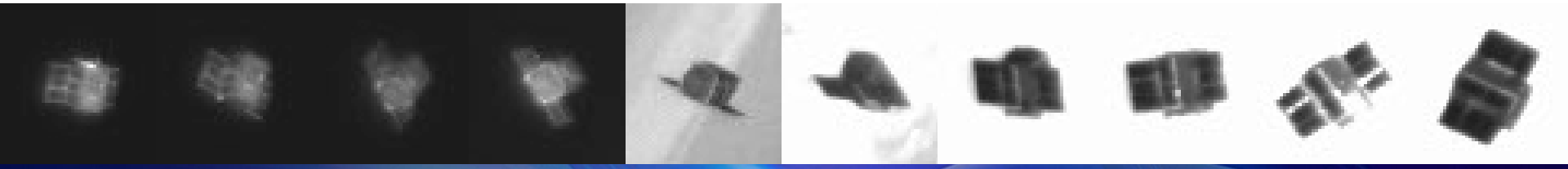
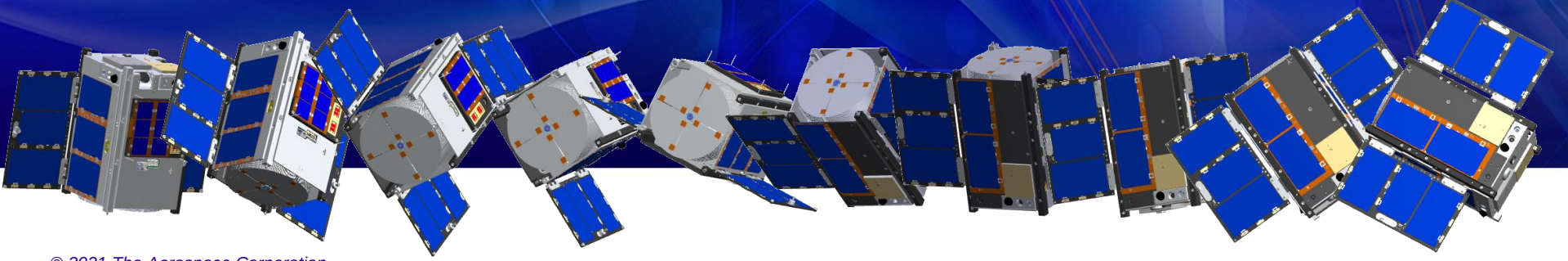
THE AEROSPACE CORPORATION



A Sat-to-Sat Inspection Demonstration with the AeroCube-10 1.5U CubeSats

Joseph W. Gangestad
Catherine C. Venturini
David A. Hinkley
Garrett Kinum

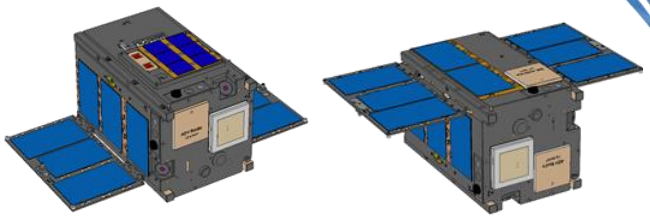
Small Satellite Conference
7-12 August 2021



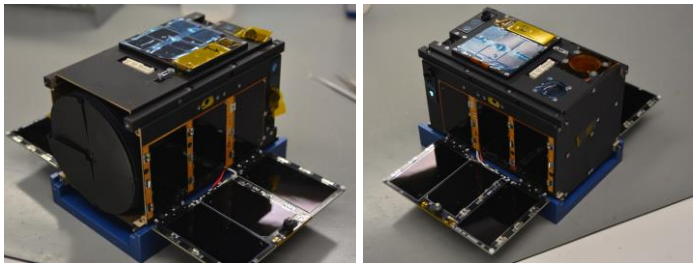
AeroCube-10: Tech Demo and Space Science

Concept to Orbit in 24 Months

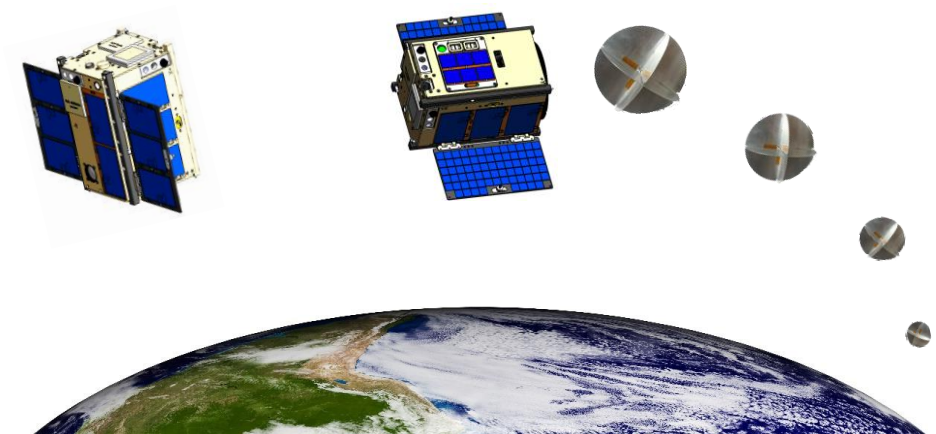
- **Project initiated in April 2017, on orbit in April 2019**
- **Mission Objectives:**
  - *Demonstrate new technology developments*
    - Ultra-low-SWaP star tracker
    - Experimental solar cells
    - Next-generation propulsion unit
  - *Support atmospheric science experiment with deployable probes, collection of GPS L1/L2 data*
  - *Collect radiation dosimetry data*
    - Charged particle telescope
    - Low/high energy electron/proton dosimetry
- **Mission Configuration:**
  - *Pair of 1.5U CubeSats (10 x 10 x 15 cm, 2 kg)*
  - *Orbit: LEO, 475 km altitude, 51° inclination*



From SRR to ship in 22 months



Satellite A	Satellite B
Beacon Tx	Propulsion
Probes	Beacon Rx
GPS L1/L2	Camera360
Solar Cell experiment	GPS L1/L2
Dosimeters	Charged particle telescope
	Solar Cell experiment
	Dosimeters

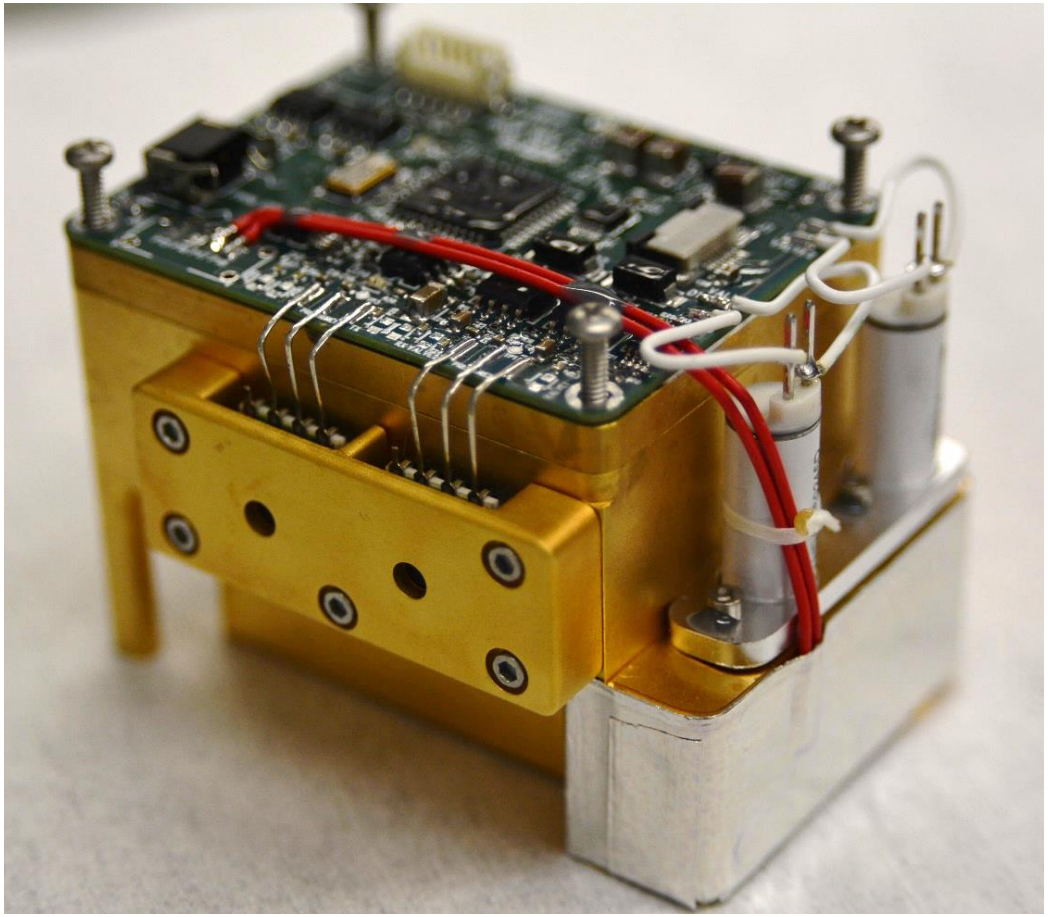


GPS = Global Positioning System
LEO = Low Earth Orbit
Rx = Receive
SRR = System Requirements Review
SWaP = Size, Weight, and Power
Tx = Transmit

AeroCube-10 Propulsion Unit (AeroCube-10B)

Second Generation Steam-Propulsion System

- First version flew on AeroCube-7
- 20 gram water propellant load in a 34 cc tank
- Two valves in series
- 5 W heater on manifold
- Redundant pressure sensors
- 137.5 gram dry mass
- Gold plated
  - *Corrosion resistant to water*
  - *Low radiated heat loss*
- I_{sp} @ 40°C = 70 s
- Thrust @ 40°C : 2.3 mN
- Total ΔV: 6.6 m/s



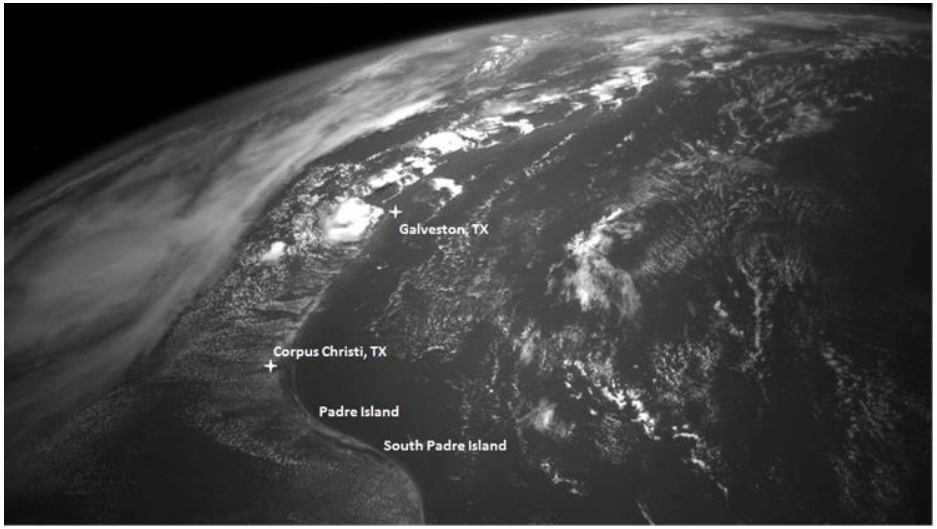
I_{sp} = Specific Impulse
ΔV = Velocity Change

AeroCube-10B Camera

"Prox Ops Camera"

- SiOnyx XQE-0920 imager (monochrome)
  - *Set to 8x gain*
- Marshall V-4416.0-1.2-HR lens
  - *Focal length 16.0 mm*
  - *Aperture diameter 16.0 mm*
  - *No IR-cut filter*
- FOV: 29.5° (diagonal)
  - *1280 x 720 pixels (IFOV 0.02°)*

Test image taken in lab before flight



First-light image taken on orbit, 27 Aug 2019, showing the Texas and Florida coastline

Constraints on AC10 Operations

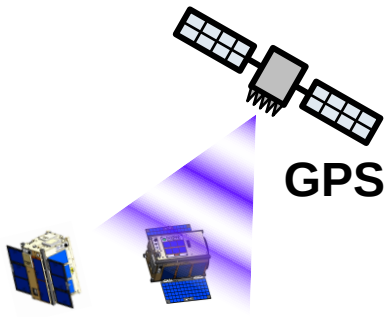
- **Attitude Control**: Stray light contamination in star tracker → Can only initialize ACS in (or shortly before/after) eclipse
- **Navigation**: Legacy OD process uses GPS fixes (time + states), GPS receiver uses L1 signal only → fix accuracy ~5 meters
- **Imaging**:
  - *Large FOV (29° diagonal), IFOV = 0.02° → must get very close to resolve 1.5U target*
  - *Lens distortion*
  - *Minimum exposure time (20 µsec) → easy to overexpose when imaging cloudy Earth*
- **Communications**:
  - *Low bandwidth (<1 MB per pass) → use JPEG compression for image series*
  - *Distribution of ground sites leads to 4+ hour comm gaps → sometimes have to propagate 4+ hrs for activities in close RPOs*
- **Mass Properties**: Release of three probes by April 2020 introduced 3% mass differential between vehicles → differential drag kicks in quickly, can maintain configuration passively for ~1 day

Bottom line:
AeroCube-10 was not designed for RPO or inspection,
but operators were confident to give it a try

ACS = Attitude Control System
OD = Orbit Determination
FOV = Field of View
IFOV = Instantaneous FOV
RPO = Rendezvous & Proximity Operations

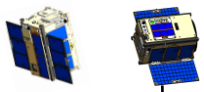
AC10 Navigation and Prox Ops Planning

- AC10 navigation and ops planning is ground-in-the-loop
  - *No on-board navigation (in development, though)*
  - *No crosslinks to share data*
- AC10 vehicles collect GPS data and downlink, operators complete orbit determination, plan maneuvers, uplink maneuver plans
- Individual GPS fixes are accurate to ~10 m @ 1σ,
  - *High-accuracy orbit determination gets ephemeris accuracy to 3-5 m*
- In-track error tends to grow by ~100 m per day after end of fixes
  - *Largely due to drag uncertainty → CubeSats have high A/m, tumble until start of imaging*



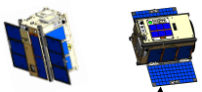
Collect GPS

1-3 days

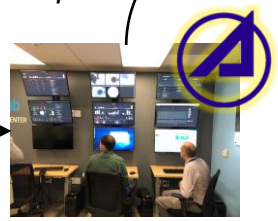


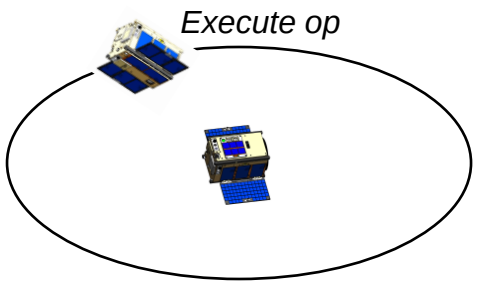
Downlink GPS

Perform OD
Plan ops



Uplink
mission plan





Hope for
the best

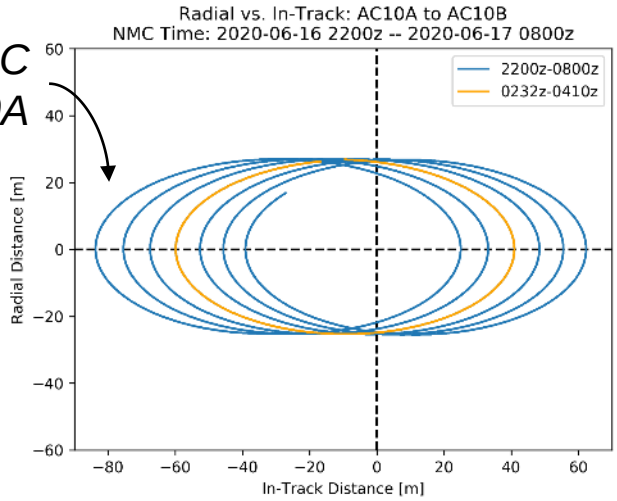
<1 day →

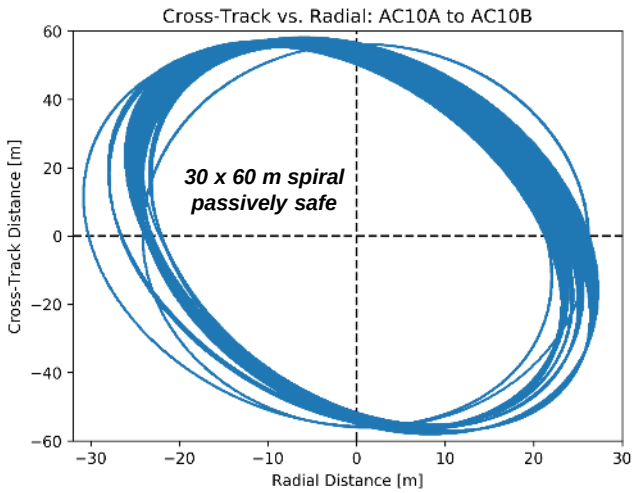
Close Approach Imagery and NMC

AeroCube-10B imaging AeroCube-10A

- Used propulsion system to maintain formation, induce close approaches, enter natural motion circumnavigation (NMC)
- Lots of details under the hood on mission-planning methodology (see paper)
  - *Important focus: ensure safety of both vehicles throughout operations*
- Execute series of imagery collections in May and June 2020 during close approaches and NMC
- Operations got progressively closer: 60 m → 40 m → 20 m
- Collected resolved imagery of AC10A, resolution as low as 7 mm
- Small subset of imagery highlights on following slides

AC10B NMC around AC10A



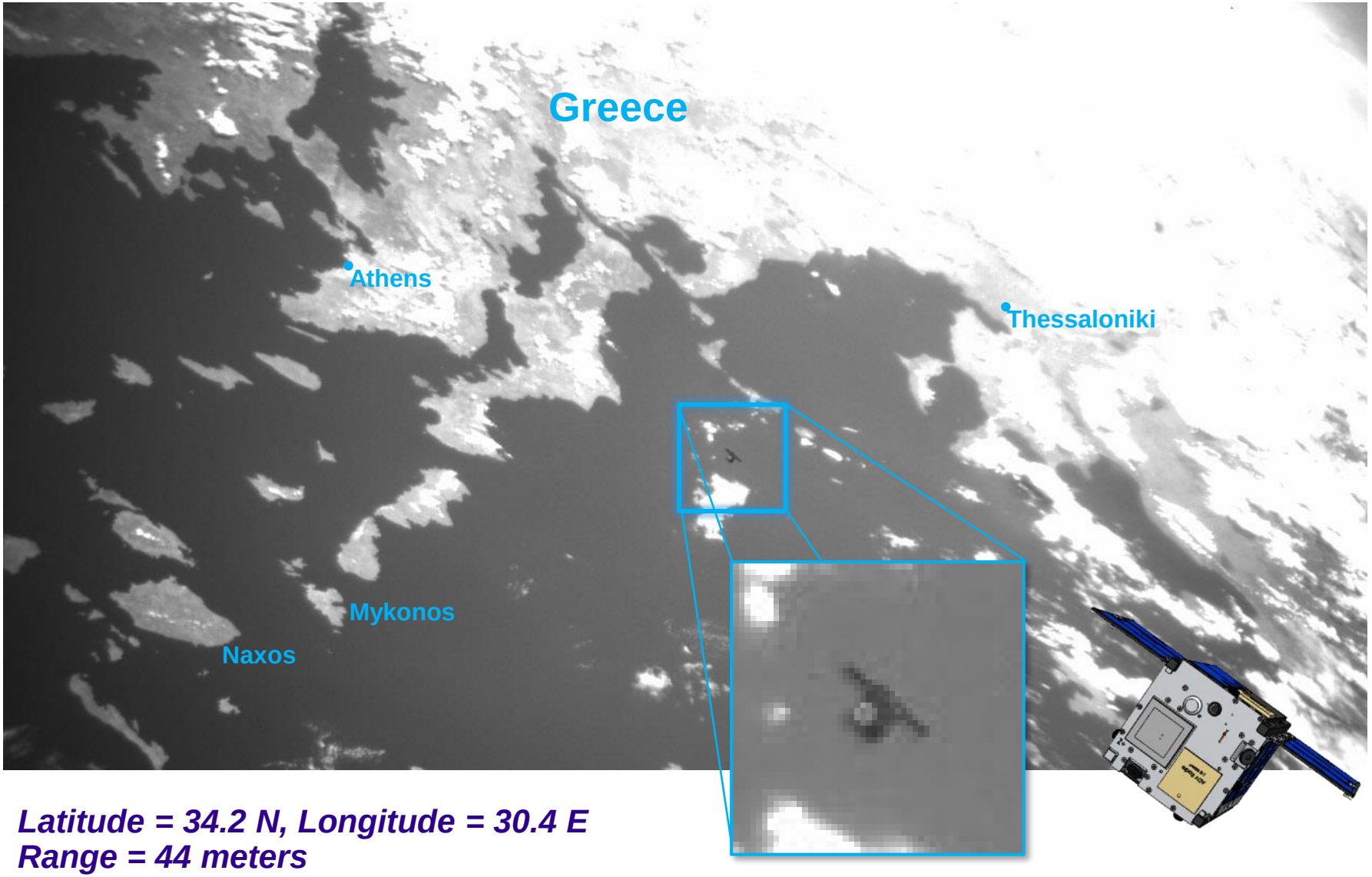


AC10 NMC: 2020-06-17

(animated GIF – view in full-screen mode)

AC10 NMC: Max-to-Min Range Imaging 2020-06-17

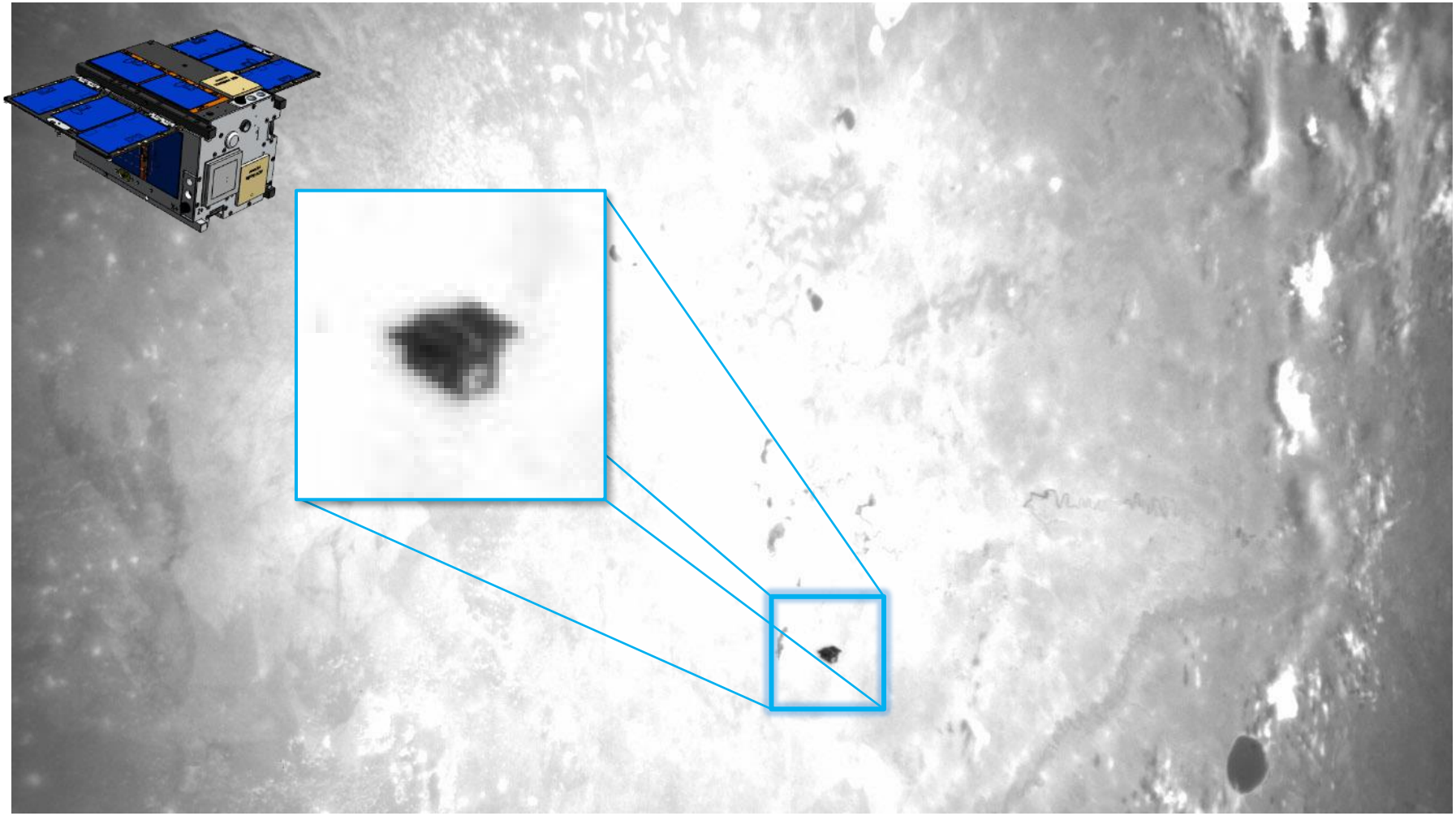
Frame 233 - 2020 Jun 17 @ 08:40:05.12z



Latitude = 34.2 N, Longitude = 30.4 E
Range = 44 meters

AC10 NMC: Max-to-Min Range Imaging 2020-06-17z

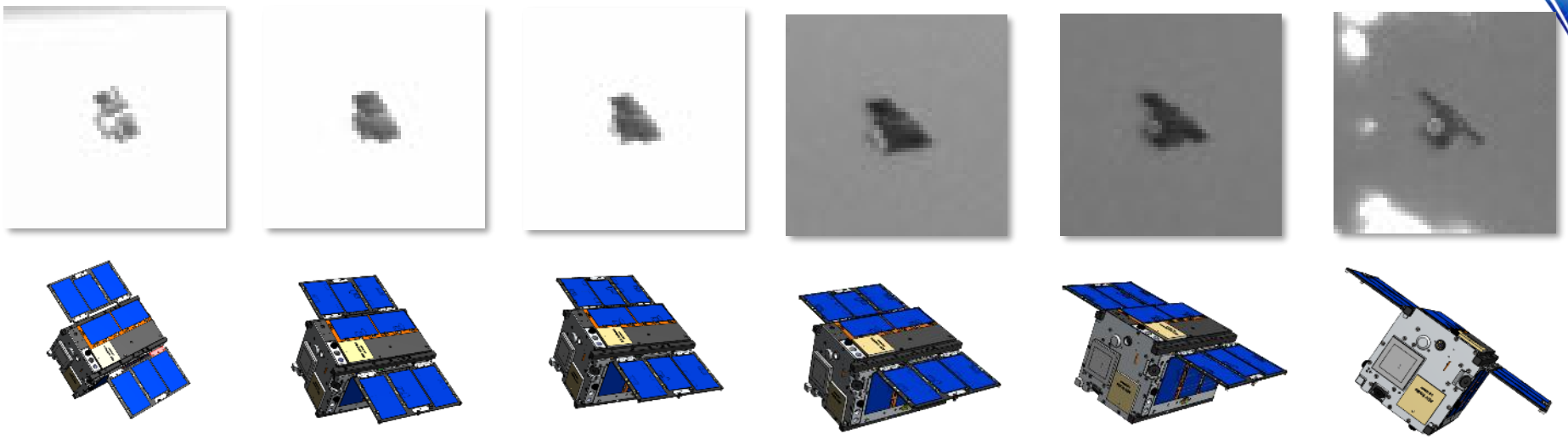
Frame 238 - 2020 Jun 17 @ 08:45:05.12



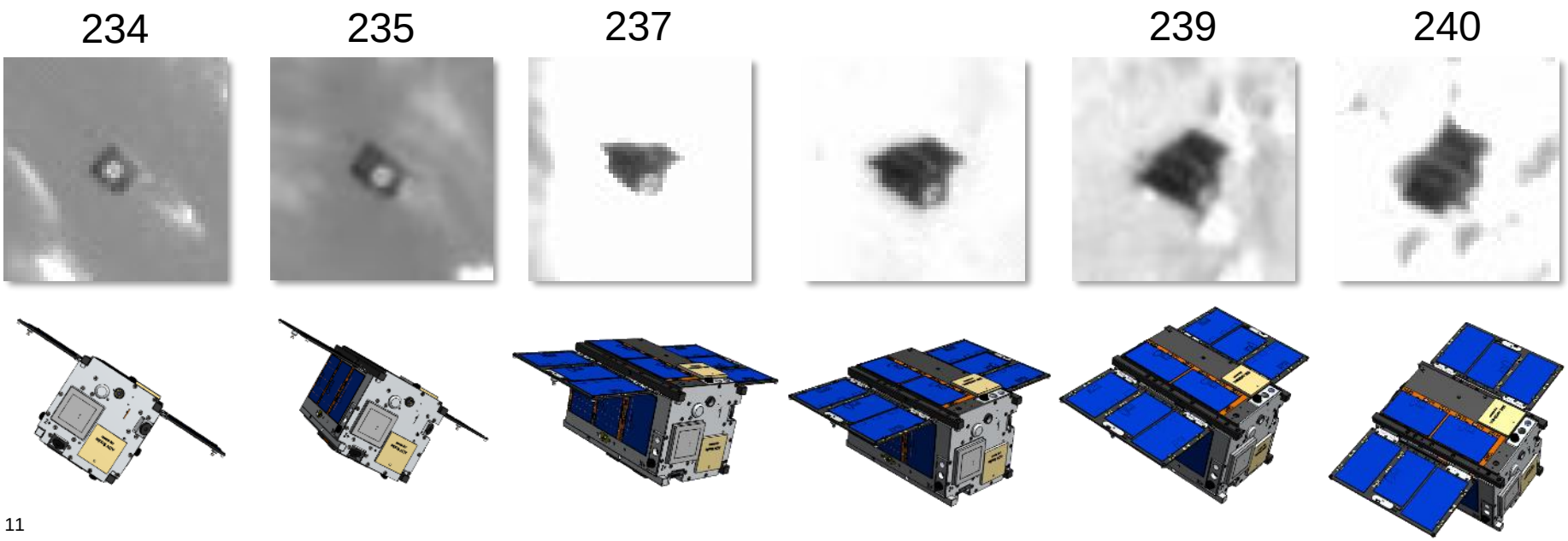
Latitude = 45.3 N, Longitude = 49.5 E
Range = 35 meters

Composite of AC10A Images

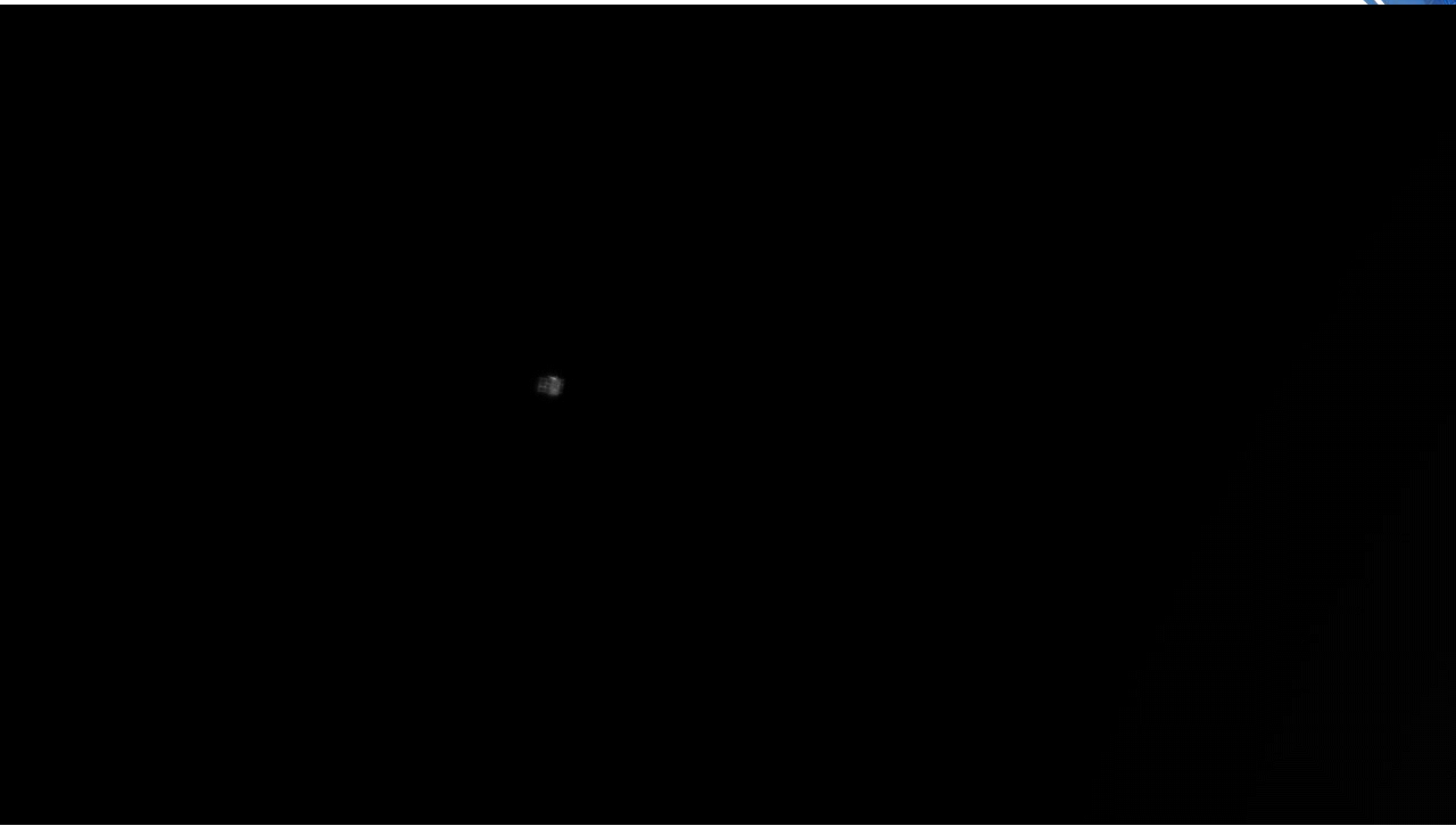
228 229 230 231 232 233



234 235 237 239 240



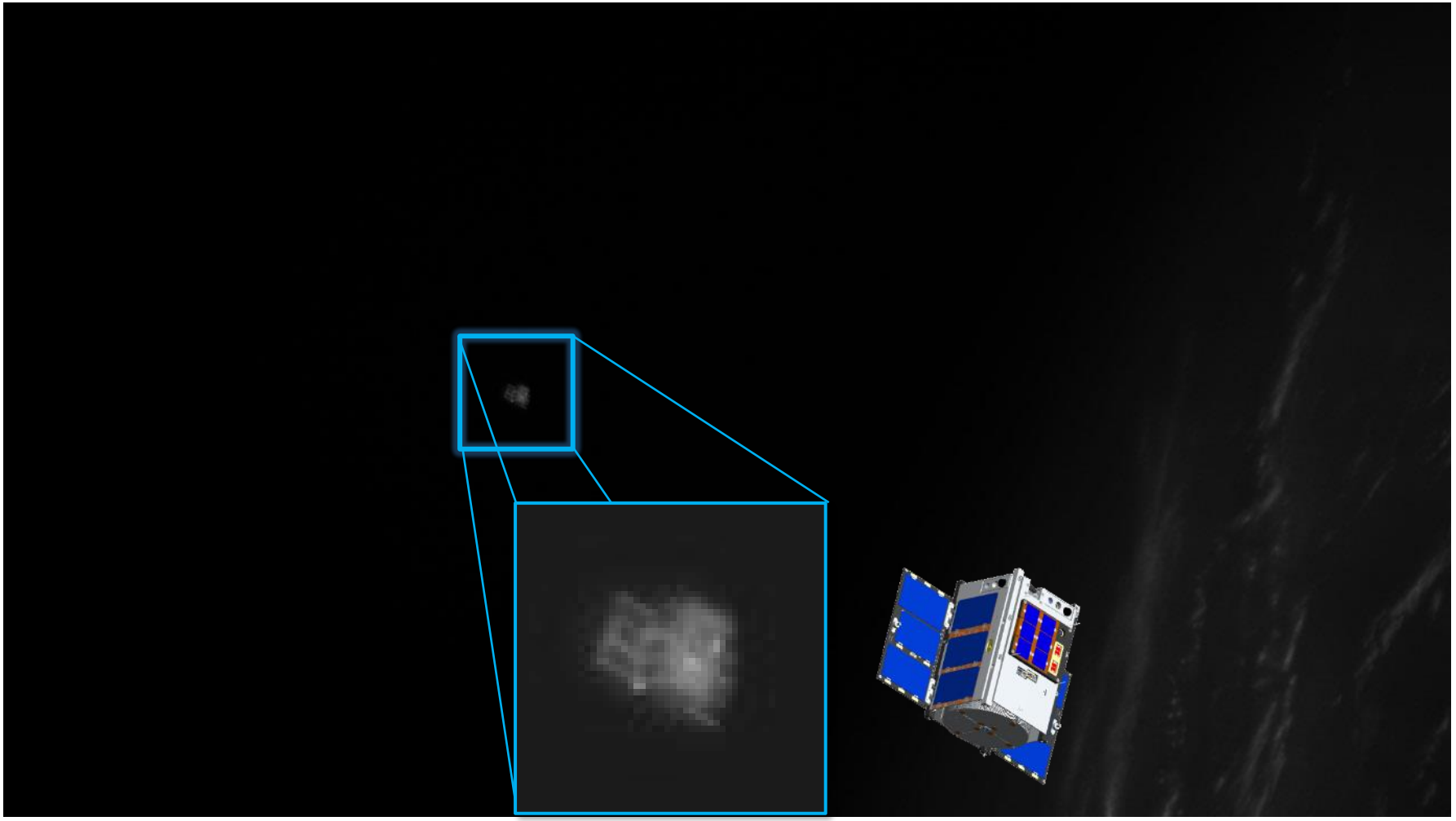
AC10 NMC: 2020-07-01



(animated GIF – view in full-screen mode)

AC10 Close Approach 2020-07-01

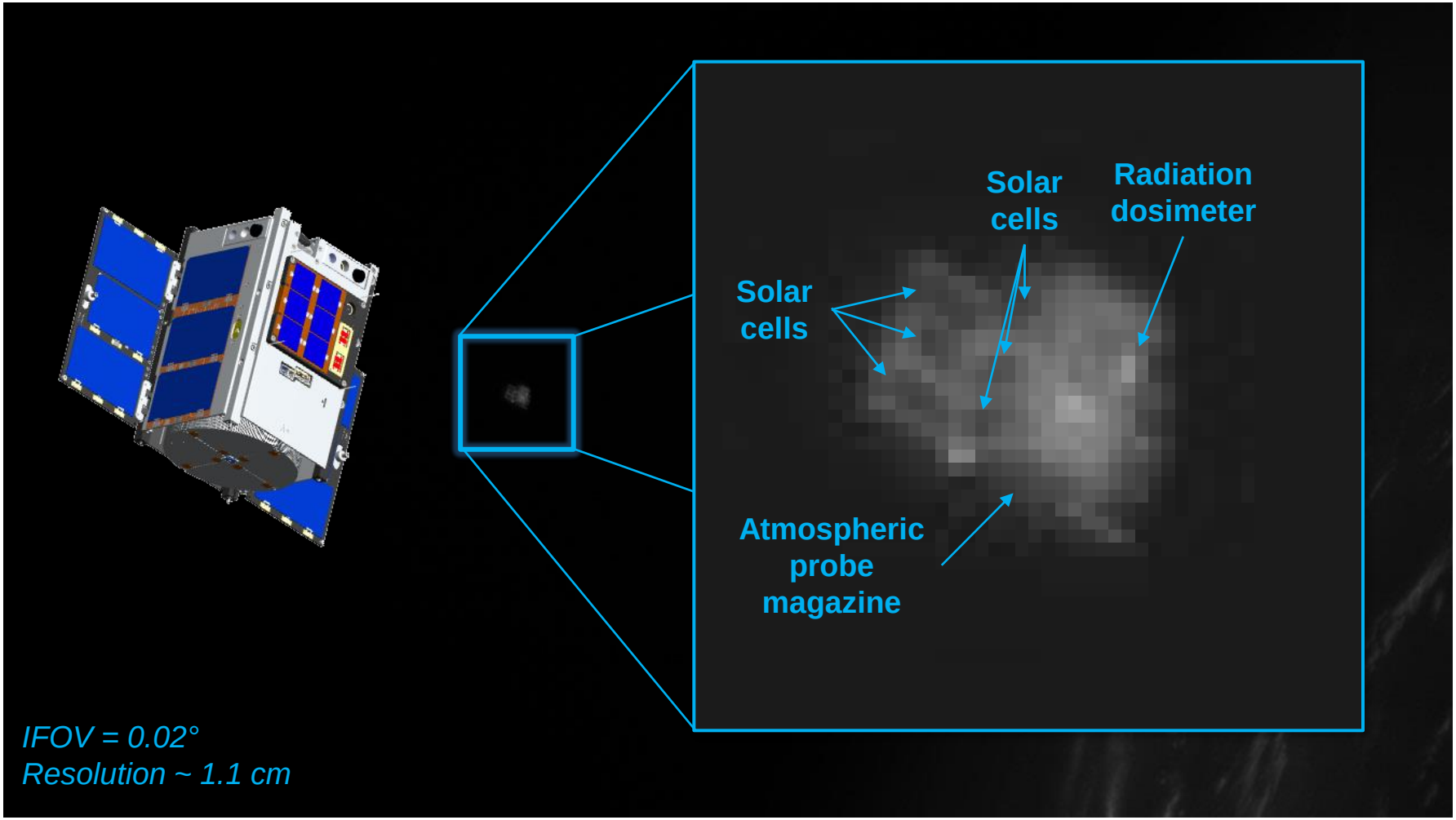
Frame 276 - 2020 Jul 1 @ 20:40:05.08



Latitude = 39.7 N, Longitude = 135.0 E
Range = 30.8 meters

AC10 Close Approach 2020-07-01

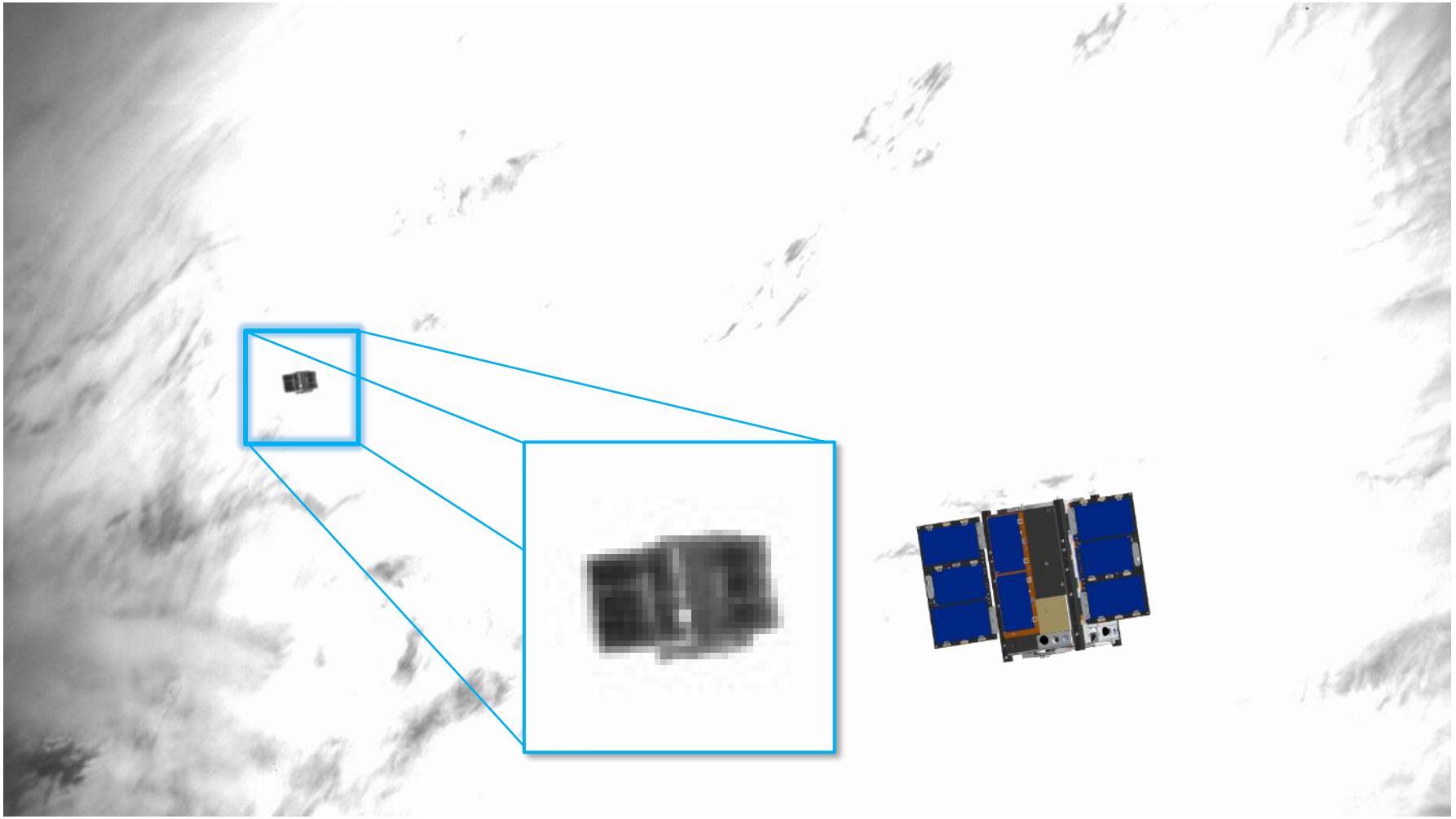
Frame 276 - 2020 Jul 1 @ 20:40:05.08



Latitude = 39.7 N, Longitude = 135.0 E
Range = 30.8 meters

AC10 Close Approach 2020-07-01

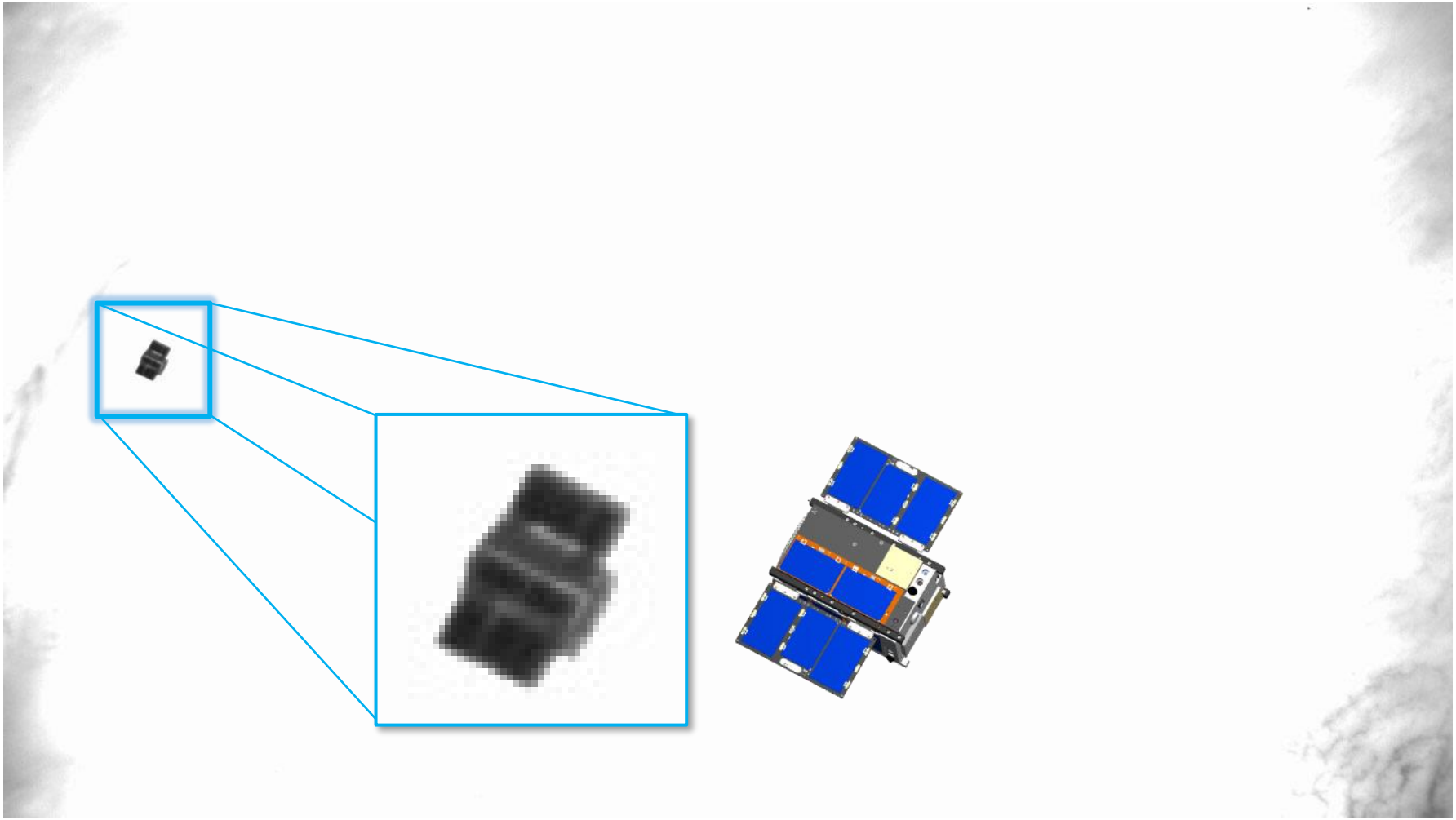
Frame 282 - 2020 Jul 1 @ 20:46:05.12



Latitude = 50.1 N, Longitude = 162.7 E
Range = 24.0 meters

AC10 Close Approach 2020-07-01

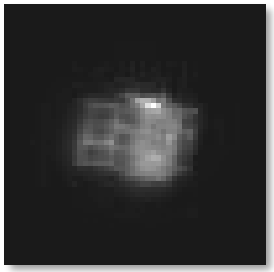
Frame 284 - 2020 Jul 1 @ 20:48:05.12

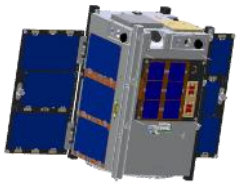


Latitude = 51.5 N, Longitude = 174.1 E
Range = 21.8 meters

Composite of AC10A Images – 2020-07-01

275





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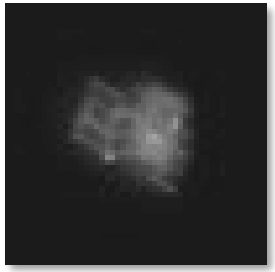

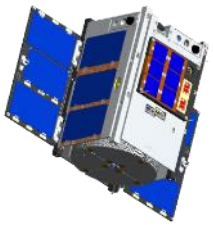

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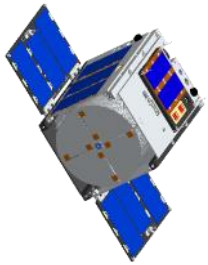

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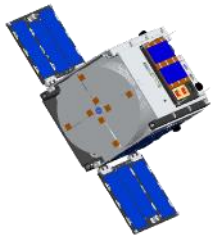

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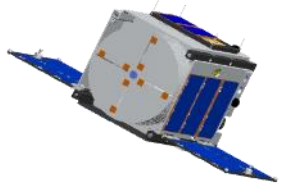

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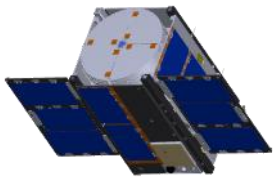

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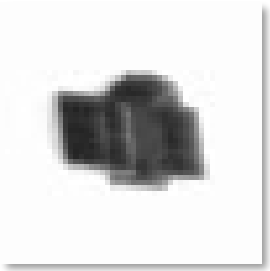

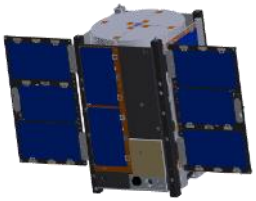

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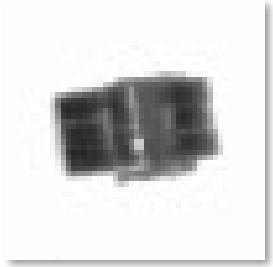

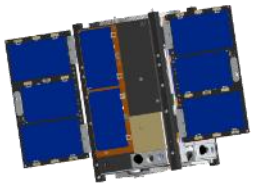

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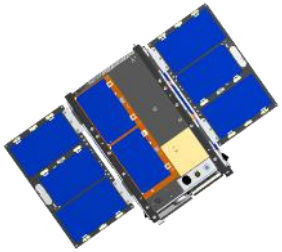

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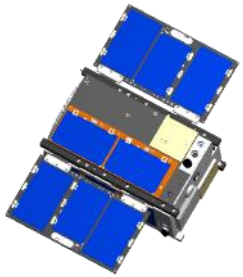

Takeaways

- Operational constraints often (usually) swamp orbit-design considerations
  - *Example: spent more time investigating the weather of sites that would be in imagery background than planning the NMC maneuvers → clouds impact exposure time*
- Seek mission-design methodologies that are effects-based, intuitive, simple to plan and execute, and tolerant of error
  - *Don't have time to juggle maneuver optimizations with lighting conditions, image exposure times, propulsion uncertainty, uplink/downlink schedules, etc.*
- Even getting as close as 20-30 meters, you don't need a vehicle much more sophisticated than AC10 to do an inspection mission
  - *AC10 wasn't designed for close RPO or inspection, but necessary upgrades (e.g., camera, lens, GPS, crosslink) are not challenging and not significant SWaP penalty*
- Above all, autonomous (closed-loop) tracking will be essential to execute dedicated inspection missions
  - *For cooperative RPO, sharing navigation data via crosslink may be sufficient*
  - *For non-cooperative RPO (e.g., active debris removal), will need on-board image processing and auto-track*
- Inspection in 1.5U package opens opportunity for carrying inspector sats on diverse range of hosts (not just space stations)
  - *Where diagnostic needs are modest, but agility and flexibility are paramount*