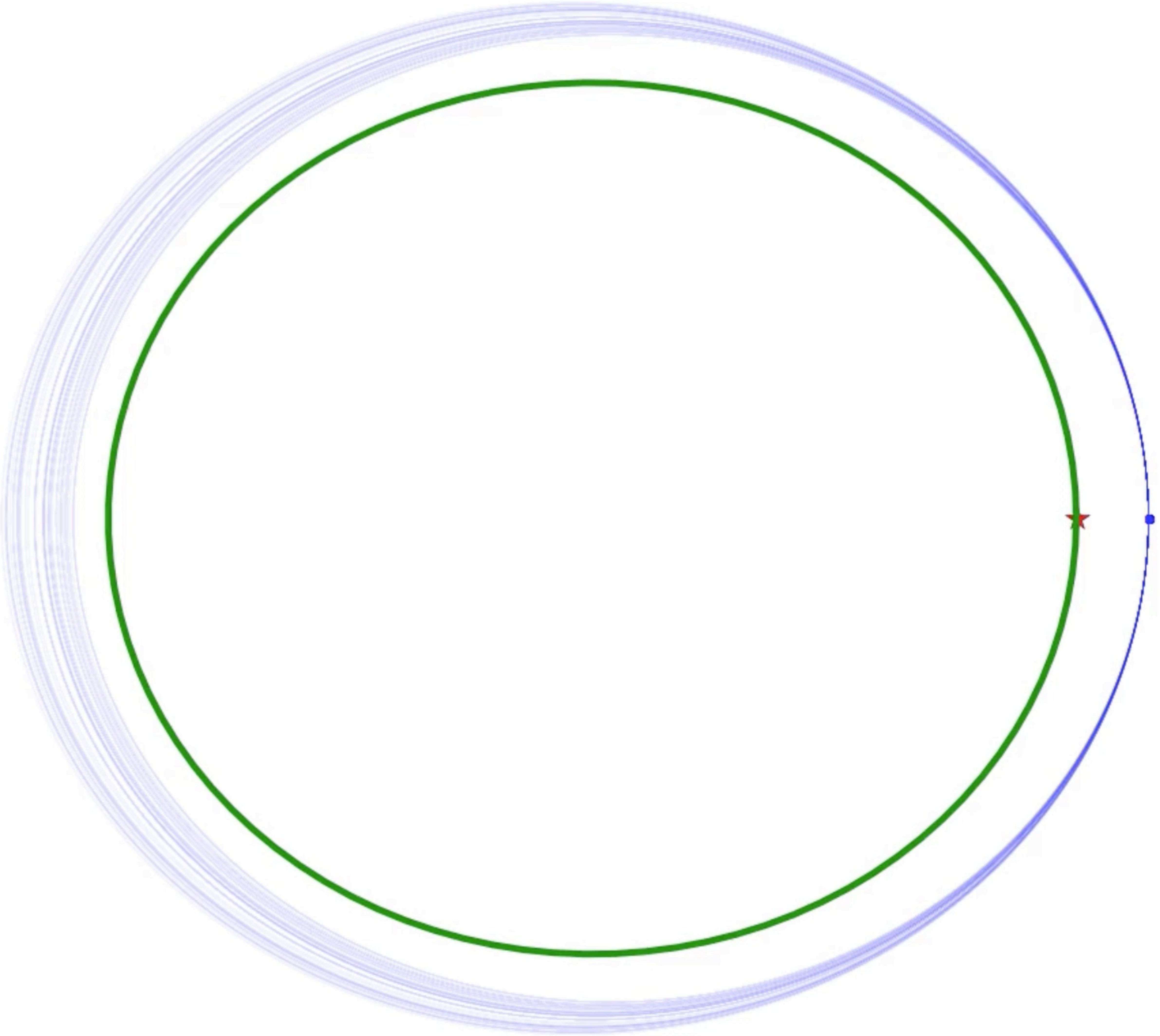
More on the emerging smallsat launch economy in a coming lecture

Credit: Planet



Achieving coverage

- Maximizing constellation coverage usually involves
  - Multiple orbital planes and multiple satellites per plane
  - Even spacing between planes and even spacing between satellites within a plane
- Most cubesats use a 1-plane configuration (string of pearls)
  - Minimizes launch cost, and is compatible with no-propulsion options
- Strategies exist for spacing satellites within a plane without propulsion.
  - Inject in different directions
  - Inject at different times
  - Generate differential drag
- ISS does not allow injection in different directions
- These spacing maneuvers can take a significant fraction of the satellites' lifetimes

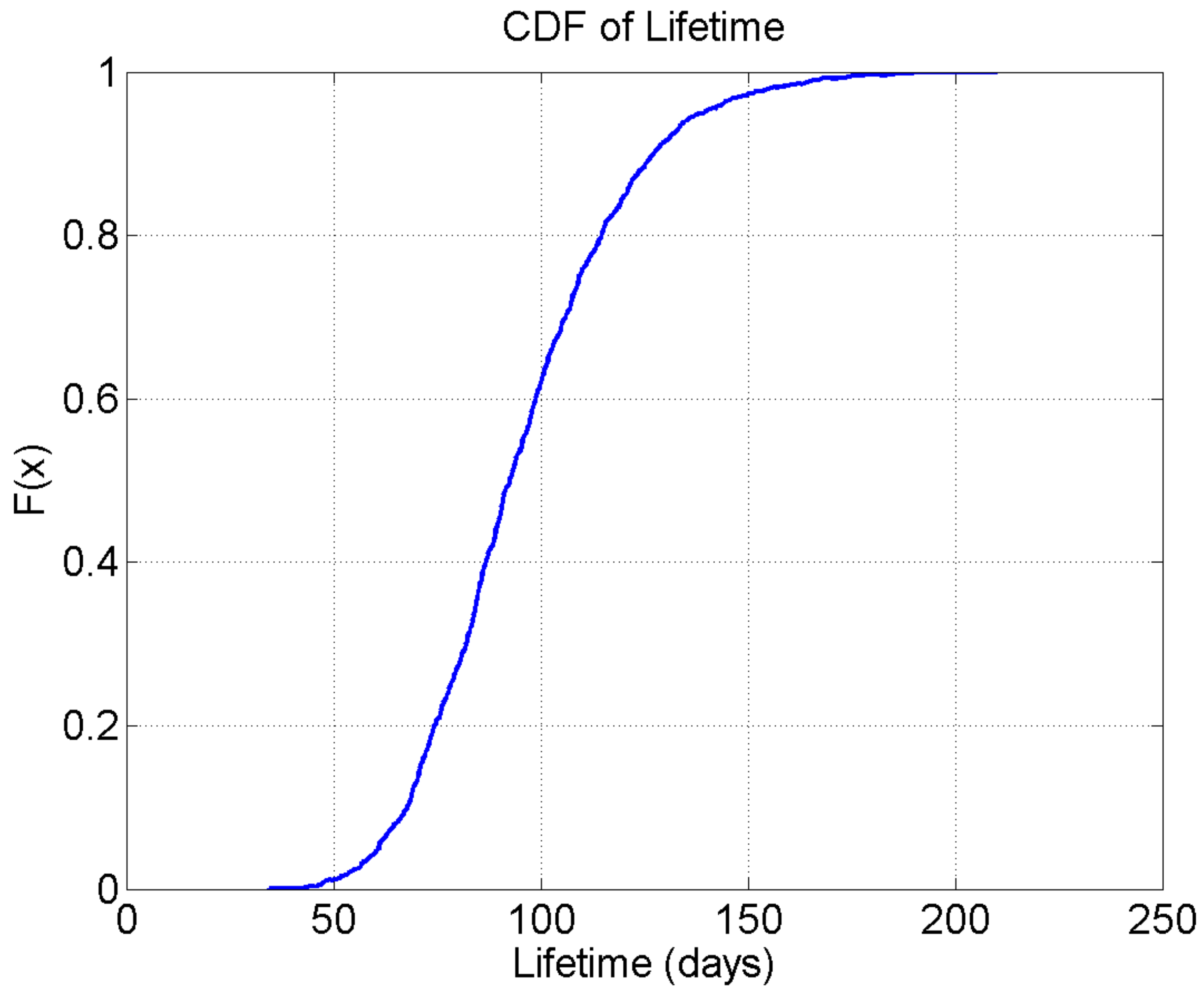


Lifetime at ISS altitude

Courtesy of Prof. Selva:

- Monte-Carlo simulation using AGI Systems Tool Kit (STK)
- Fixed parameters: 60s timestep, drag coefficient of 2.2, solar radiation pressure coefficient of 1.0
- Simulation parameters:

Parameter	Mean	Stdev
Semi-major axis (km)	**425**	2%
Inclination (deg)	**51.6**	2%
Eccentricity (*)	0.000	0.001
Mass (kg)	4.5	10%
Area (m^2)	0.0865	10%



Median = 93 days
Mean = 96 days
Stdev = 24 days

Deorbiting cubesats

- NASA “recommendation” to deorbit all satellites — including cubesats — in less than 25 years
- For cubesats, this is a problem for orbits >600km
- Deorbiting from LEO usually accomplished by performing a burn to decrease the perigee to the high-drag region (e.g. 300km)
  - Requires propulsion
- Other methods to meet this requirement
  - Sails, balloons

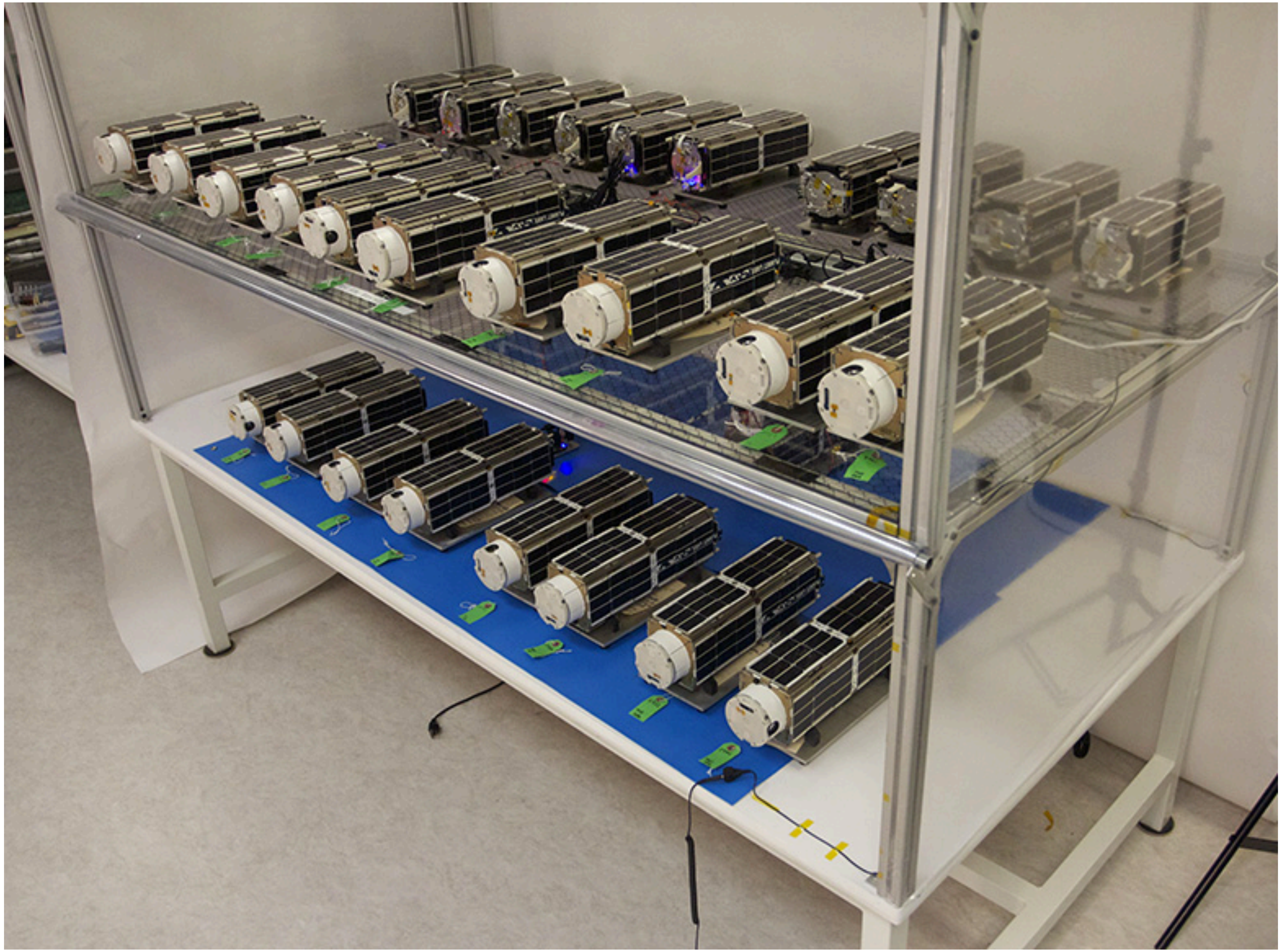
Area m^2	600 ISS Lifetime (yrs)	600 SSO Lifetime (yrs)	825 SSO Lifetime (yrs)
0.0816	**116**	**123**	**>500**
0.42	16	17.3	**470**
0.5016	13.9	14.5	**391**

Courtesy of Prof. Selva and STK

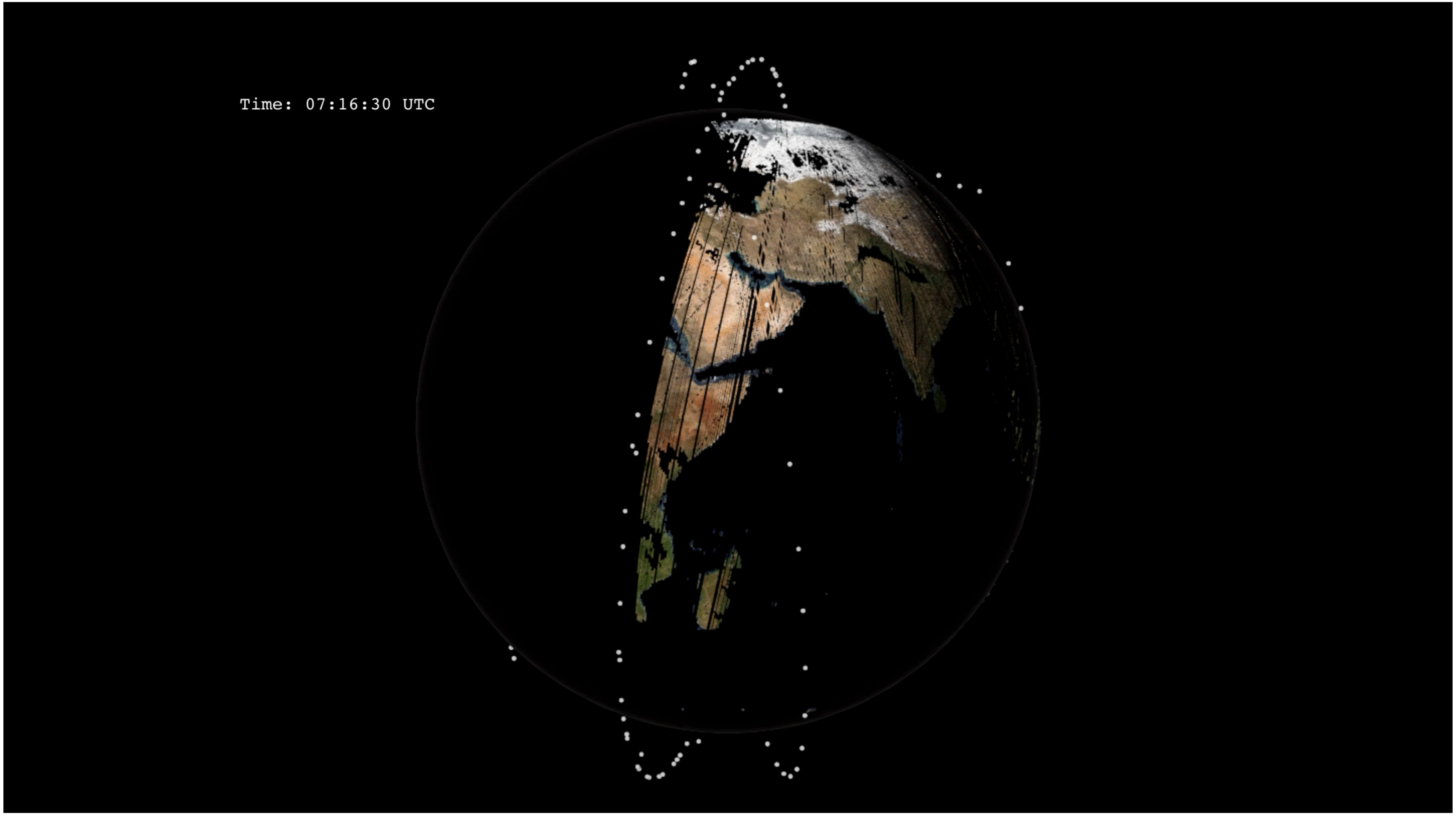
Cubesats creating commercial value . . .

planet.

- Has deployed 351 satellites, over 100 of which are presently active in their constellation
- Gathering 250 million square kilometers of imagery daily
- Present dataset includes, on average, 1200 images of every location on Earth's landmass
- Able to image anywhere on the Earth’s surface at 3-5 meter resolution on a daily basis
- Market these images to a number of different industries (agriculture, government, energy/ infrastructure, finance/business, forestry and land use, insurance, and mapping)
- Build all of their own satellites

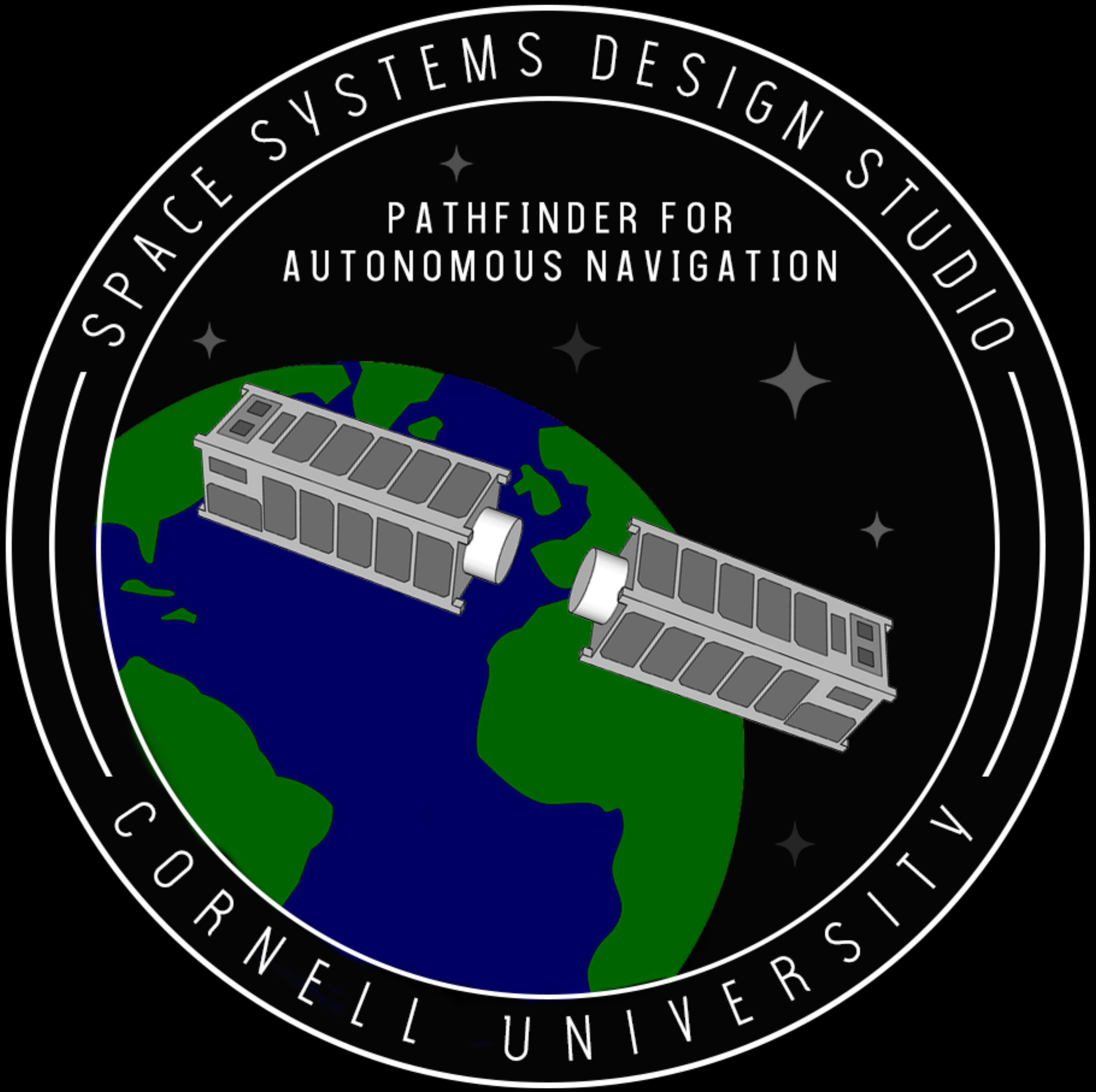


A flock of doves



https://storage.googleapis.com/planet-ditl/day-in-the-life/index.html

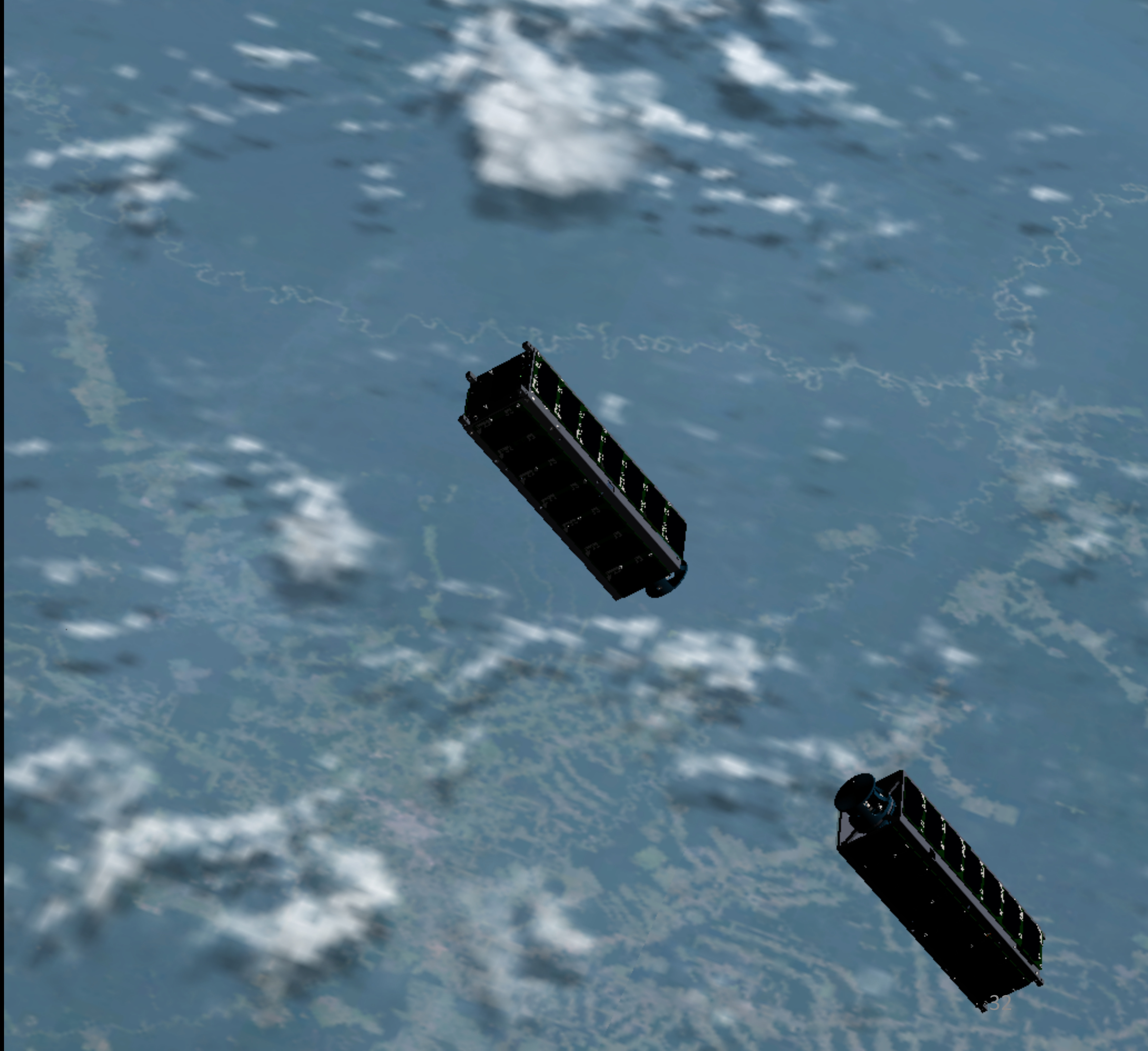
A cubesat case study . . .


SPACE SYSTEMS DESIGN STUDIO
PATHFINDER FOR
AUTONOMOUS NAVIGATION
CORNELL UNIVERSITY

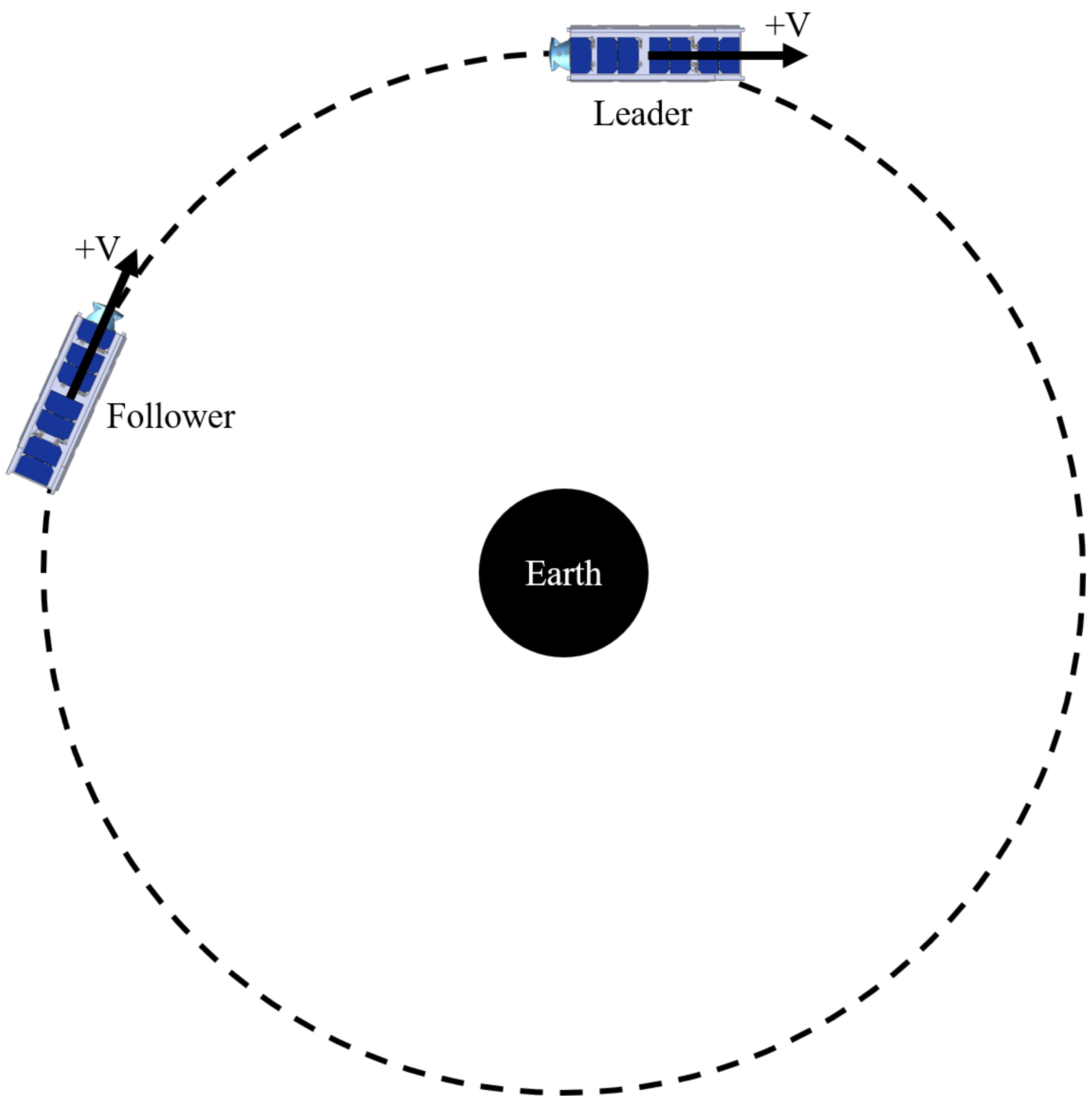
4/27/20

PAN Mission Objective

Demonstrate low-cost CubeSat autonomous rendezvous and docking technology

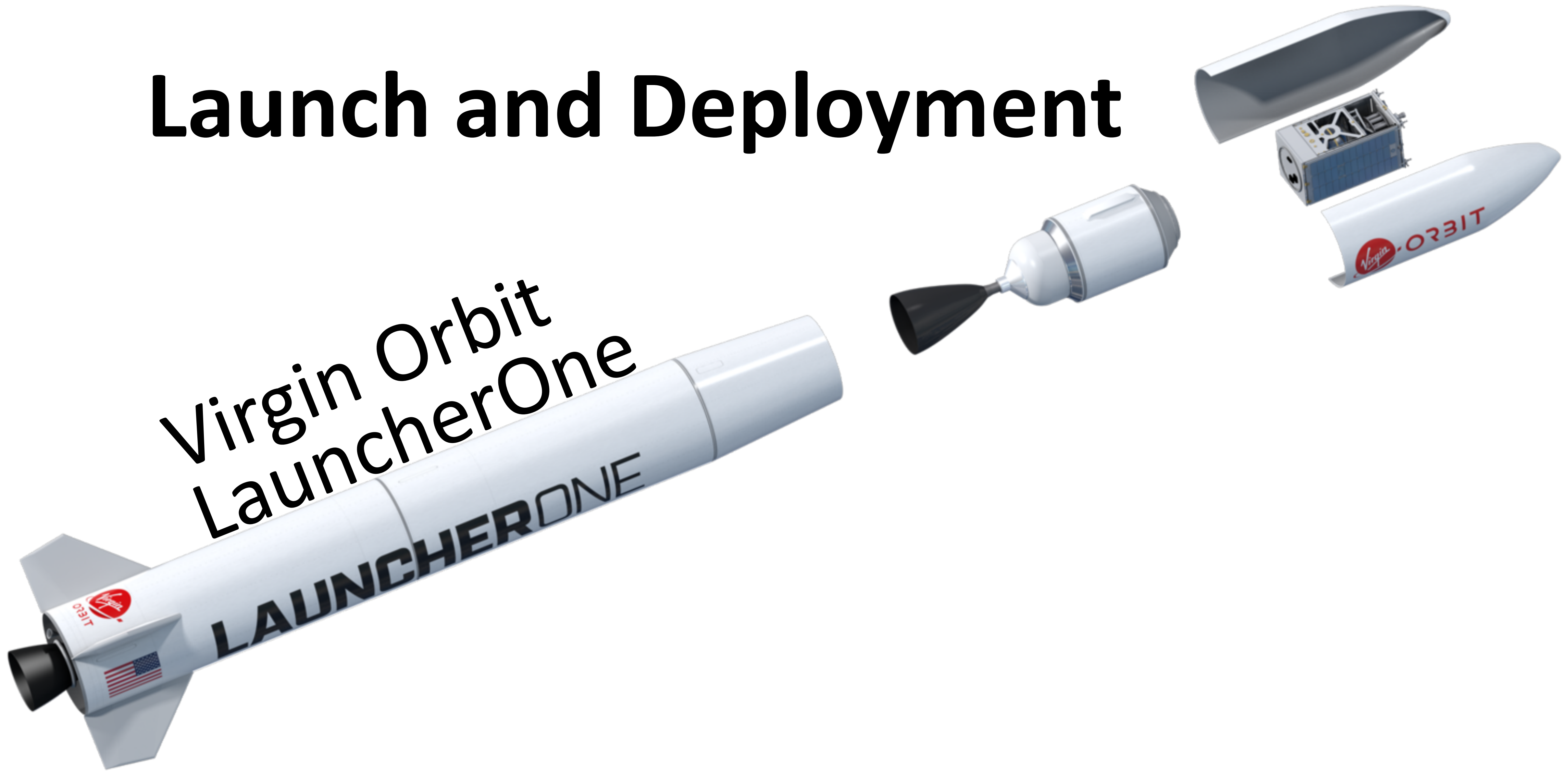


Concept of Operations



Launch and Deployment

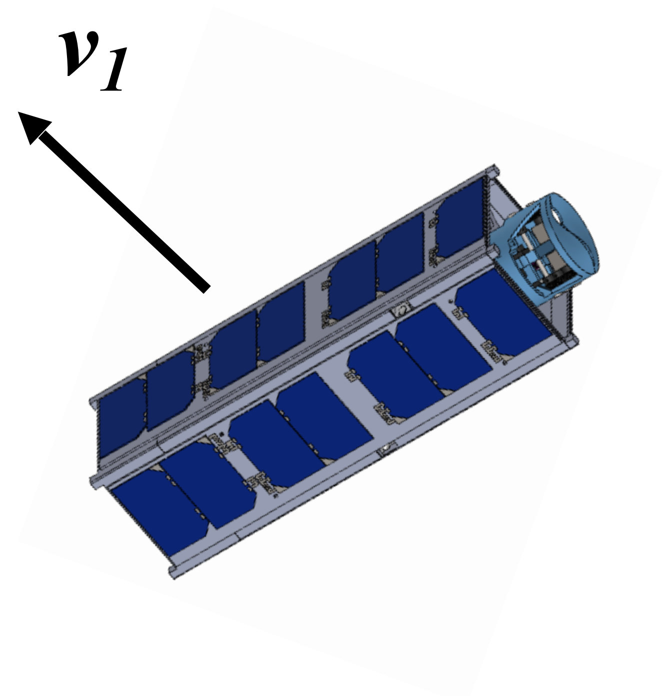
Virgin Orbit LauncherOne



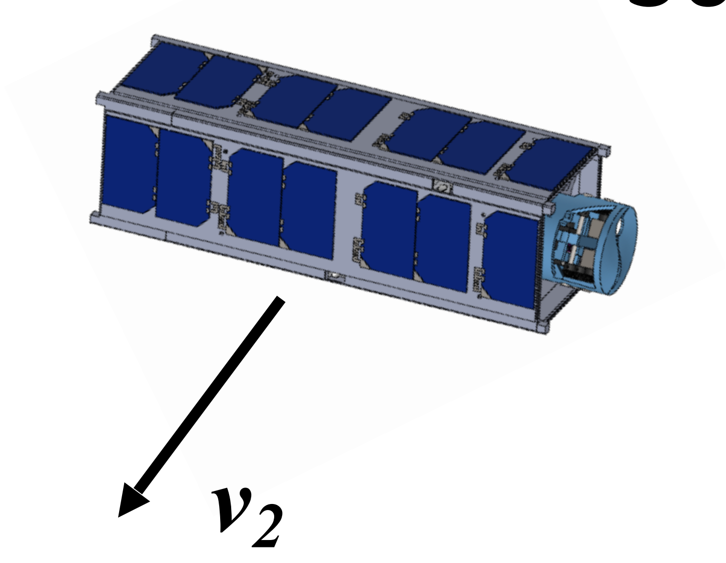
Tyvak NLAS 6U Dispenser

Detumble, Checkout, Drift

1-3 weeks



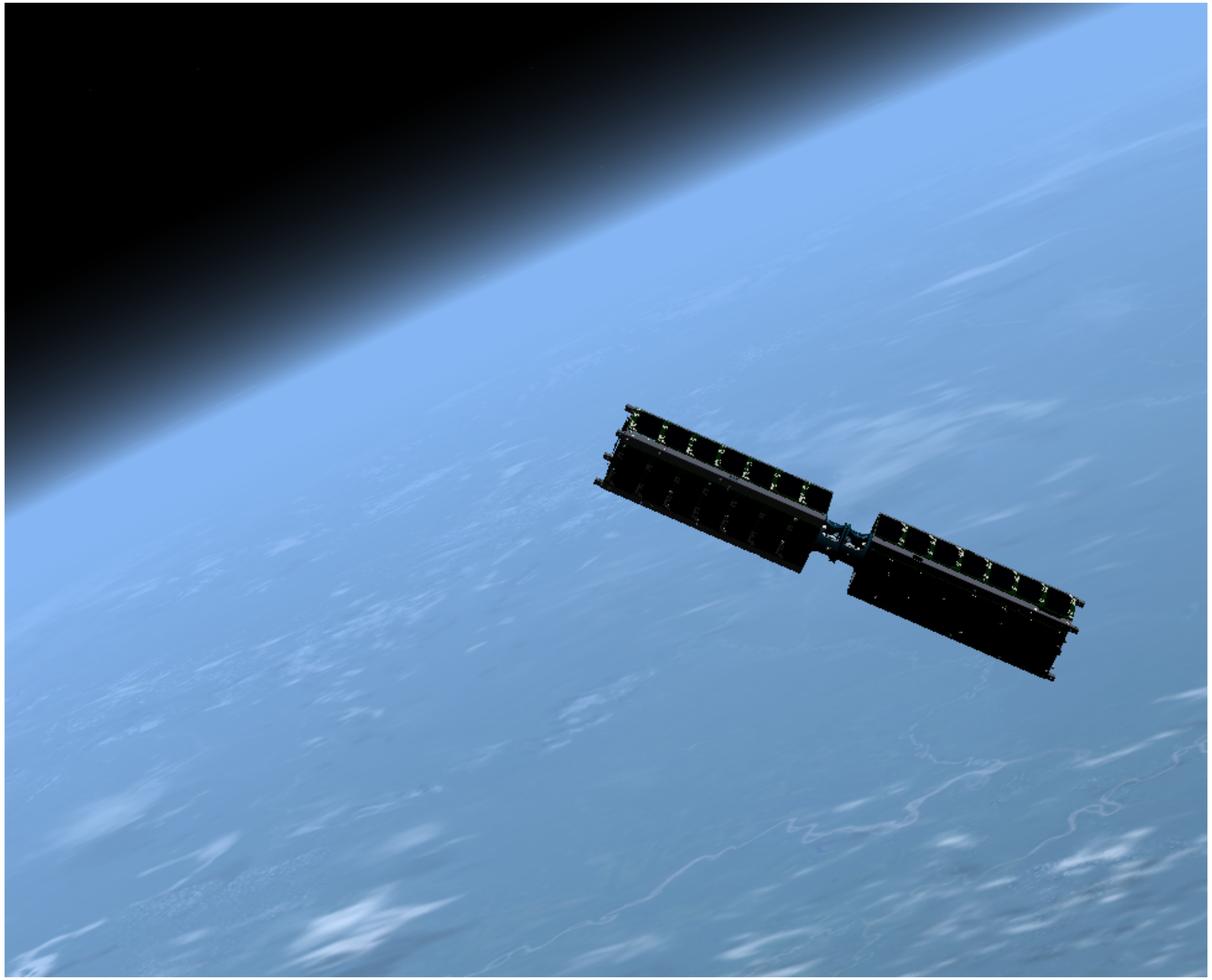
- Determine attitude
- Zero angular rate
- Point antennas for ground comms
- Relative distance 10 – 300 km



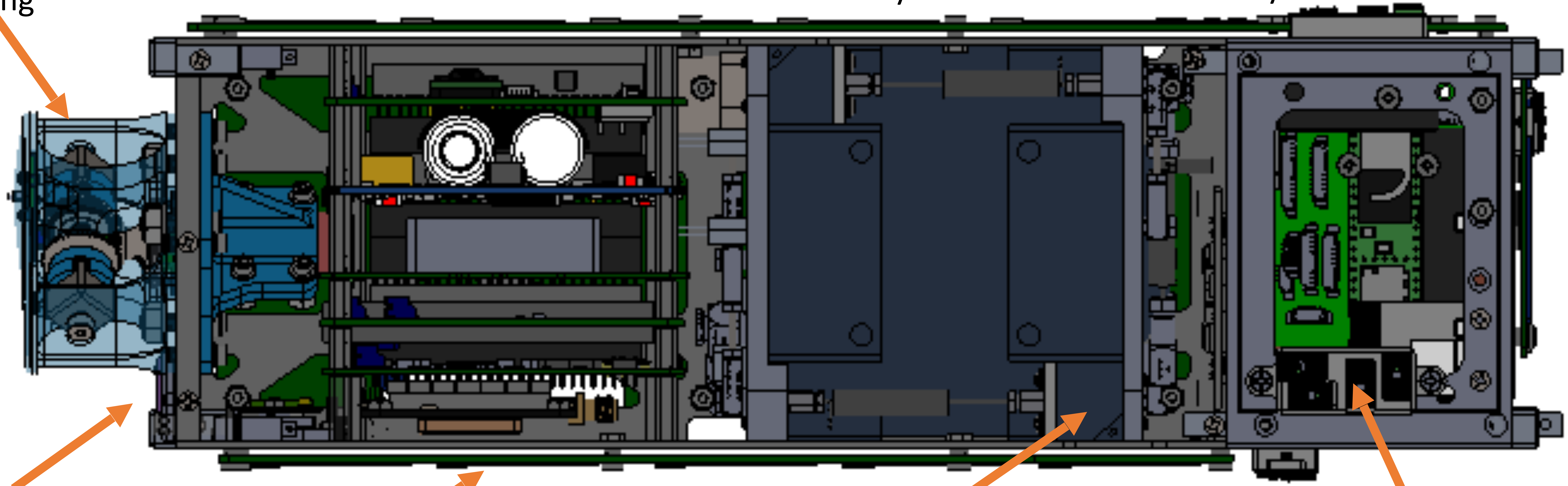

Far Field Rendezvous
1-2 months
Near Field Rendezvous
1 week
Iridium
GPS
Inter-satellite link
1km range

Docking
1 hour

- One set of docking magnets per spacecraft
- Effective range 40cm
- Propulsion disabled for both spacecraft
- Attitude control disabled for one spacecraft



Spacecraft Layout



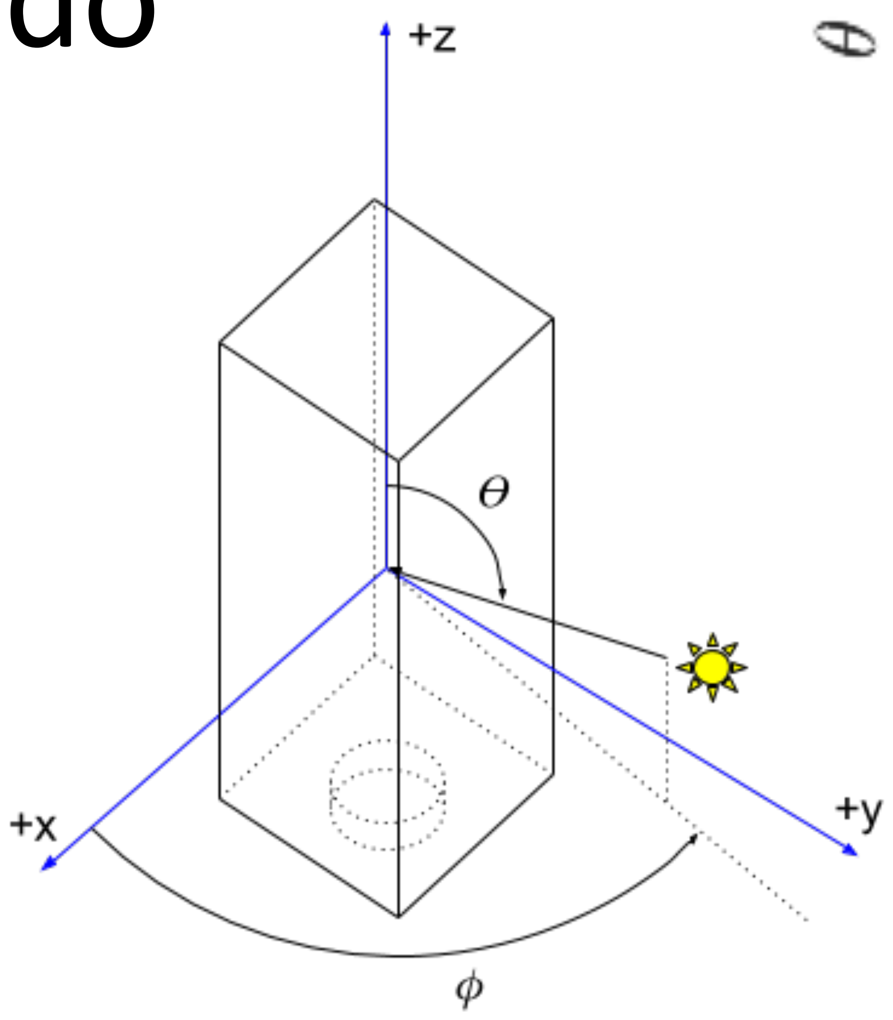
Power Subsystem

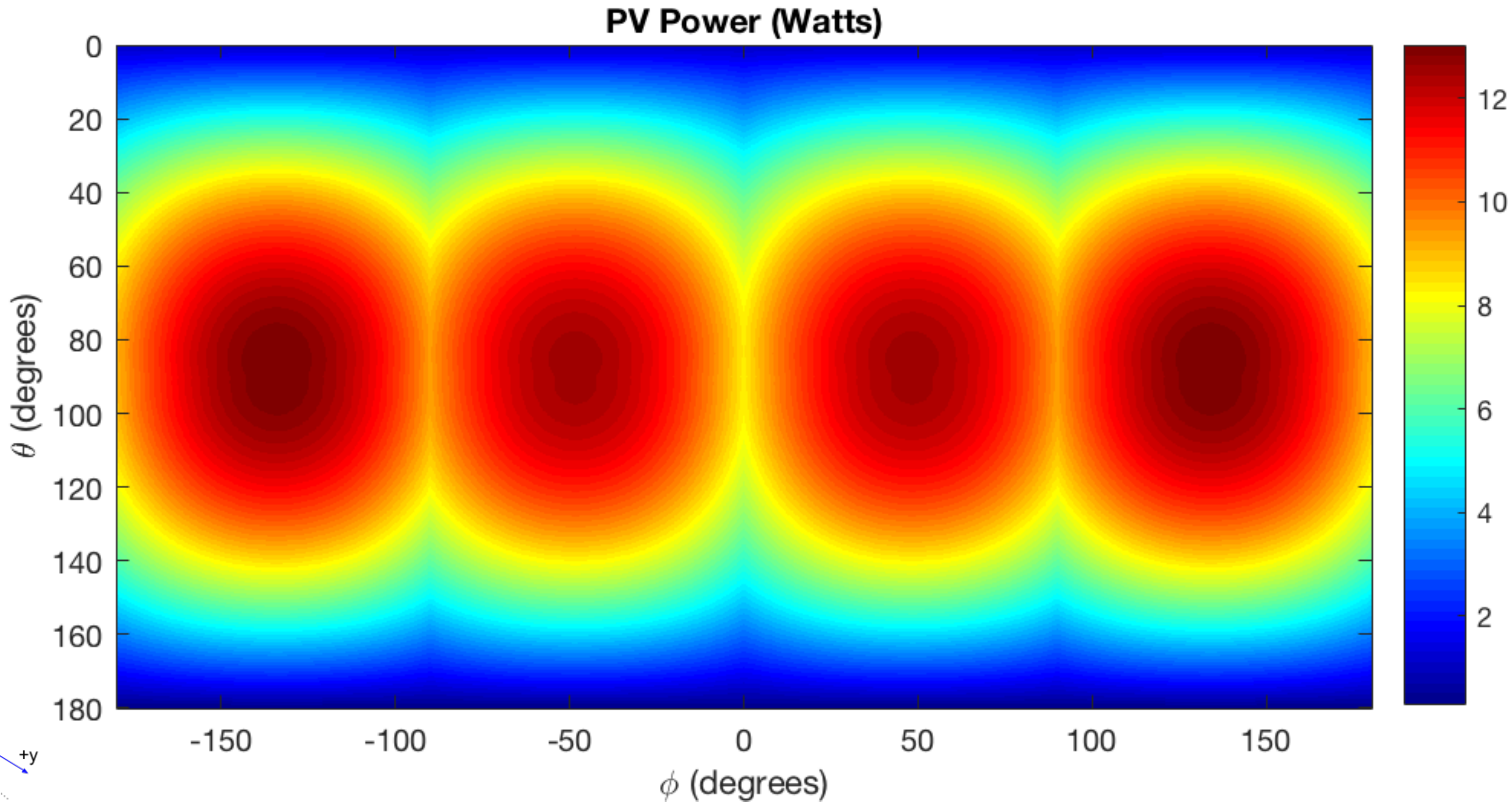
Power Budget

Far Field Rendezvous					Day			Eclipse		
	Min. Power (W)	Max. Power (W)	Avg. Power (W)	Number Active	Avg. Duty Cycle	Avg. Watts	Max. Watts	Avg. Duty Cycle	Avg. Watts	Max. Watts
COMMUNICATIONS SYSTEM										
Quake + Taoglas Patch Antenna TX	0.950	7.500	0.950	1	8.146296%	0.077	0.611	5.687037%	0.054	0.427
Quake + Taoglas Patch Antenna RX	0.225	0.975	0.225	1	91.9%	0.207	0.896	94.3%	0.212	0.920
COMMAND AND DATA HANDLING										
Teensy 3.5 SpaceFlight Computer	0.300	0.300	0.300	1	100%	0.300	0.300	100%	0.300	0.300
Teensy 3.5 ADCS Computer	0.300	0.300	0.300	1	100%	0.300	0.300	100%	0.300	0.300
ADCS										
Umbilical Board	0.0460	0.0460	0.0460	1	100%	0.046	0.046	100%	0.046	0.046
ADCS Board	0.0568	0.1269	0.0848	1	100%	0.085	0.127	100%	0.085	0.127
7V to 24V Converter Board	0.000	0.400	0.400	1	20%	0.080	0.080	20%	0.080	0.080
Motor Controller + Motor + Encoder	0.000	5.520	1.920	3	20%	1.152	3.312	20%	1.152	3.312
Magnetic Torque Rods	0.000	0.132	0.099	2	12%	0.024	0.032	12%	0.024	0.032
Sun Sensors	0.000	0.033	0.033	15	100%	0.495	0.495	0%	0.000	0.000
AltIMU-10 v5 IMU	0.017	0.025	0.025	4	100%	0.100	0.100	100%	0.100	0.100
Docking Magnet Motor + Controller	0.000	6.000	6.000	1	0%	0.000	0.000	0%	0.000	0.000
PROPULSION										
7V to 24V Converter Board	0.000	0.400	1.430	1	7.46%	0.107	0.030	0.0000%	0.000	0.000
Thruster Control	0.000	0.405	0.405	1	0.0746%	0.000302	0.000	0.0000%	0.000	0.000
GNC										
Piksi + Yageo Directional Antenna	0.000	0.500	0.500	1	100%	0.500000	0.500	100%	0.500000	0.500
3DR Radio + Intersat TX	0.500	0.500	0.500	1	0%	0.000	0.000	0%	0.000	0.000
3DR Radio + Intersat RX	0.125	0.125	0.125	1	0%	0.000	0.000	0%	0.000	0.000
BATTERY CHARGE										
GomSpace Battery	0.160	0.160	0.160	1	100%	0.160	0.160	100%	0.160	0.160
Battery charging				1	100%	2.103	4.400			
	TOTAL	22.663	13.503	**Total Watts Used**		5.736	11.388		3.013	6.303

Power Generation

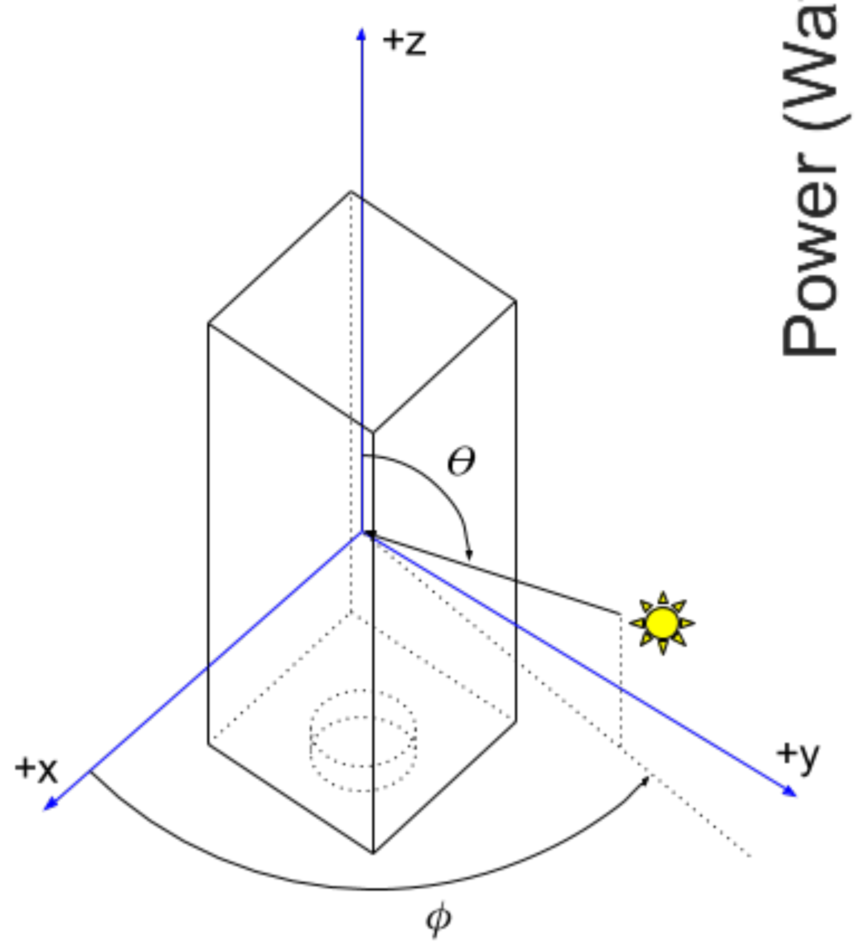
- Solar power depends on sun-angle of each cell
- Random tumble: 5.29W-6.87W depending on albedo

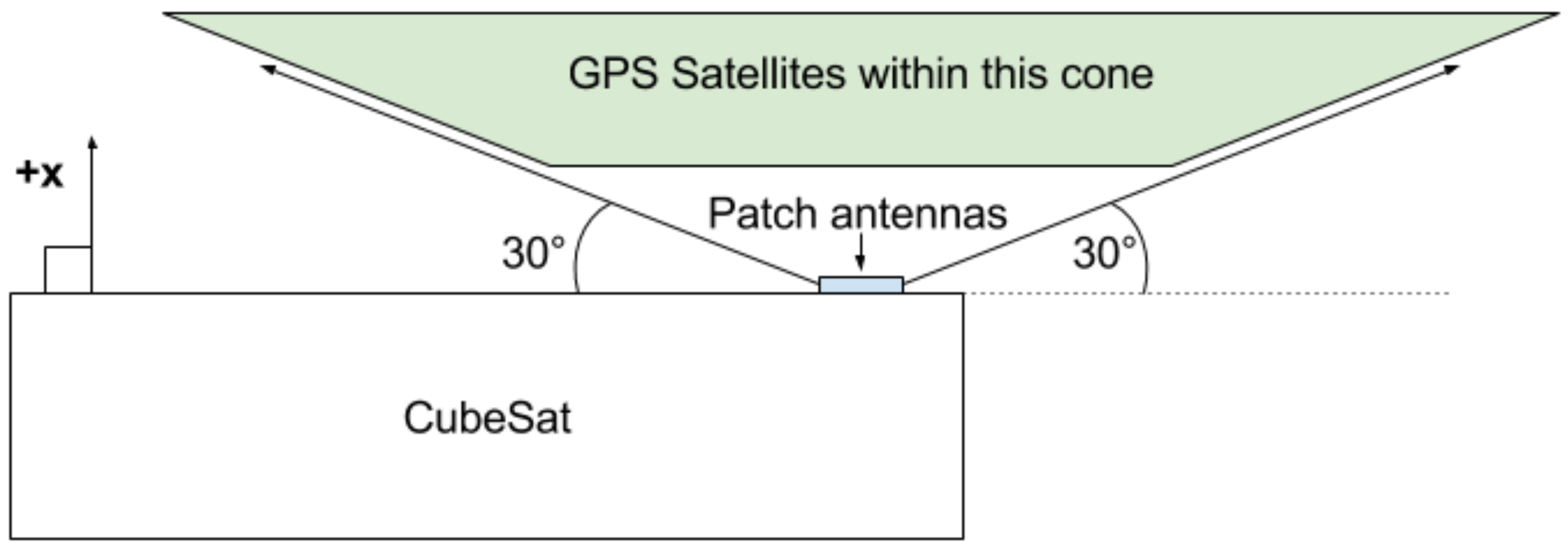


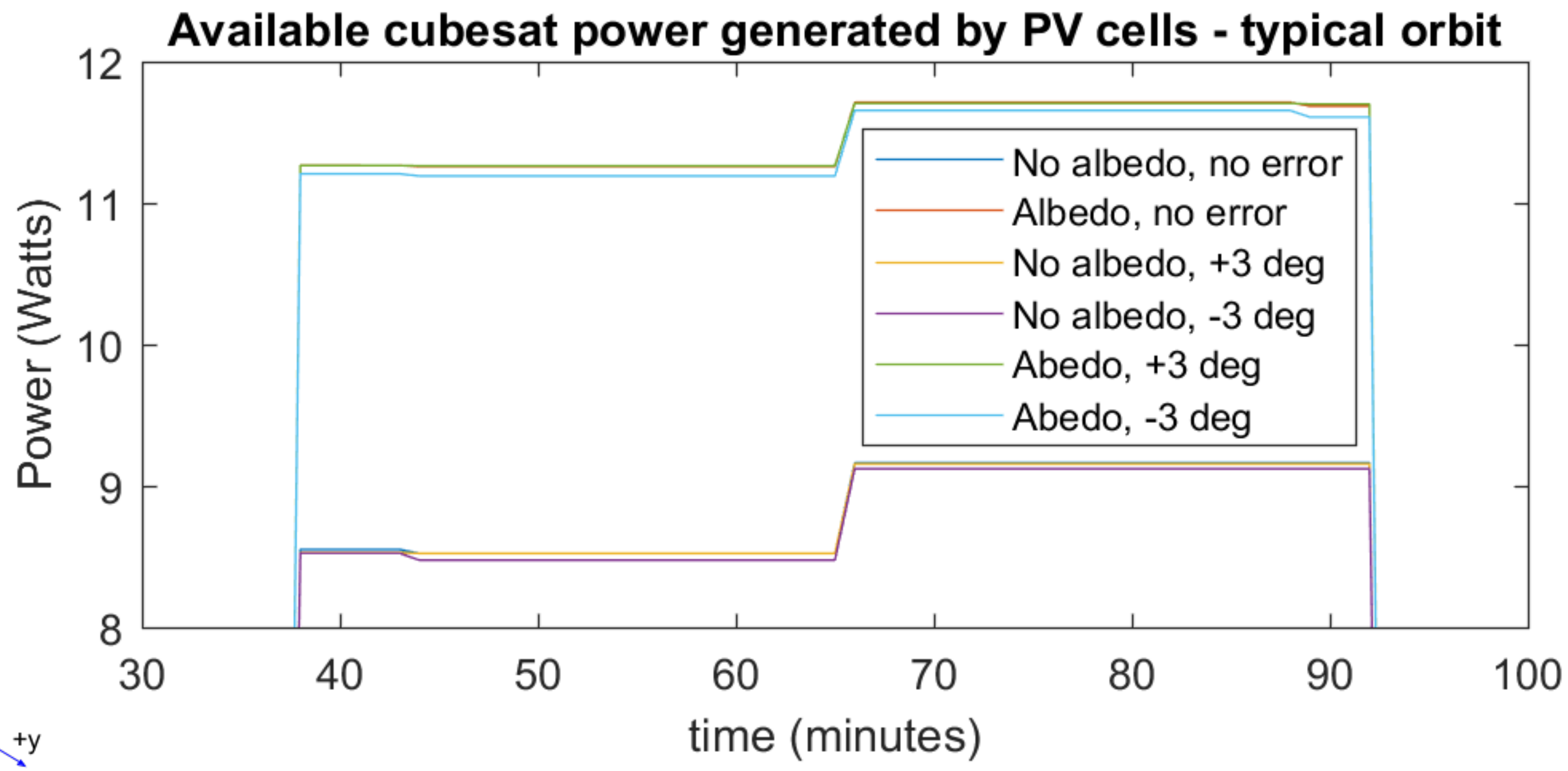


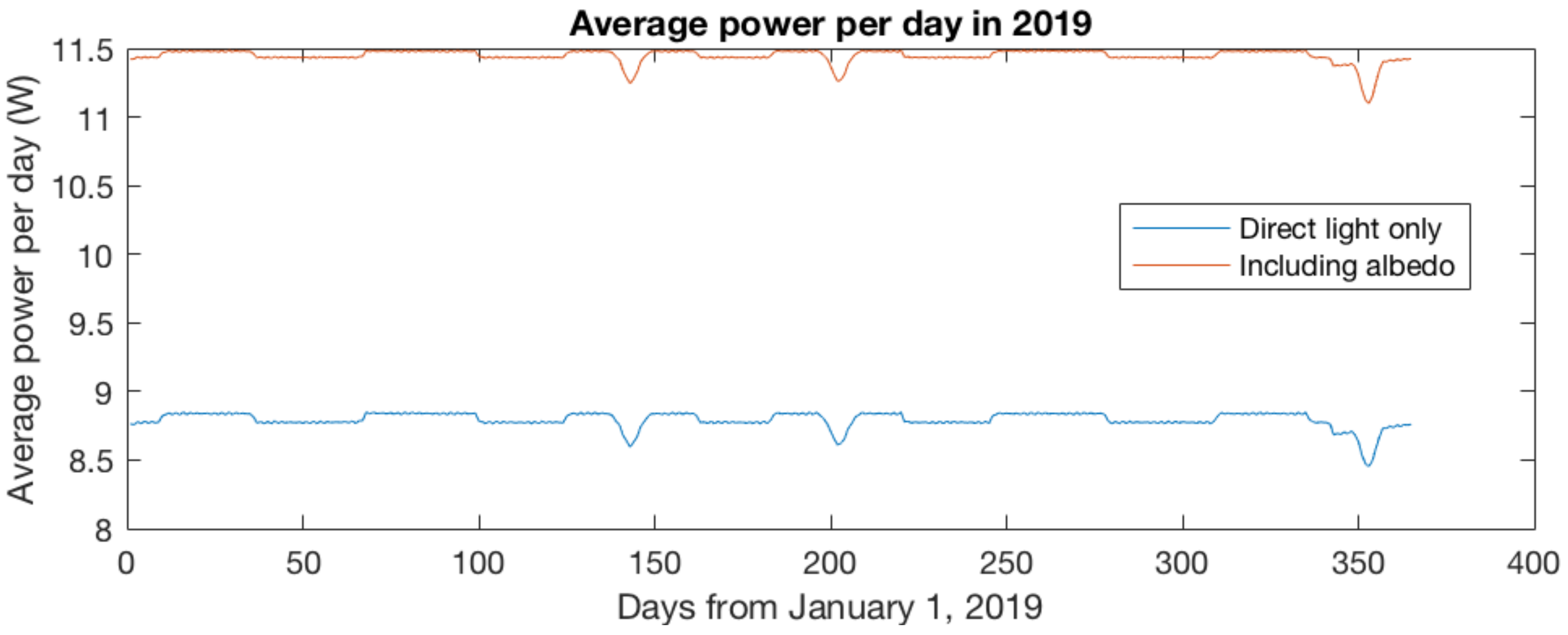
Power Simulation

- Pointing constraints
  - Maintain contact with Iridium and GPS satellites
  - Maintain contact between the two PAN satellites





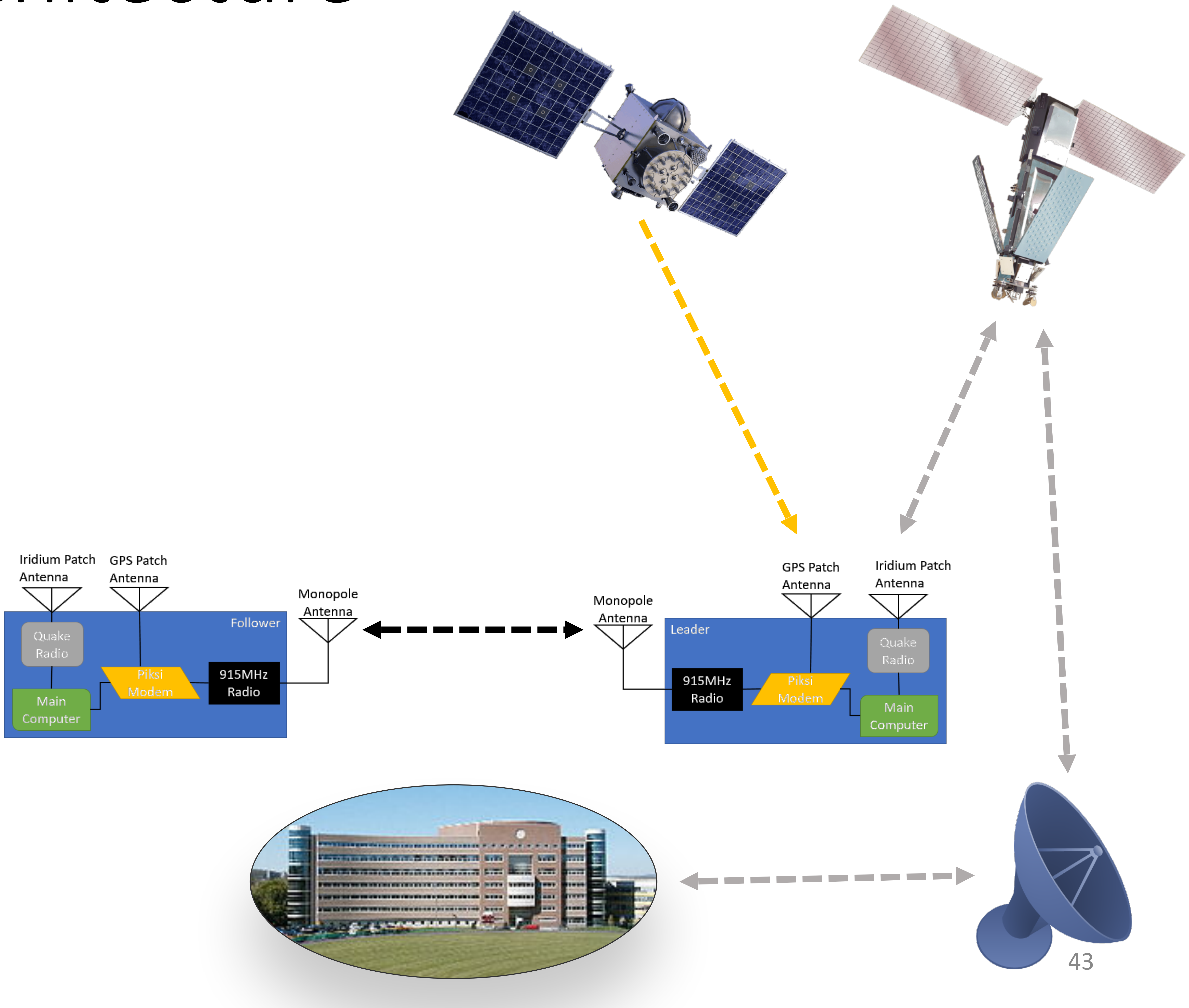




Communications Subsystem

Communications Architecture

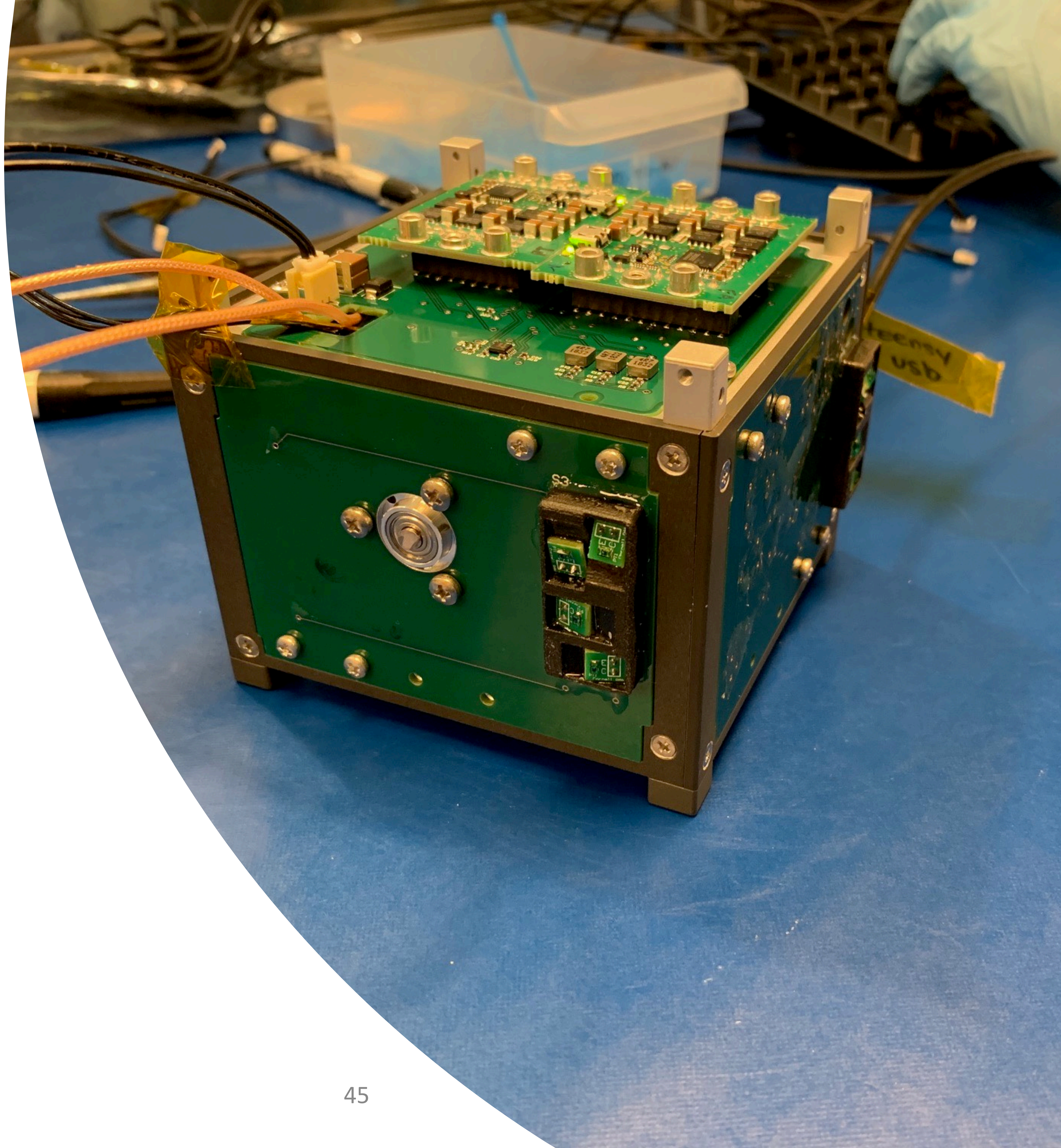
- Short-burst data transmissions each contain one packet of 70 bytes.
- Infrequent and limited comms require changes to mission ops
  - Increased autonomy
  - Long-term, high-accuracy orbit propagation



Attitude Determination and Control Subsystem

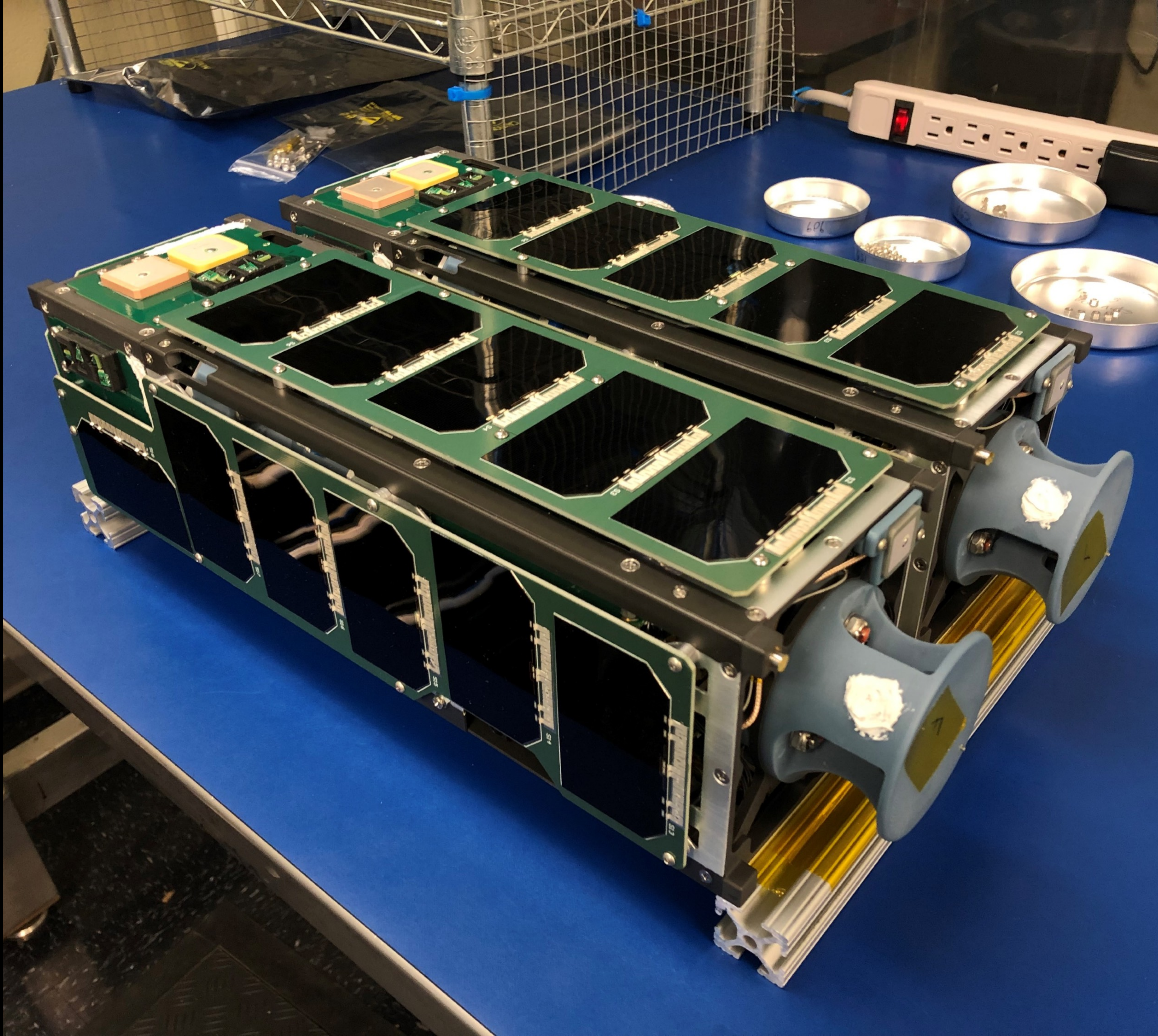
Modular CubeSat ADCS

- 3 COTS DC motors store angular momentum
- 3 Magnetorquers manufactured in-house for momentum dumping
- 20 photodiode-based sun sensors determine sun vector to within 3 degrees
- Attitude determination and control precision < 1 degree



Current Status

- Hardware development complete
- Environmental testing complete
- Software development in progress
- HITL testing in progress
- Hardware delivery 7/1/20
- Launch 8/15/20



A Quarantined CubeSat