Deciphering the Enigma of Satellite Computing with COTS Devices: Measurement and Analysis

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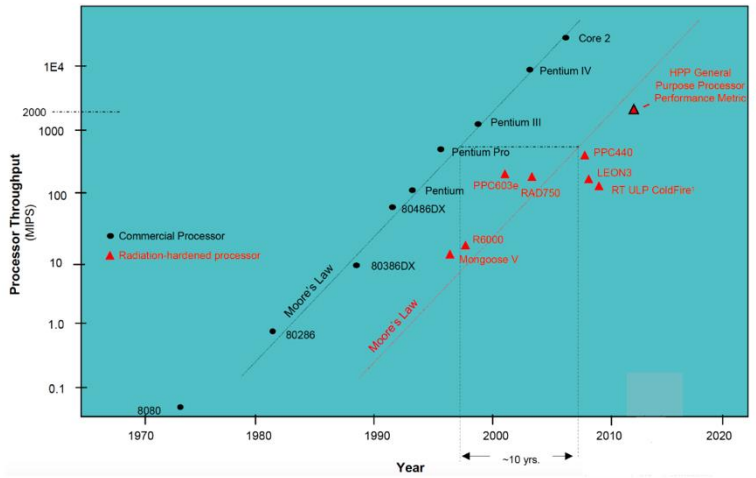
1. Background

- "New Space" trend is enabling the massive adoption of Commercial Off-The-Shelf (COTS) processors for satellite computing

200$ cost

For starship launching
1KG payload to LEO



10-year gap

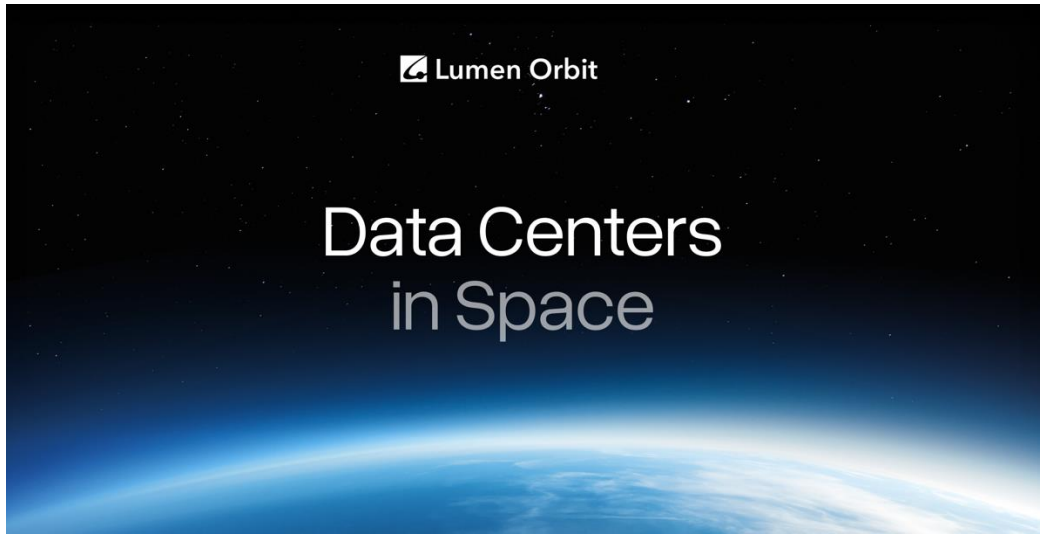
COTS VS Legacy
(radiation-hardened) processors

1000X cheaper

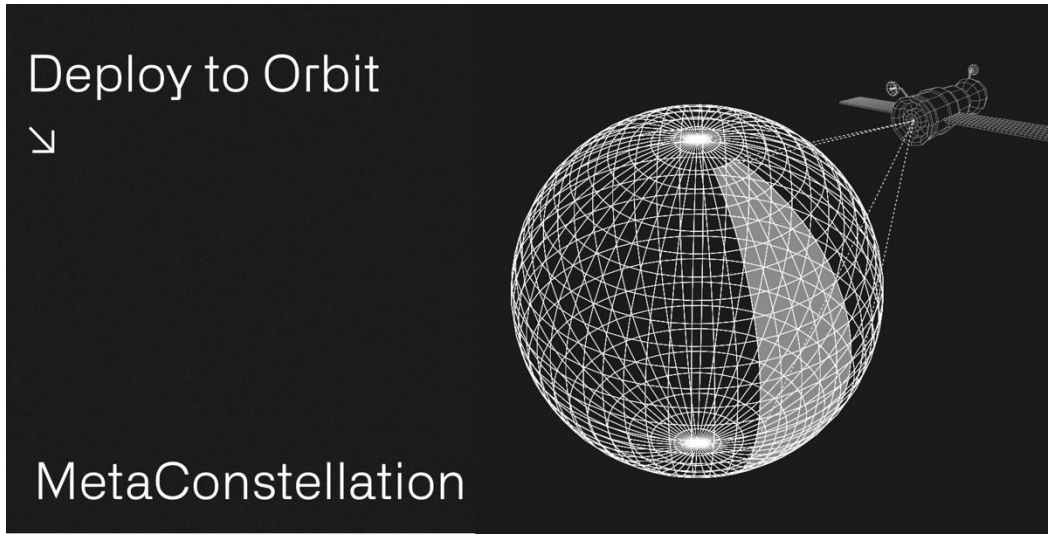
COTS vs Legacy
(radiation-hardened) processors

1. Background

- **Satellite Computing** is reshaping "New Space" applications



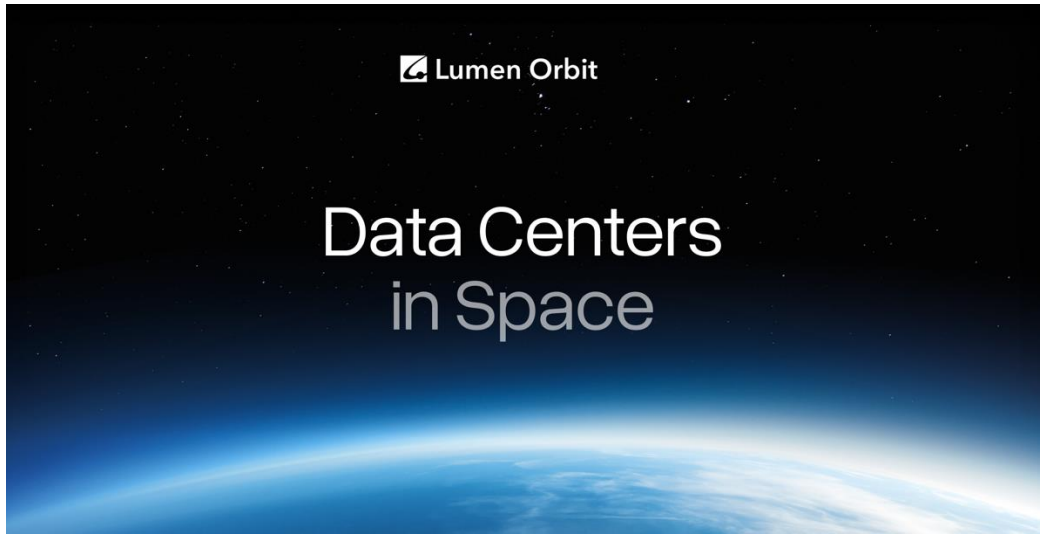
Converting solar energy into AI training power

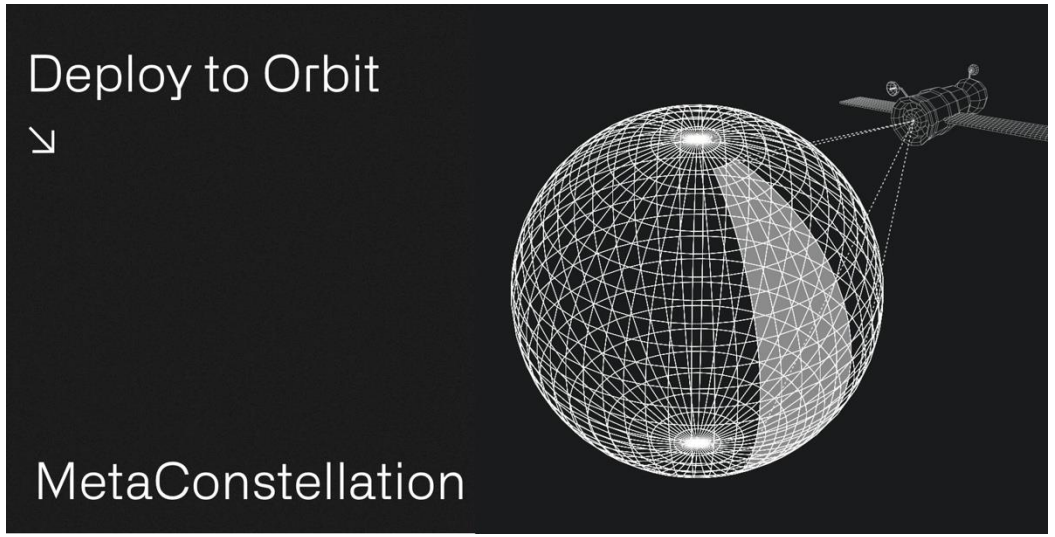


Leveraging computing to gather real-time intelligence

1. Background

- **Computing Availability** must be known for these applications





Requirement: compute **longer**

When computing is **unavailable**?

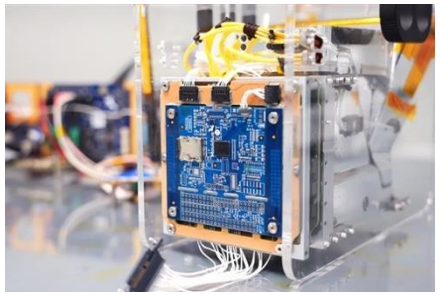
Requirement: compute **quicker**

Is computing **available** for now?

2. Motivation

- **Satellite Computing Availability** has different characteristics than those on the ground due to the distinct environments

On the Ground



On Satellites

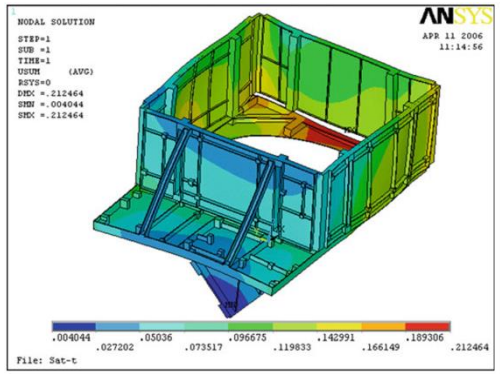
Air/Liquid cooling	Thermal	*Passive radiation*
Almost unlimited energy	Power	*Only solar power*

2. Motivation

So given the differences, how do we know when the satellite computing is available or not considering the thermal and power conditions?

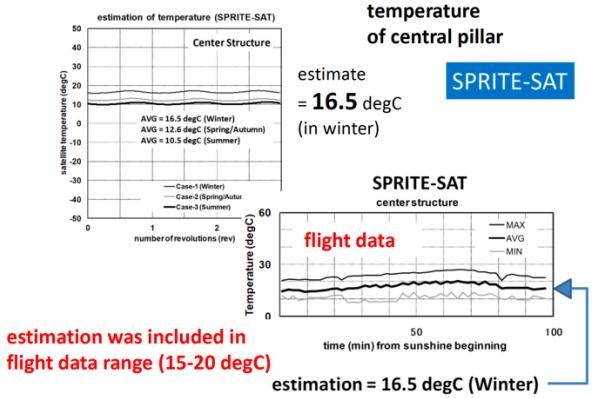
2. Motivation

Industrial Approaches



Lack Flexibility

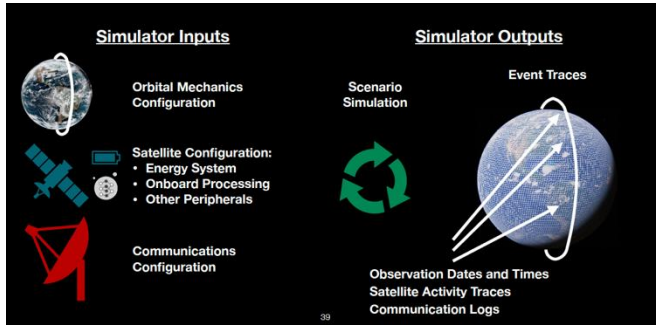
Margin-based Design



Threshold-based Scheduling

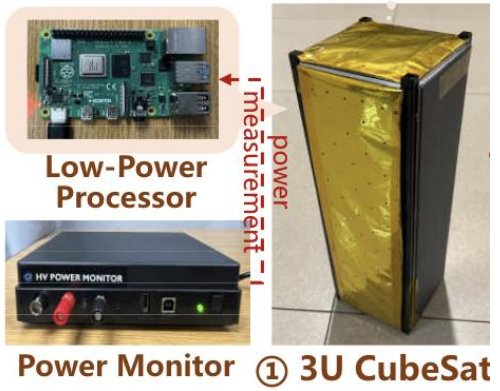
Academic Approaches

COTE [ASPLOS' 20]



Lack Realism

Simulations/Emulations

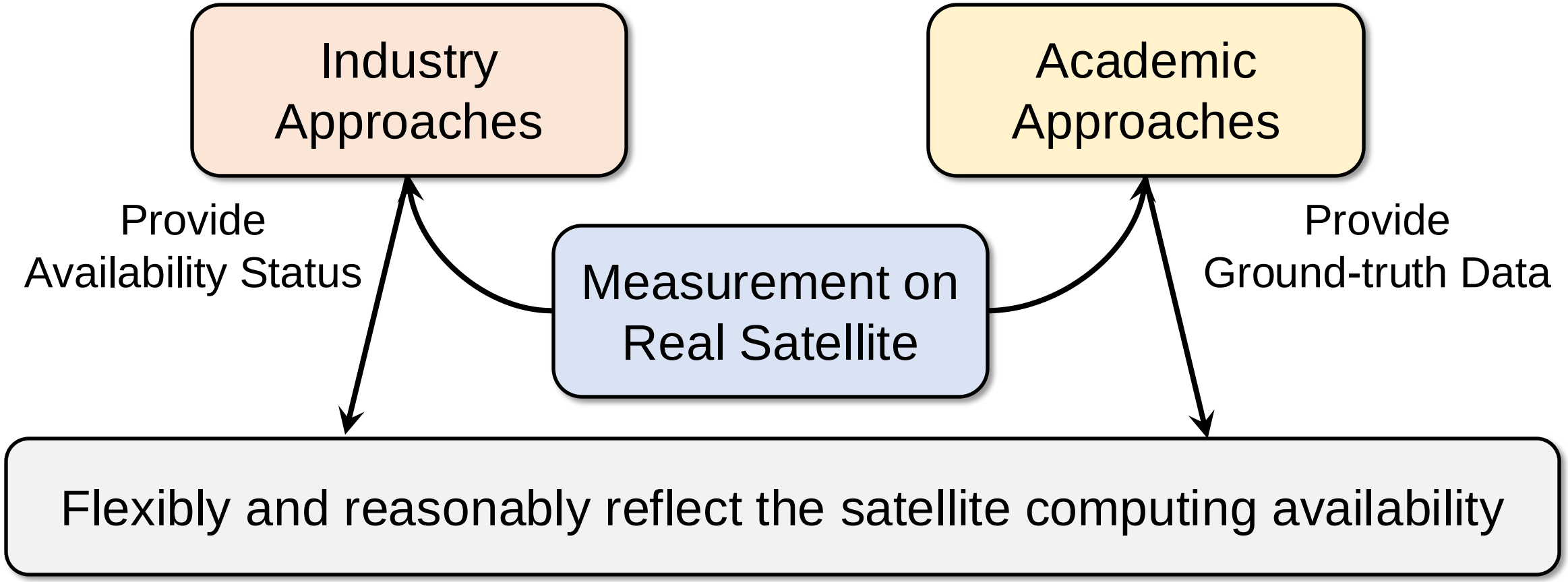


STARRYNET [NSDI' 23]

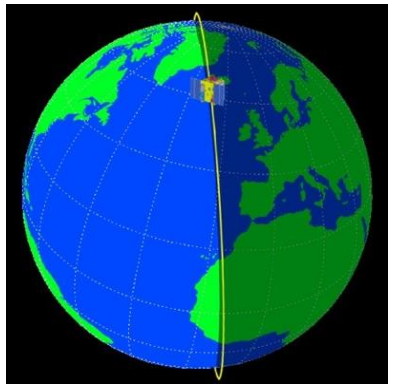
Hardware-in-the-loop Testing

2. Motivation

- **Measurement on real satellite** would enable the synergistic integration of both strands of work



3. Measurement Methodology



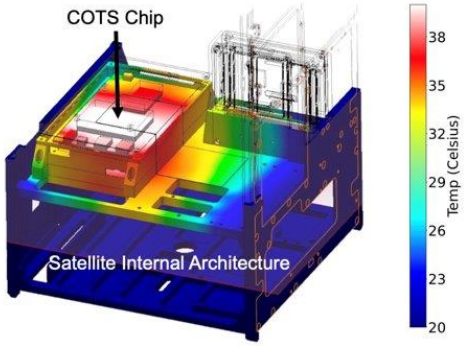
Sun-synchronous Orbit
90min Period
(60min Daylight & 30min Eclipse)

Classification	Mass Range [kg]
Nanosatellite	1- 10
Microsatellite	10 - 100
Minisatellite	100 - 1000

17.44kg in mass
12U CubeSat (Top 10%)

We did this measurement by making a real satellite!

BUPT-1 Satellite



Inner Temperature: -10℃ to 30℃
Battery Usage: Less than 30%

TT&C: 4.8kbps up & 9.6kbps down
Data Transmission: 100Mbps downlink

3. Measurement Methodology

- **Internal Temperature** and **Battery Depth of Charge (DoD)** exceeding their limits can lead to catastrophic consequences

TABLE 11-43. Examples of Typical Thermal Requirements for Spacecraft Components. The thermal control subsystem is required to maintain all spacecraft equipment within proper temperature ranges. Note that the temperature extremes on the outer portions of spacecraft can vary between ± 200 °C.

Component	Typical Temperature Ranges (°C)	
	Operational	Survival
Batteries	0 to 15	−10 to 25
Power Box Baseplates	−10 to 50	−20 to 60
Reaction Wheels	−10 to 40	−20 to 50
Gyros/IMUs	0 to 40	−10 to 50
Star Trackers	0 to 30	−10 to 40
C&DH Box Baseplates	−20 to 60	−40 to 75
Hydrazine Tanks and Lines	15 to 40	5 to 50
Antenna Gimbals	−40 to 80	−50 to 90
Antennas	−100 to 100	−120 to 120
Solar Panels	−150 to 110	−200 to 130

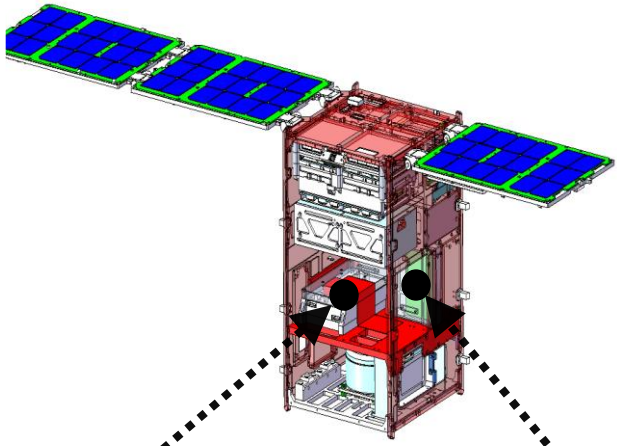
Temperature must be in proper Range (e.g. -10℃ to 30℃)

Life-Test Mode	Tests Conditions			Cycle Number done
	EOCV	DOD	TEMP	
Acceler.	4.05V	20%	20°C	37 400
Acceler.	4.05 V	30%	20°C	33 720
Real Time	4.05V	20%	20°C	27 000
Real Time	4.05V	20%	30°C	25 000
Real Time	3.9V	20%	20°C	27 000
Real Time	4.05V	30%	20°C	27 000
Real Time	4.05V	30%	30°C	15 500
Real Time	4.05V	10% 15% 20%	10°C	15 000
Real Time	4.05V	20%	20°C	15 000
Real Time	4.05 V	40%	20°C	15 500
Real Time	C/3 4.05V	20%	5°C	3 500
Real Time	4.075V	20%	20°C	15 500
Real Time	4.1 V	20%	20°C	15 500
Real Time	C/5, C/3, C/2.5, C/2 4.05V	20%	20°C	12 500
Real Time	4.05V	50%	20°C	3 500

Battery life can drop dramatically once DoD goes beyond 30%

3. Measurement Methodology

BUPT-1 Internal Architecture



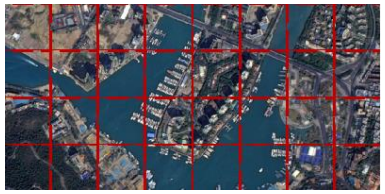
Atlas 200 DK x2

NPU
Image related Tasks

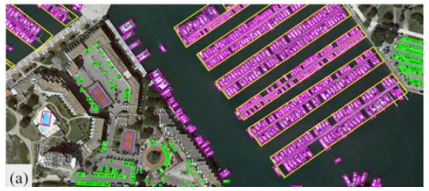
Raspberry Pi 4B x2

CPU
Generic Tasks

Image Splitting



Object Detection

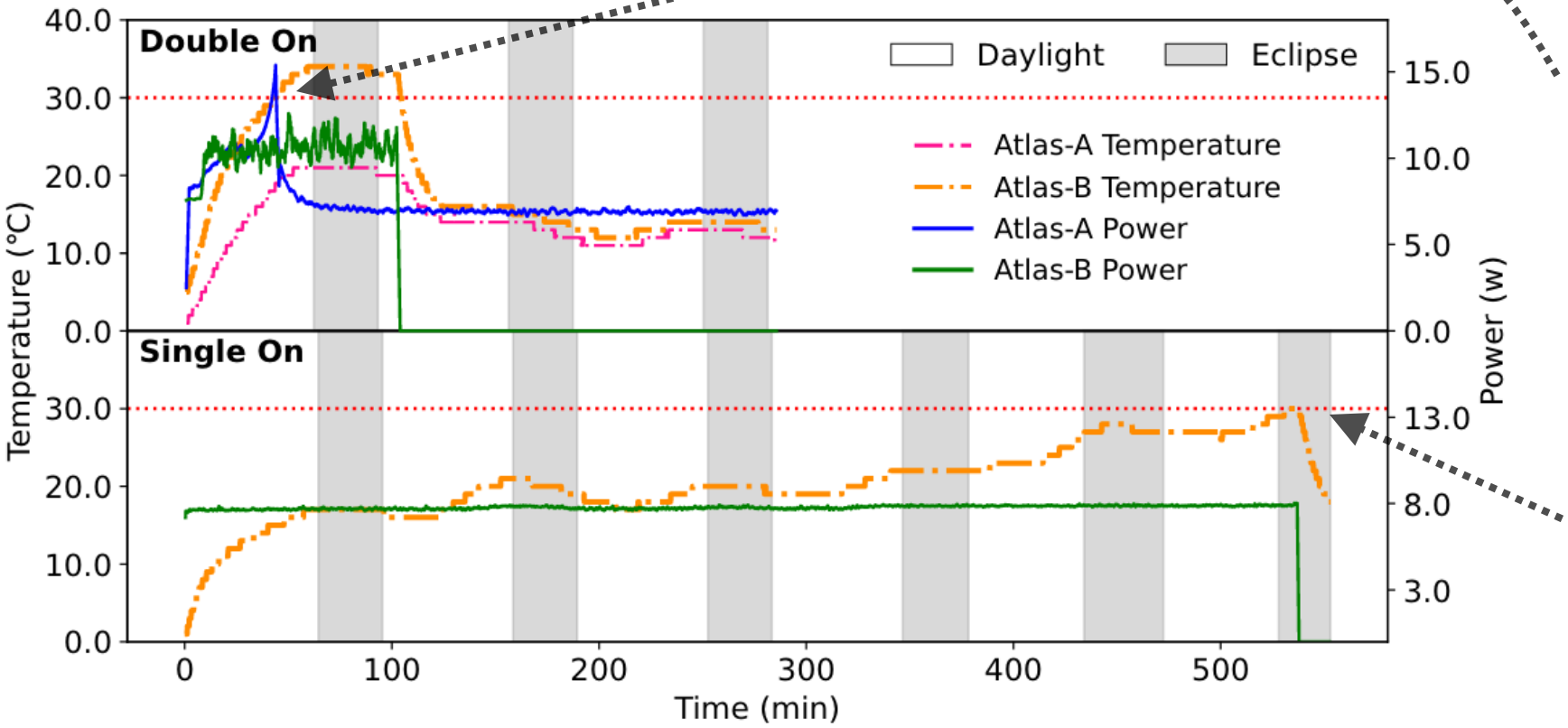


Typical Computing Tasks:

- **Data Processing**
  - Image/video Encoding, Decoding
  - Image Resizing
  - Image Splitting
- **AI Inference**
  - Operations: Classification, Object Detection
  - Models: yolofastest, yolov3_544, yolov5-lite

4. Findings: Overheating Effect

Atlas 200 DK (NPU)



Double on:

Exceed the 30℃ threshold within 1 hour

One Atlas halted

The other crushed

Single on:

Exceed the 30℃ threshold in 10 hours

Task ended Normally

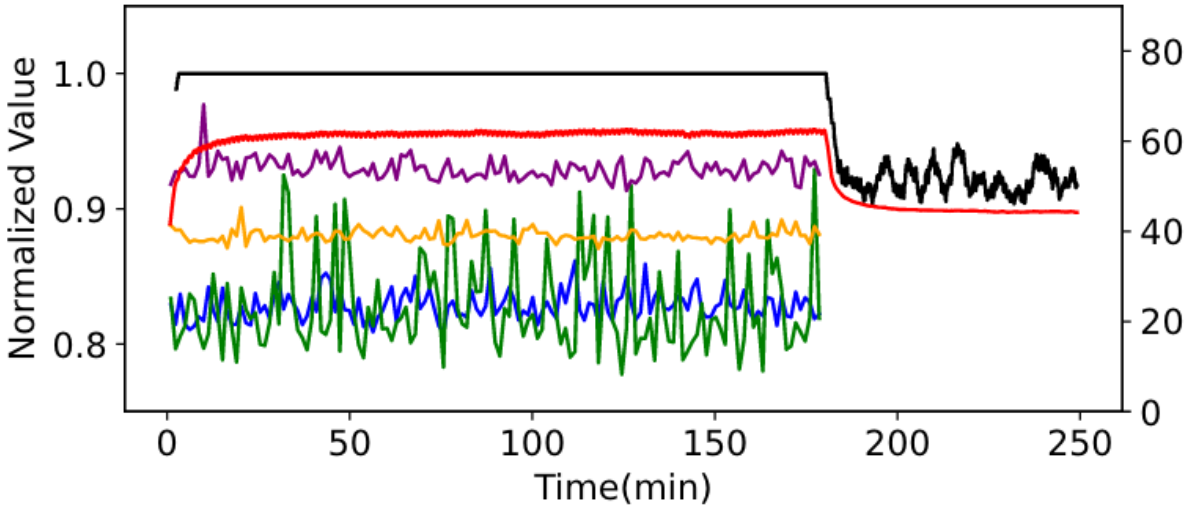
Temperature is a key factor limiting the satellite computing availability

4. Findings: Overheating Effect

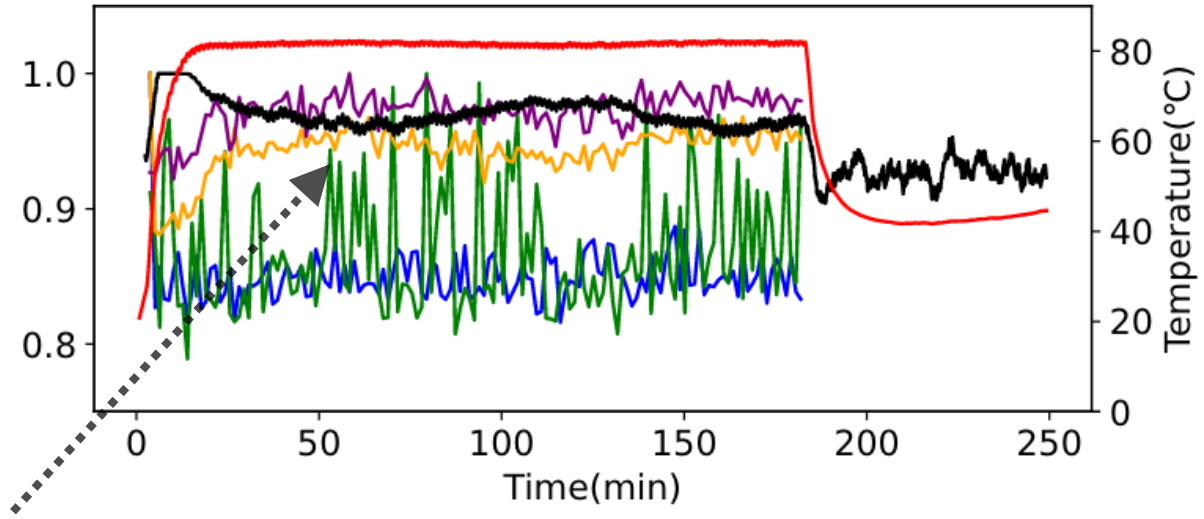
Raspberry Pi (CPU)

SSD-MV1 Latency
YOLO-Fastest Inference Latency
YOLOv3 Inference Latency
YOLOv5-Lite Inference Latency
Frequency
Temperature

Ground Replica

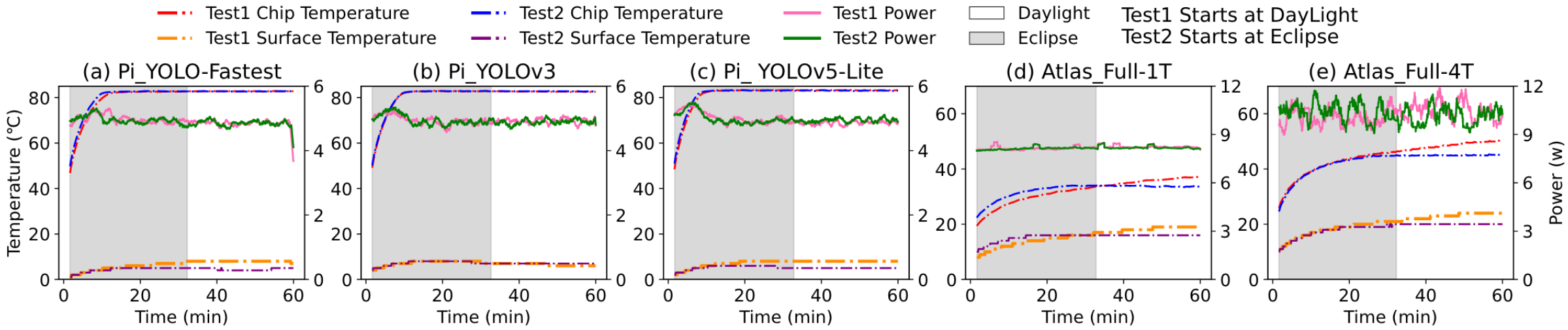


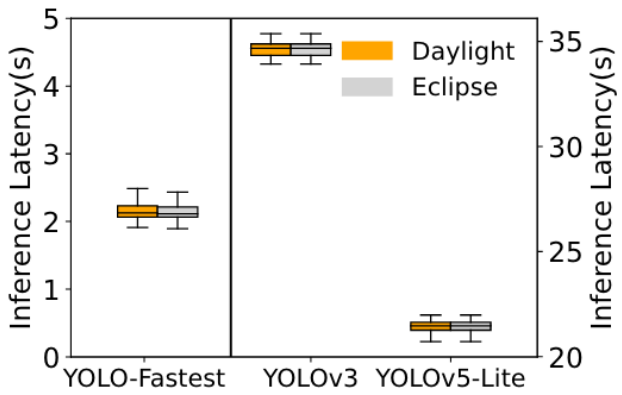
Onboard Satellite

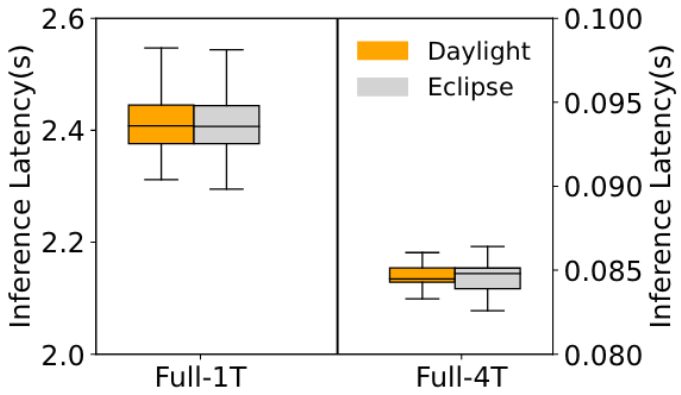


An thermal throttling results in an 10% increase on inference latency

4. Findings: Eclipse/Daylight Impact



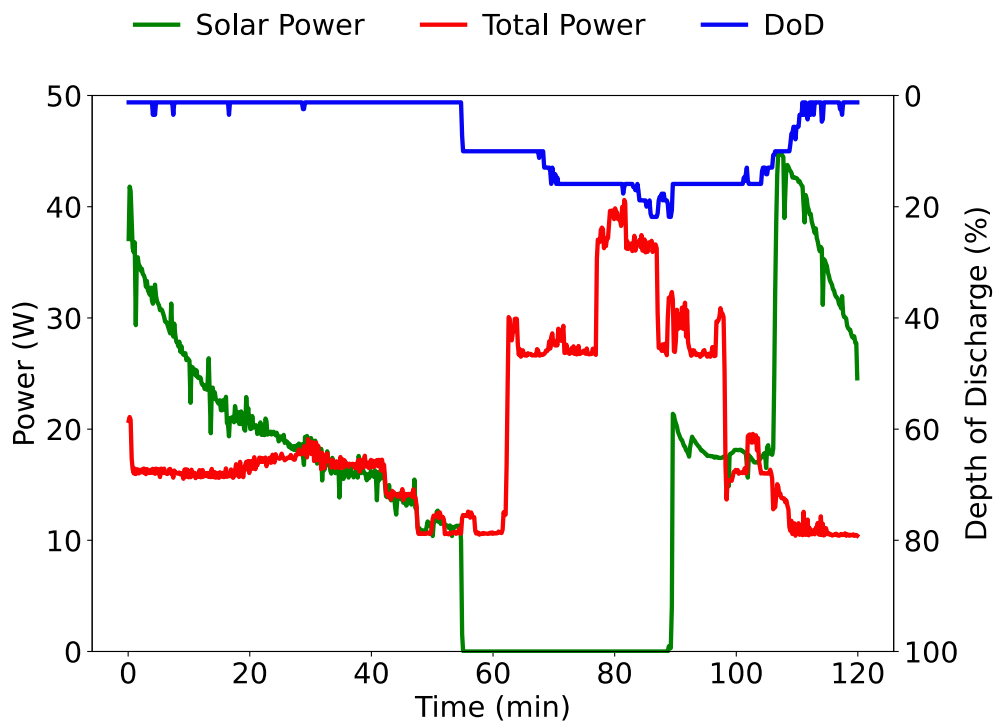




- The eclipse or daylight periods can only slightly affect payload chip and surface temperatures, with variations mostly within ±5 ◦C
- Performance is almost not affected

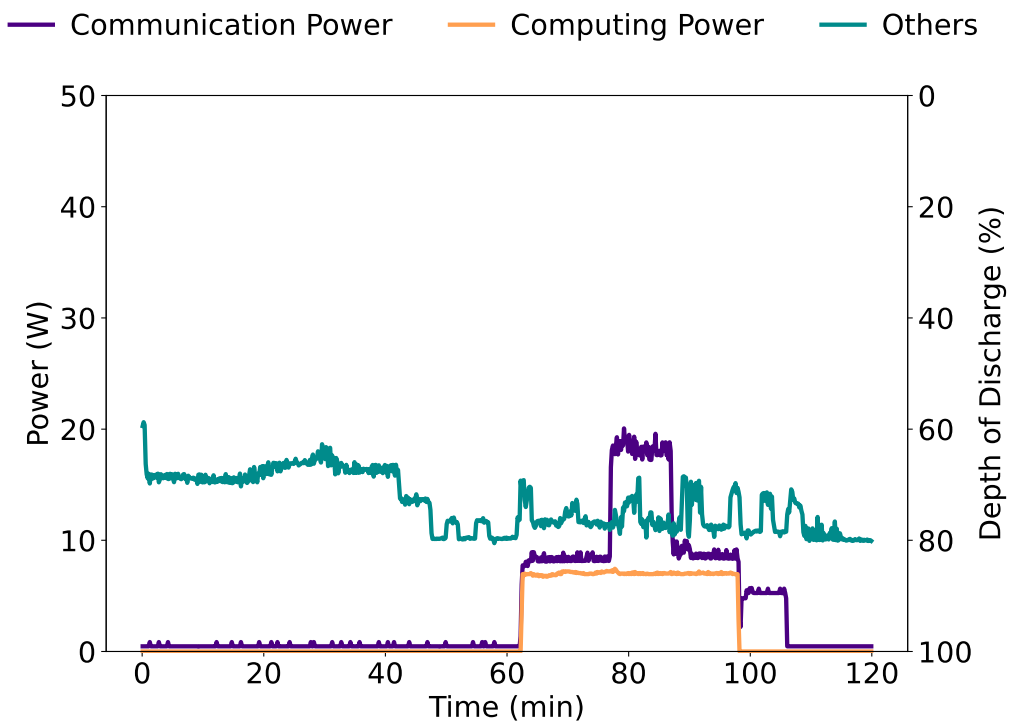
4. Findings: Power Variations

Power Input/Output Comparison



Normally, the DoD won't exceed 30%

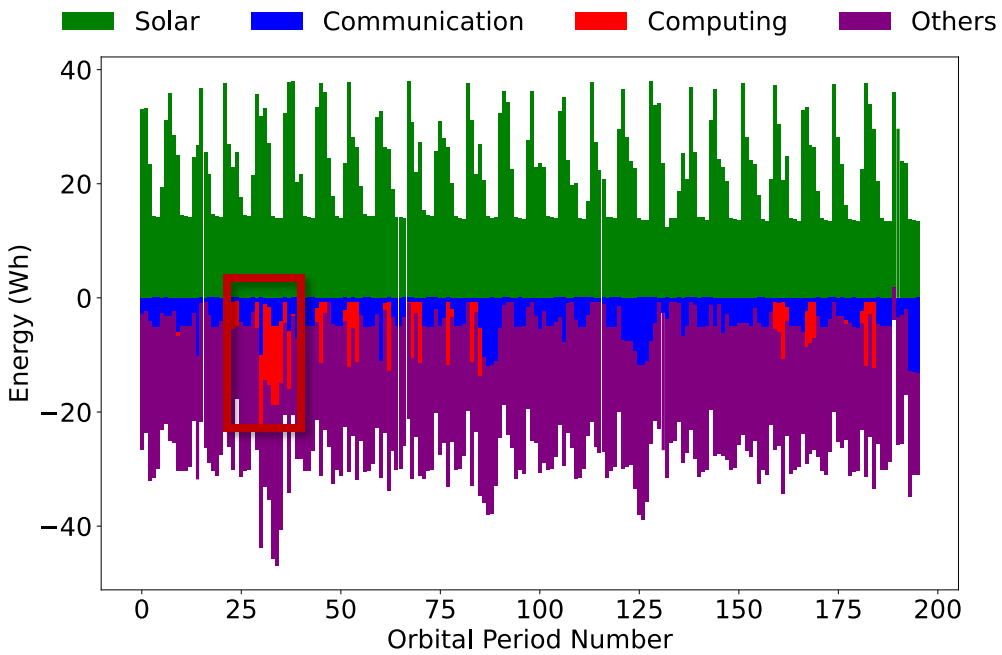
Power Consumption Comparison



Communication power consumption can be highest but won't last long

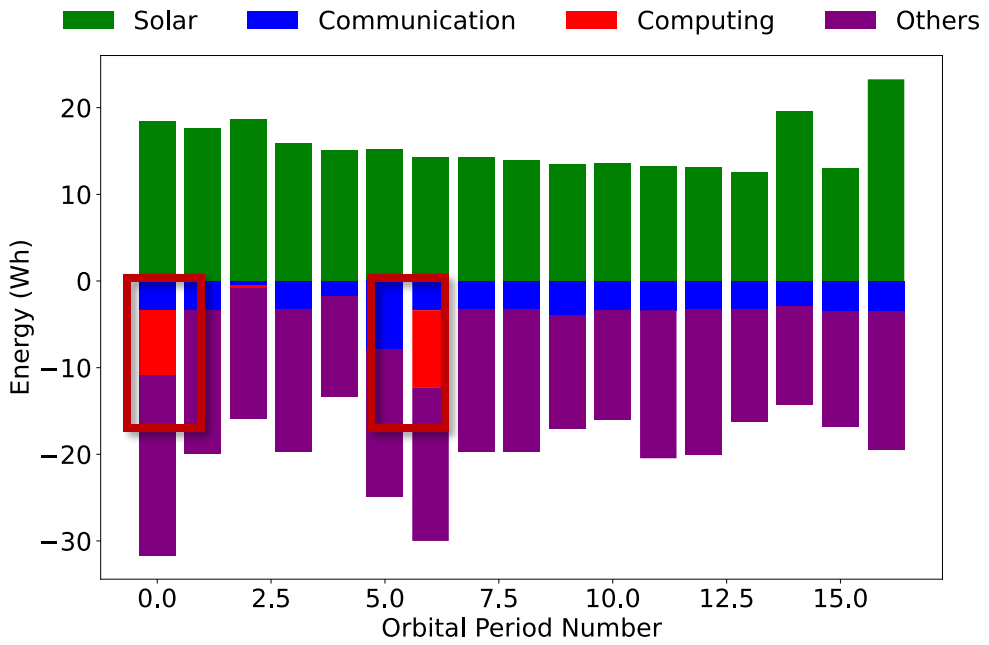
4. Findings: Power Variations

During 7 Days



Bursty computing power may dominate

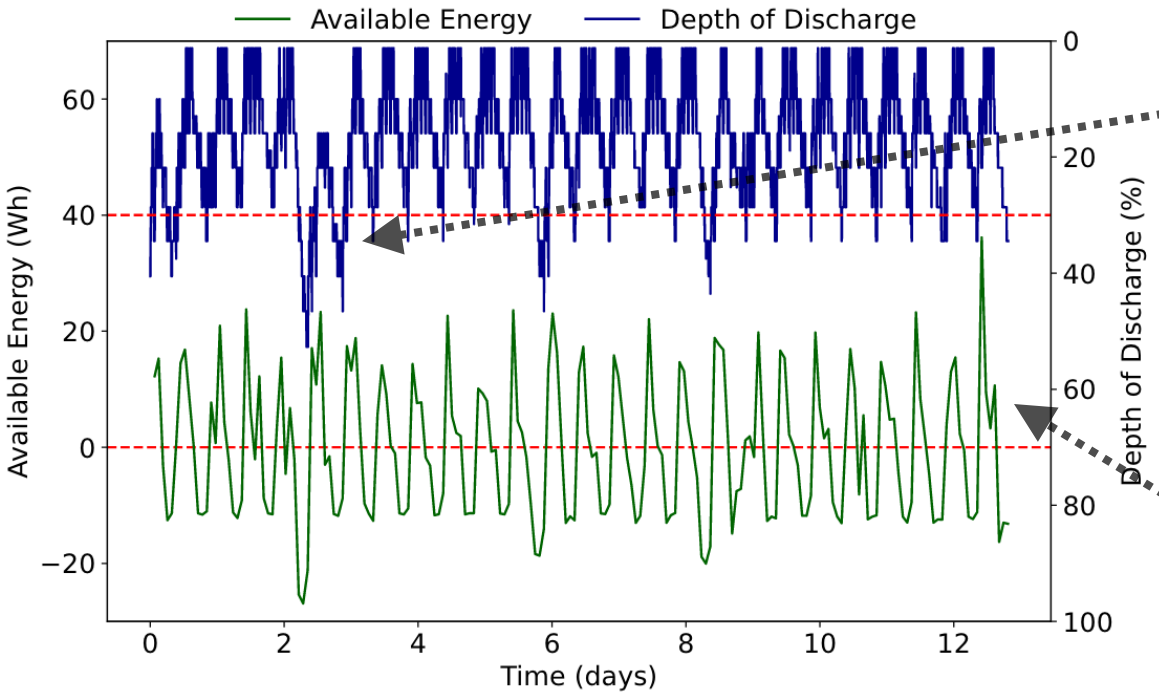
During 7 days at the same time (e.g. 1pm)



Other power consumptions are stable

Computing power consumption is the most deciding/unstable factor compared to other kinds of power consumption

4. Findings: Solar Power and Battery



DoD exceeded 30%, reaching up to 50% during intensive computing, which severely impacts satellite lifespan

Approximately 6% of the collected solar energy was wasted, which could have been utilized for computing

COTS computing devices on satellites need to both **prevent short-term excessive energy consumption** and **make full use of the available energy**

5. Conclusion

- First study on real satellite COTS computing devices in terms of thermal control and power management
- Building comprehensive datasets to facilitate researches on satellite task scheduling and satellite computing simulation/emulations
- Source code and data are available at https://github.com/TiansuanConstellation/MobiCom24-SatelliteCOTS

Github Repo

Thanks! Q & A

Tiansuan Website