USENIX ATC '25

SpaceExit: Enabling Efficient Adaptive Computing in Space with Early Exits

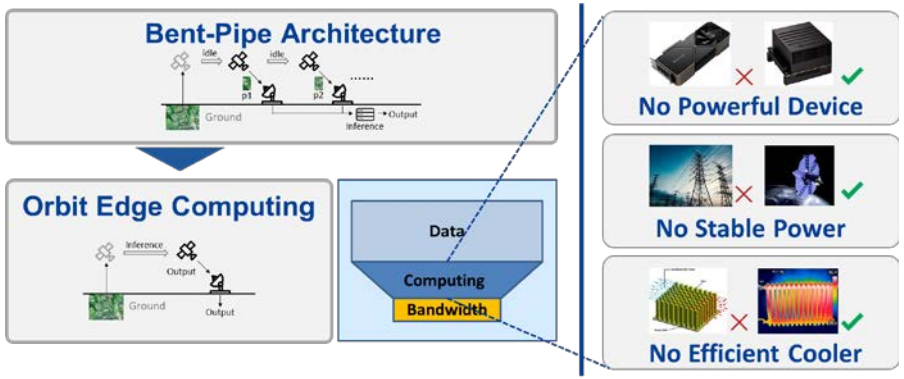
Author: Jiacheng Liu*, **Xiaozhi Zhu***, Tongqiao Xu, Xiaofeng Hou, Chao Li

USENIX ATC '25, Boston, MA, USA

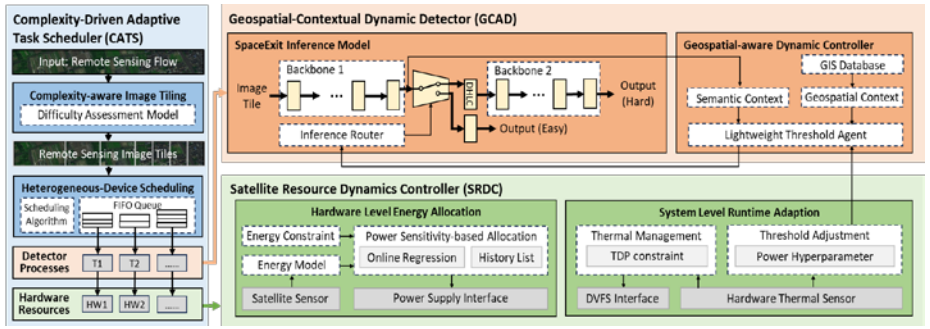
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

Content

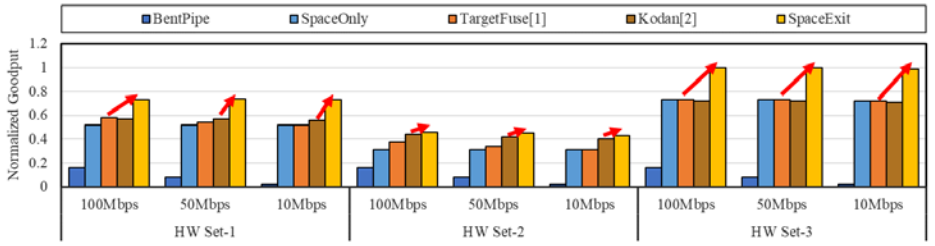
1. Background & Motivation



2. System Design



3. Workflow & Evaluation



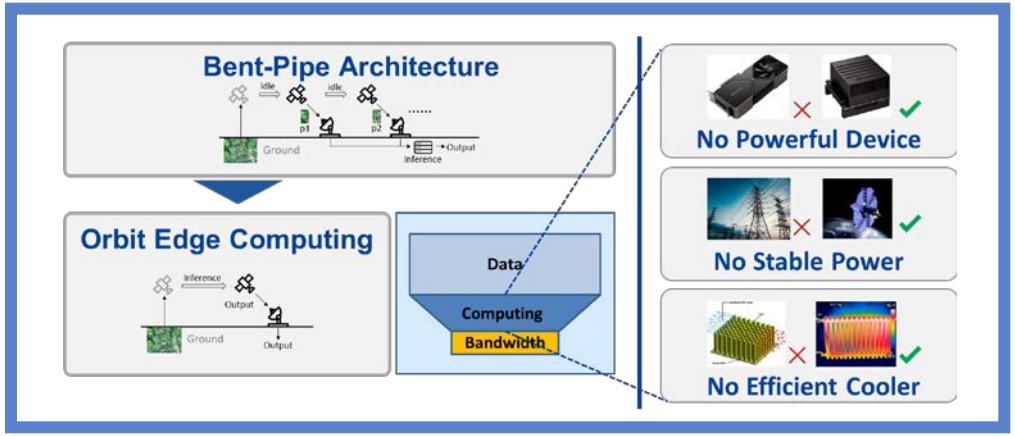
5.2%-37.6% improvement

4. Conclusion

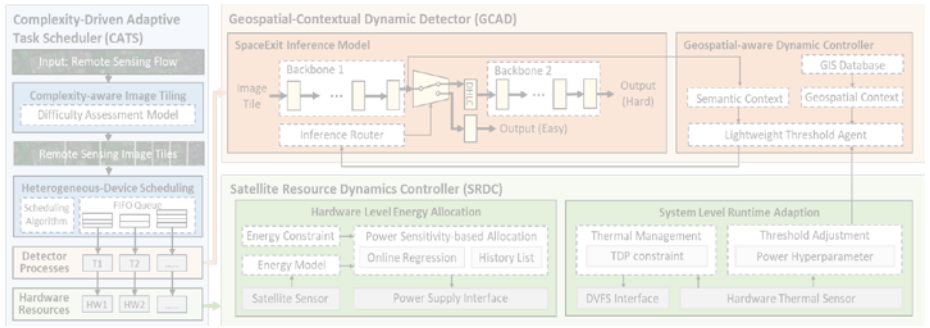
- We embrace OEC (Orbit Edge Computing), which is emerging as a solution to imbalanced data-bandwidth growth.
- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.
- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

Content

1. Background & Motivation



2. System Design



3. Workflow & Evaluation

5.2%-37.6% improvement

4. Conclusion

- We embrace OEC (Orbit Edge Computing), which is emerging as a solution to imbalanced data-bandwidth growth.
- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.
- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

BG: Earth Observation Constellation

Earth observation constellations serve as platforms for applications

Precision Agriculture

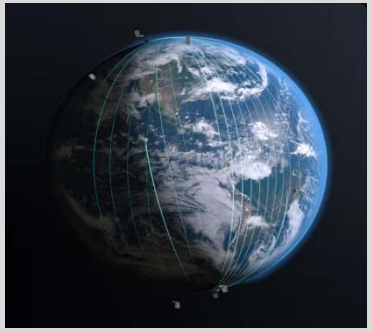
Disaster Responce

Environment Monitoring

Transportation Optimization

Support

Iteration of Nanosatellite



Earth Obvervation Constallation

Progress of Rocket Launch

BG: Earth Observation Constellation

Earth observation constellations serve as platforms for applications

Precision Agriculture

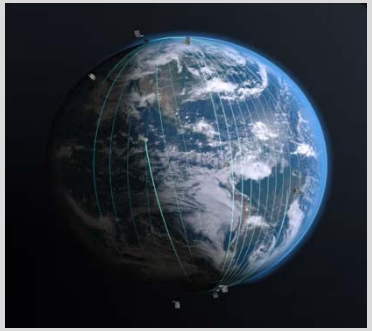
Disaster Responce

Environment Monitoring

Transportation Optimization

Support

Iteration of Nanosatellite



Earth Obvervation Constallation

Progress of Rocket Launch

BG: Earth Observation Constellation

Earth observation constellations serve as platforms for applications

Precision Agriculture

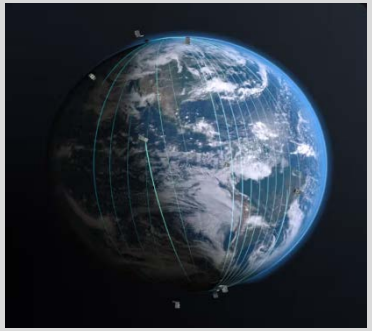
Disaster Responce

Environment Monitoring

Transportation Optimization

Support

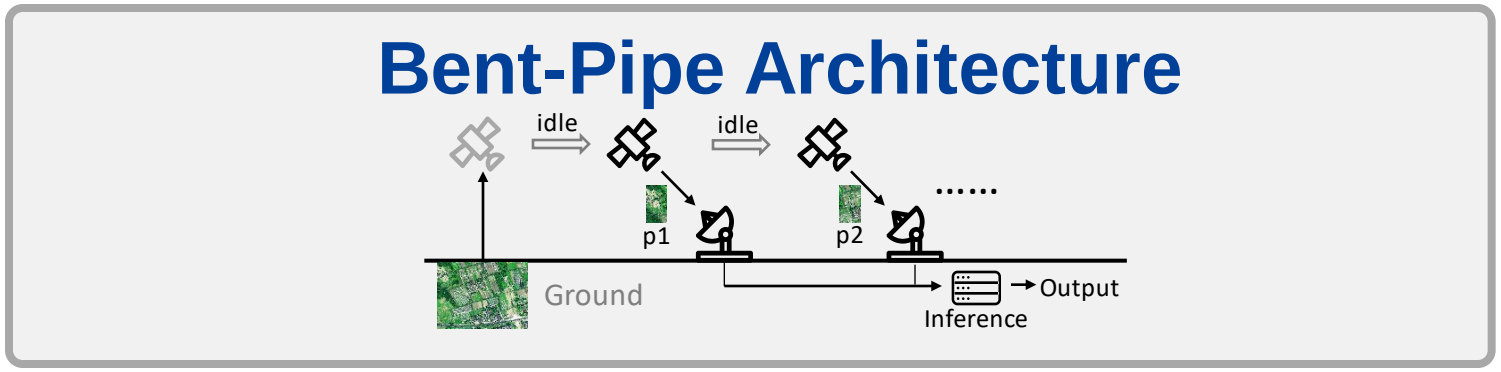
Iteration of Nanosatellite

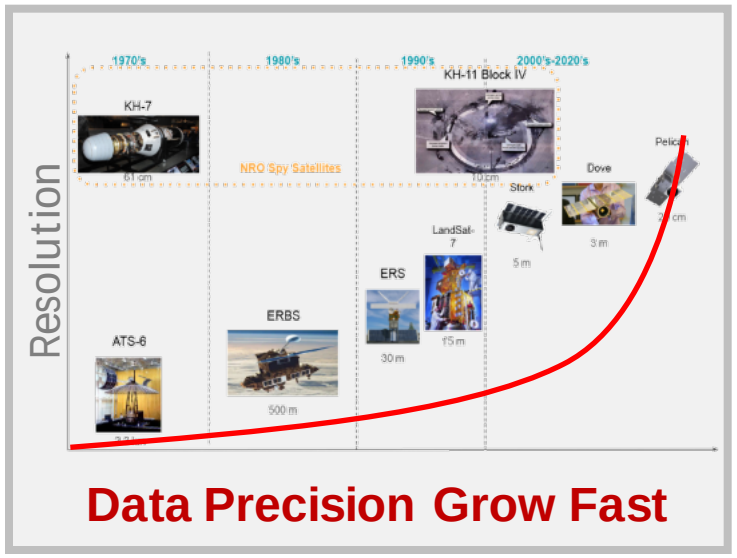


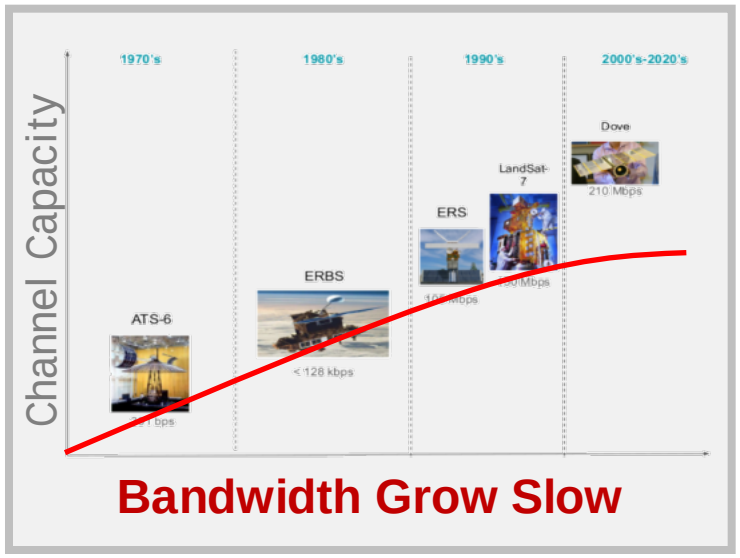
Earth Obvervation Constallation

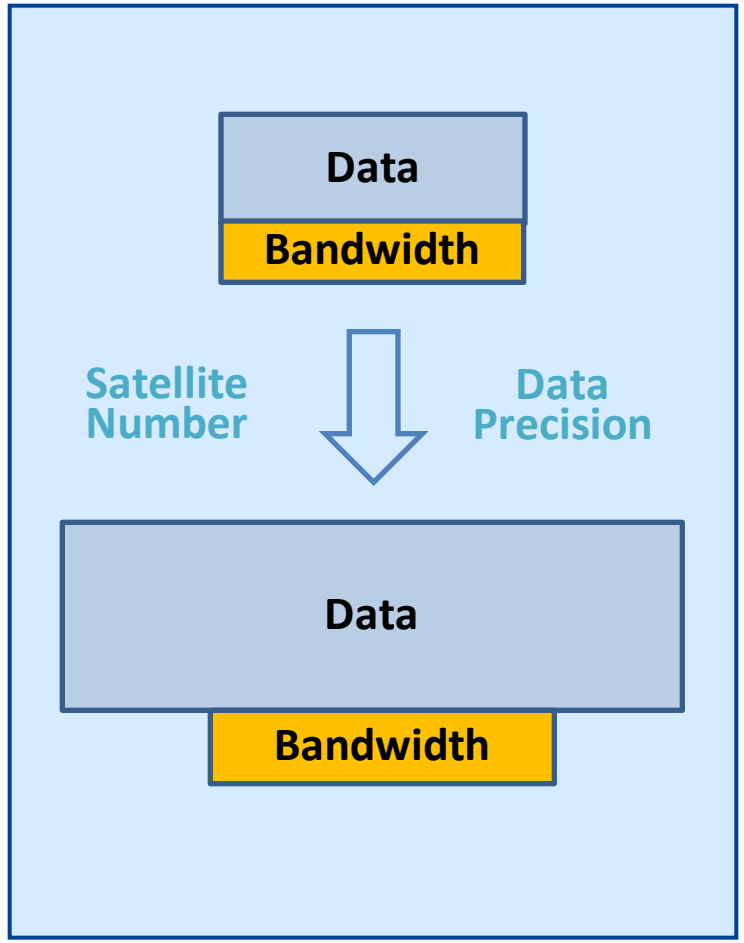
Progress of Rocket Launch

BG: Bent-Pipe Architecture







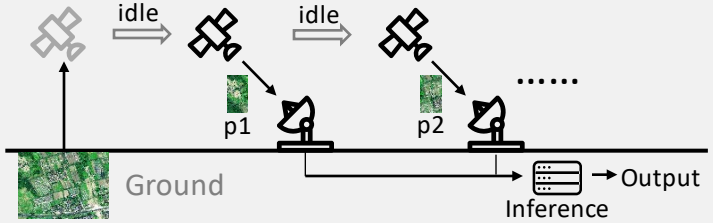


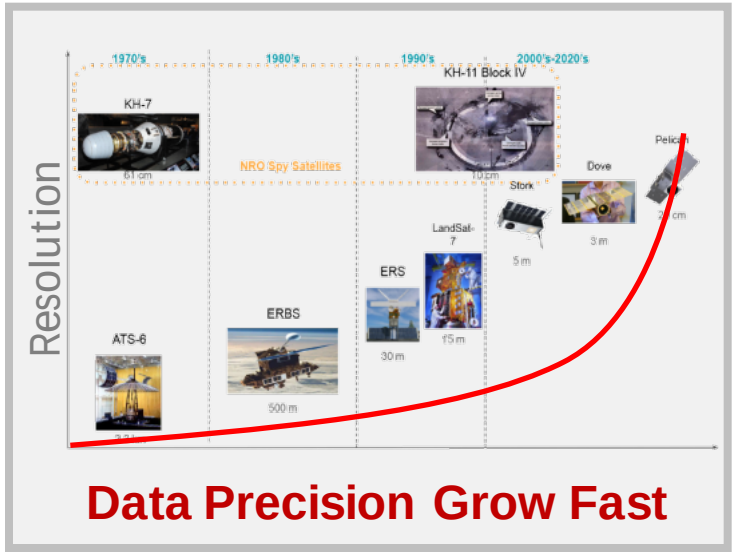
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

Data Source: Bleier, Nathaniel, et al. "Space microdatacenters." MICRO, 2023.

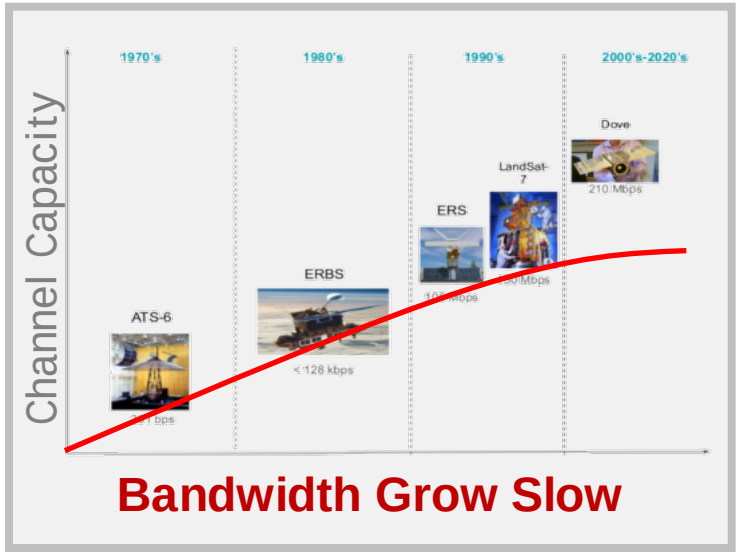
BG: Bent-Pipe Architecture

Bent-Pipe Architecture

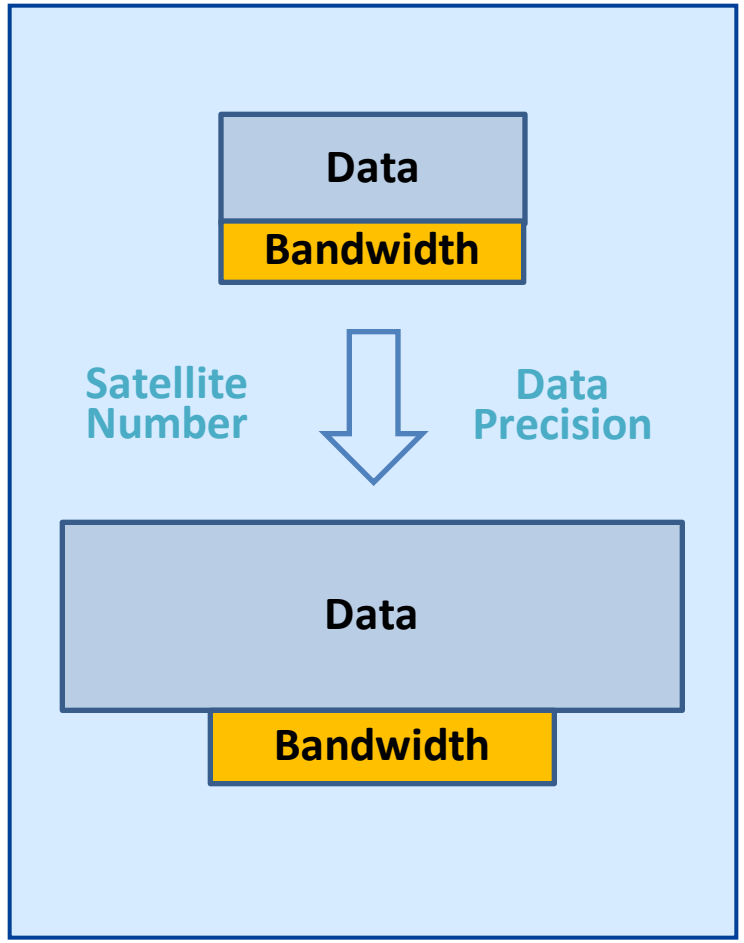




Data Precision Grow Fast



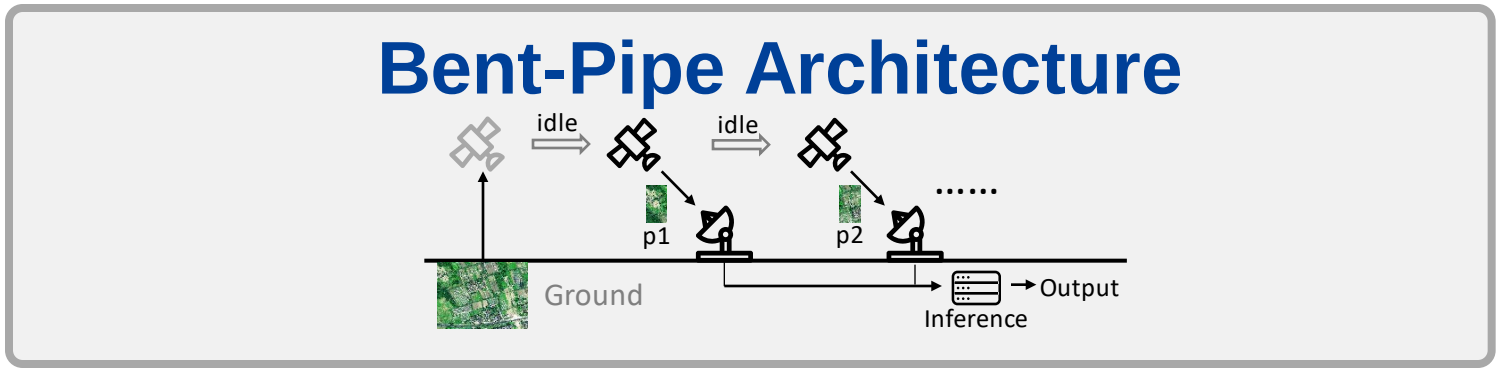
Bandwidth Grow Slow

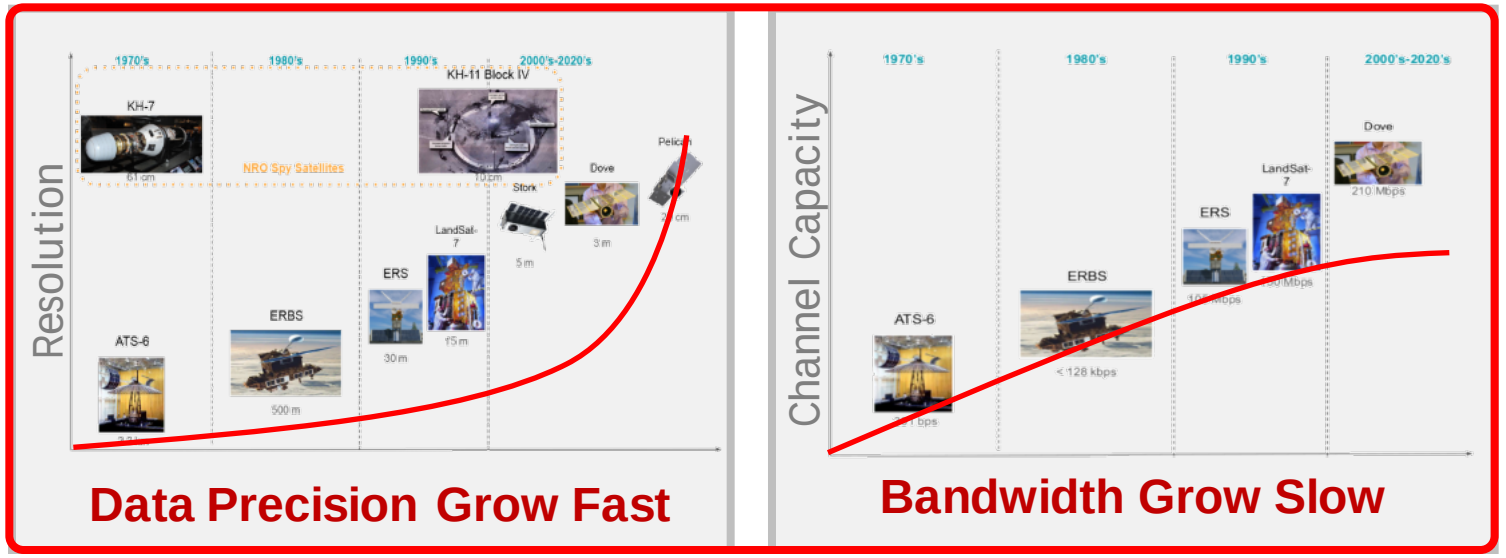


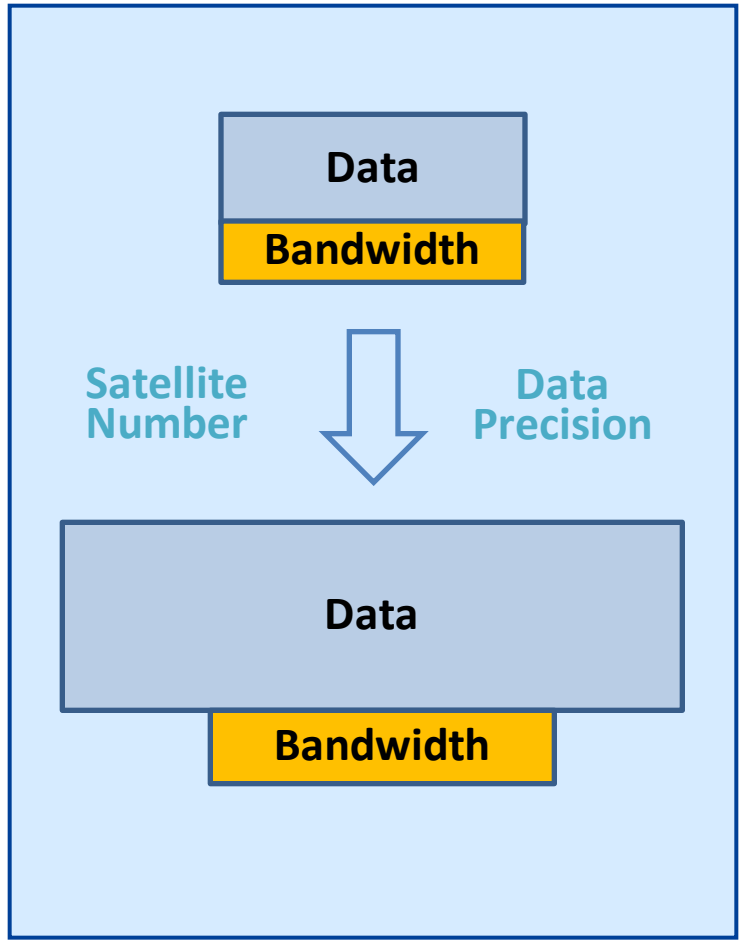
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

Data Source: Bleier, Nathaniel, et al. "Space microdatacenters." MICRO, 2023.

BG: Bent-Pipe Architecture





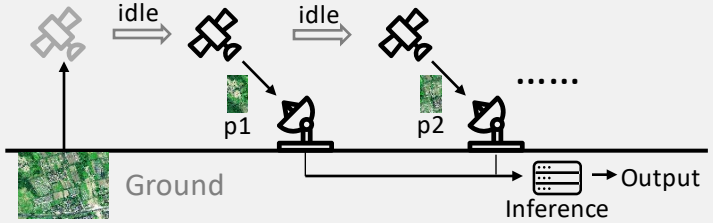


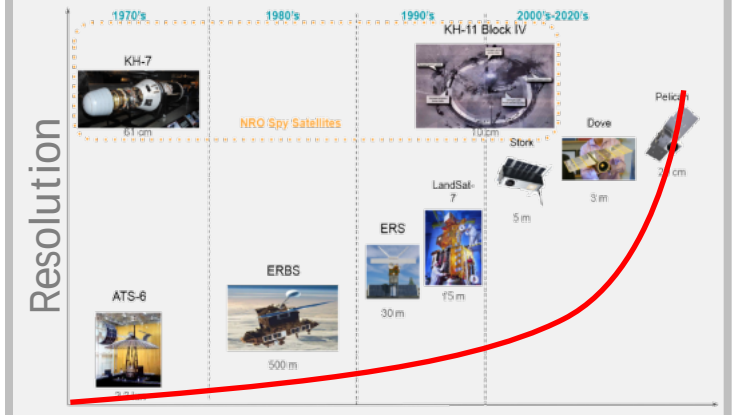
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

Data Source: Bleier, Nathaniel, et al. "Space microdatacenters." MICRO, 2023.

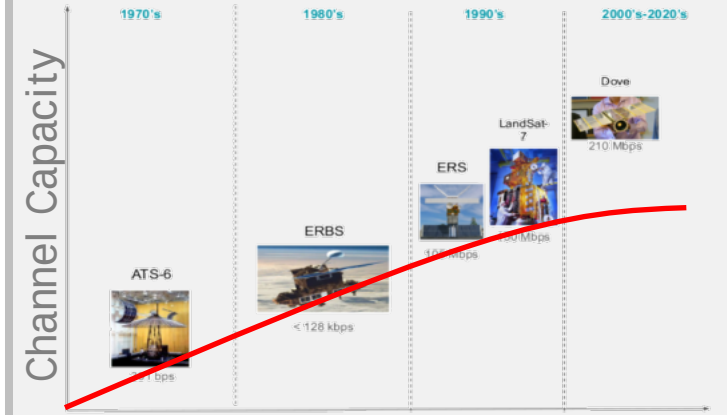
BG: Bent-Pipe Architecture

Bent-Pipe Architecture

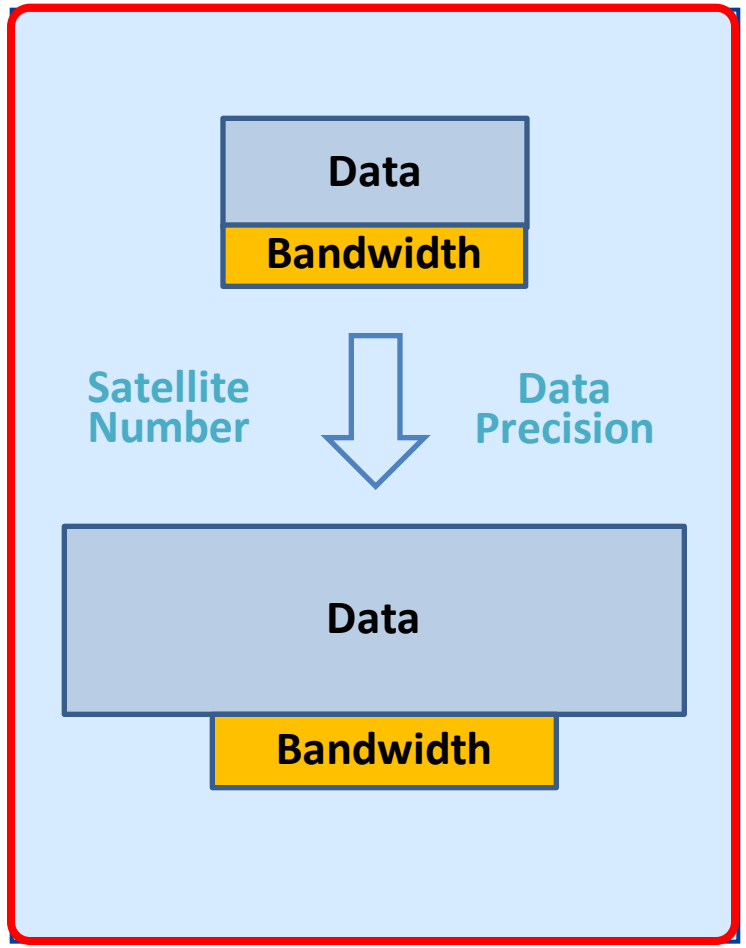




Data Precision Grow Fast



Bandwidth Grow Slow



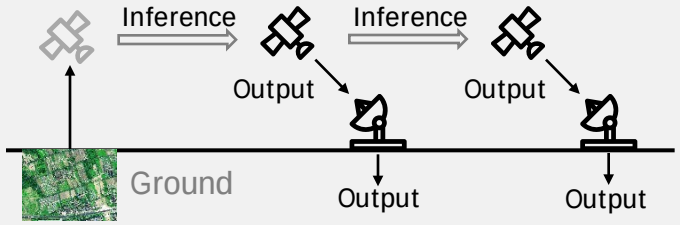
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

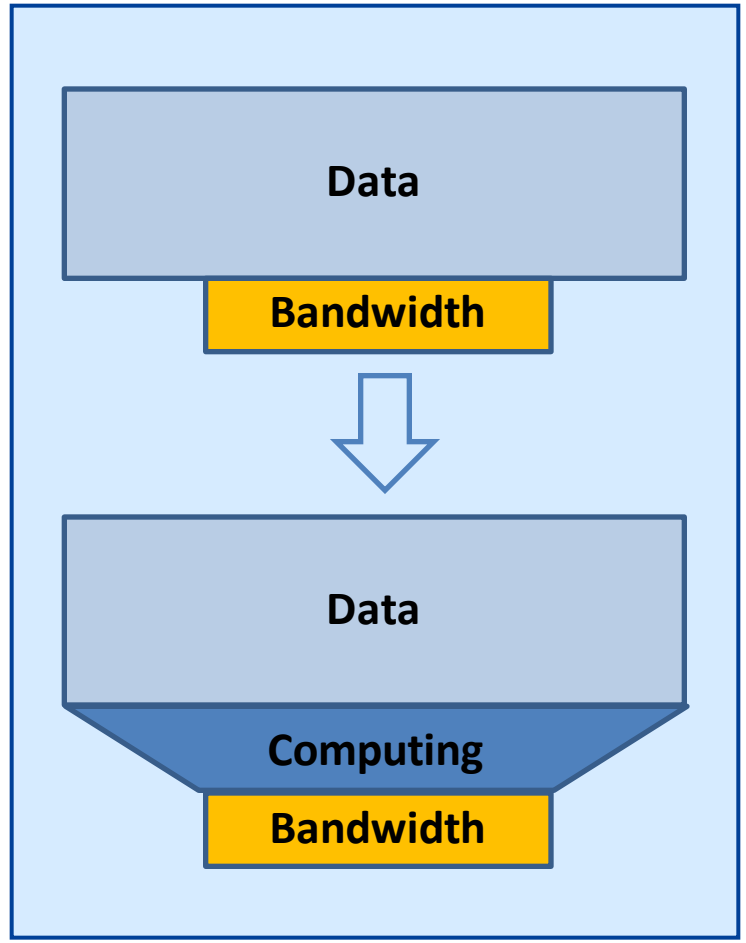
Data Source: Bleier, Nathaniel, et al. "Space microdatacenters." MICRO, 2023.

BG: Orbital Edge Computing (OEC)

Bent-Pipe Architecture

Orbital Edge Computing



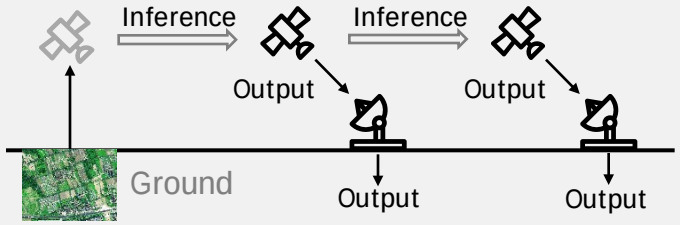


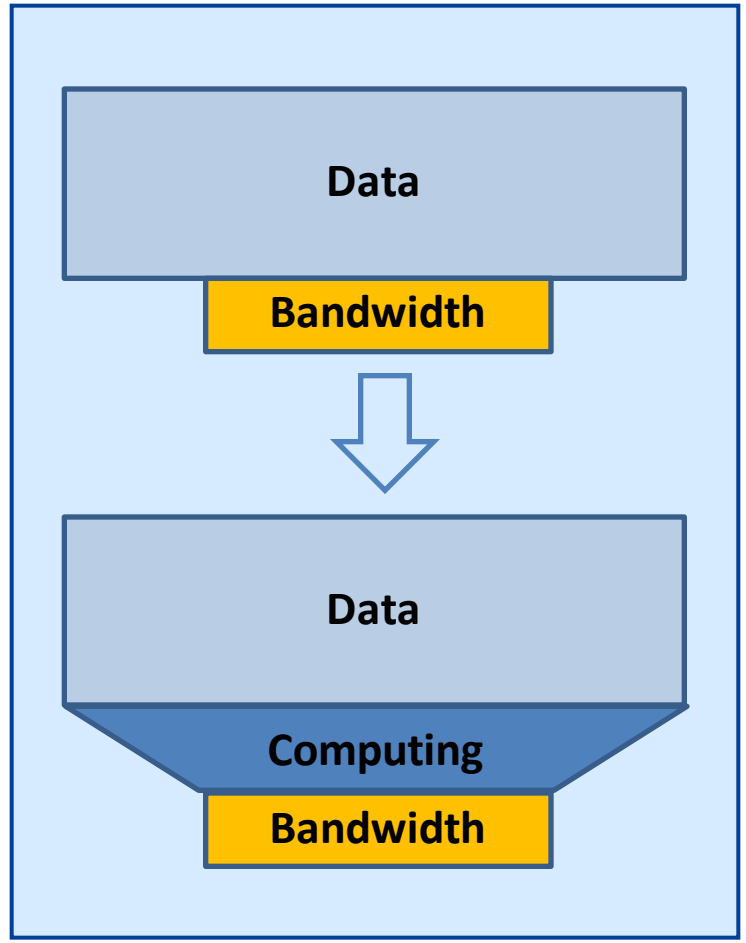
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

BG: Orbital Edge Computing (OEC)

Bent-Pipe Architecture

Orbital Edge Computing



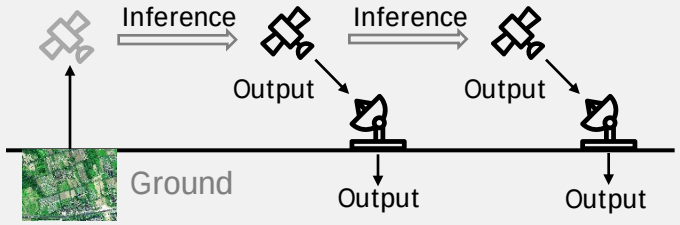


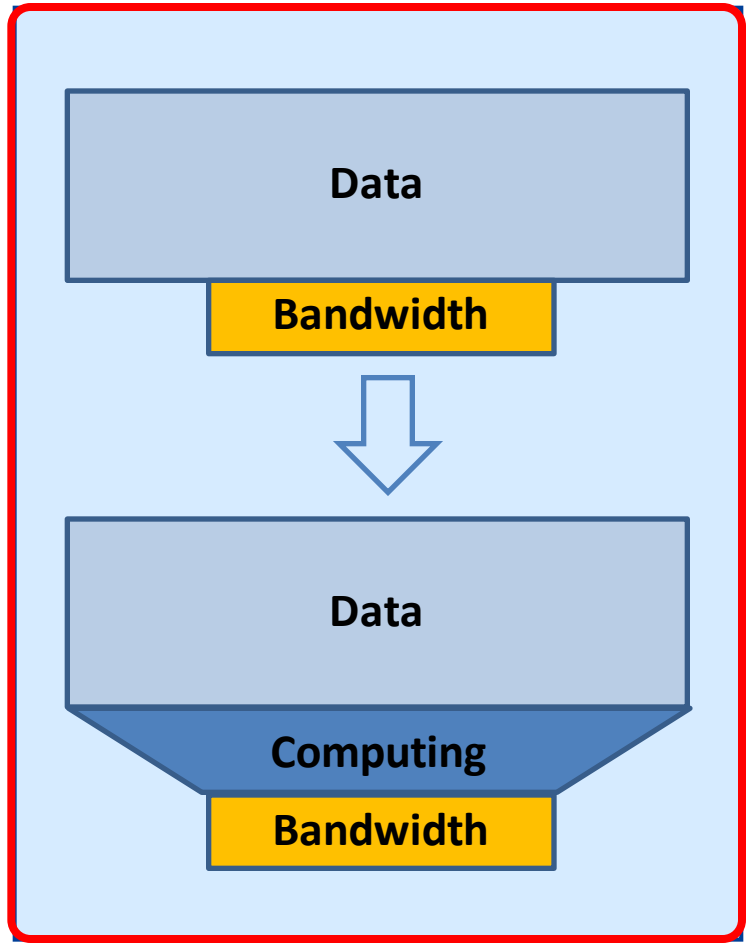
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

BG: Orbital Edge Computing (OEC)

Bent-Pipe Architecture

Orbital Edge Computing

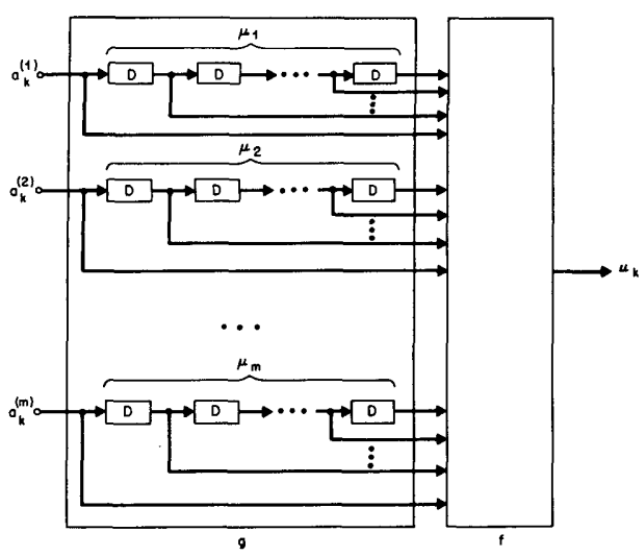




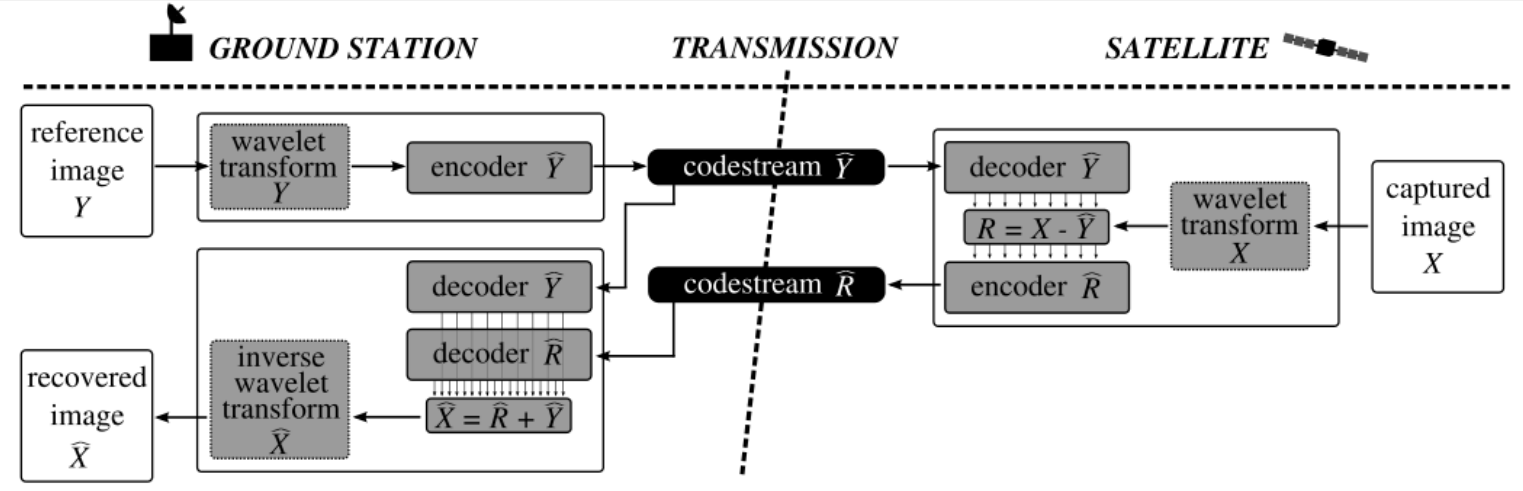
Bent-Pipe Struggle with Imbalanced Data-Bandwidth Growth

A Short Review of Satellite Downlink

Researchers Pursued Diverse Approaches in Related Fields



Coding for Nonlinear Satellite Channels[1]



Dual Link Image Coding[2]

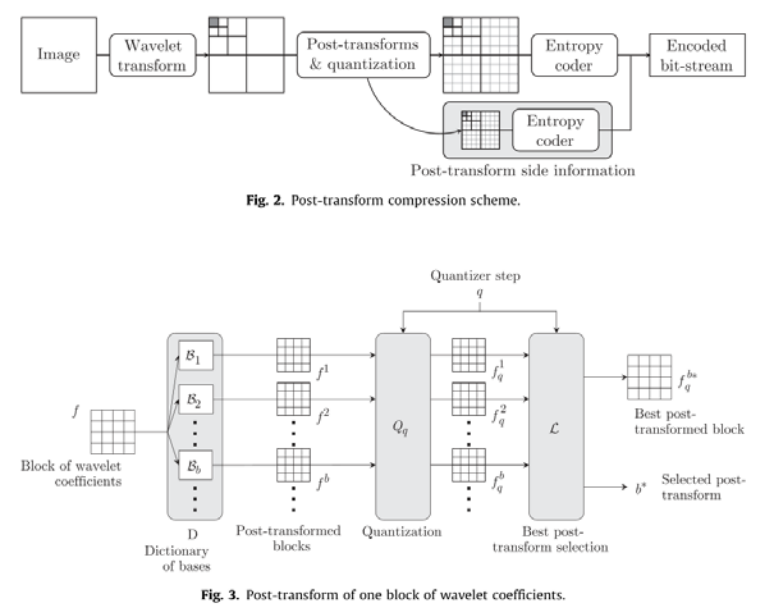
Transmission Coding | Image Compression | Orbital Edge Computing

[1] Biglieri E. TCOM, 1984.

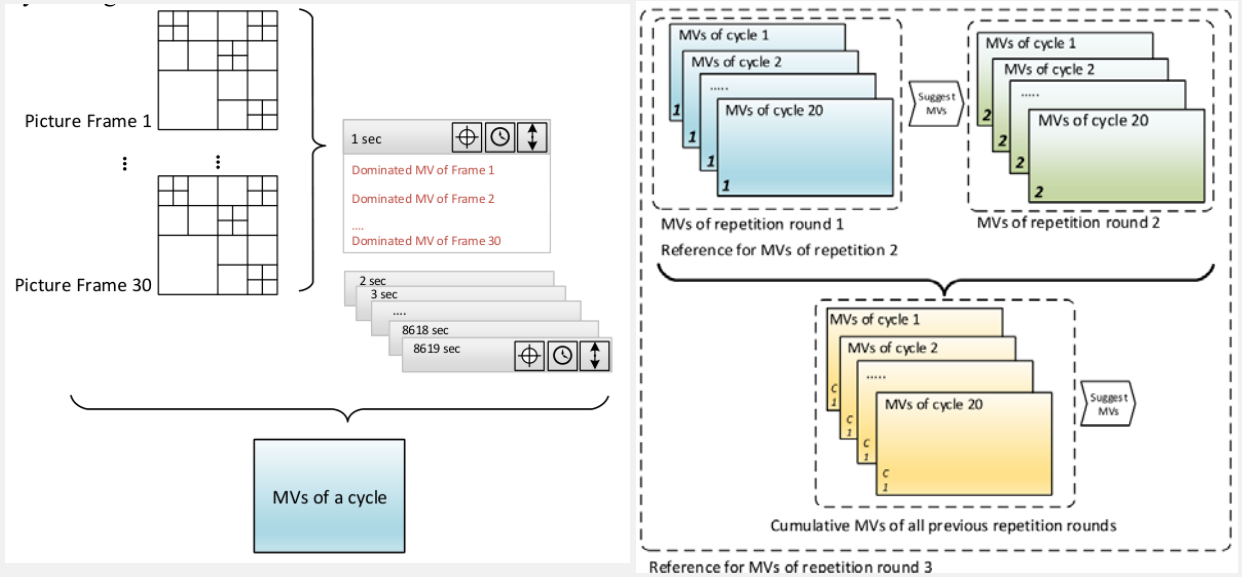
[2] Francesc Aulí-Llinàs, et al. TRGS, 2018

A Short Review of Satellite Downlink

Researchers Pursued Diverse Approaches in Related Fields



Compression by Post-Transforms[1]



Video Compression by Motion Estimation[2]

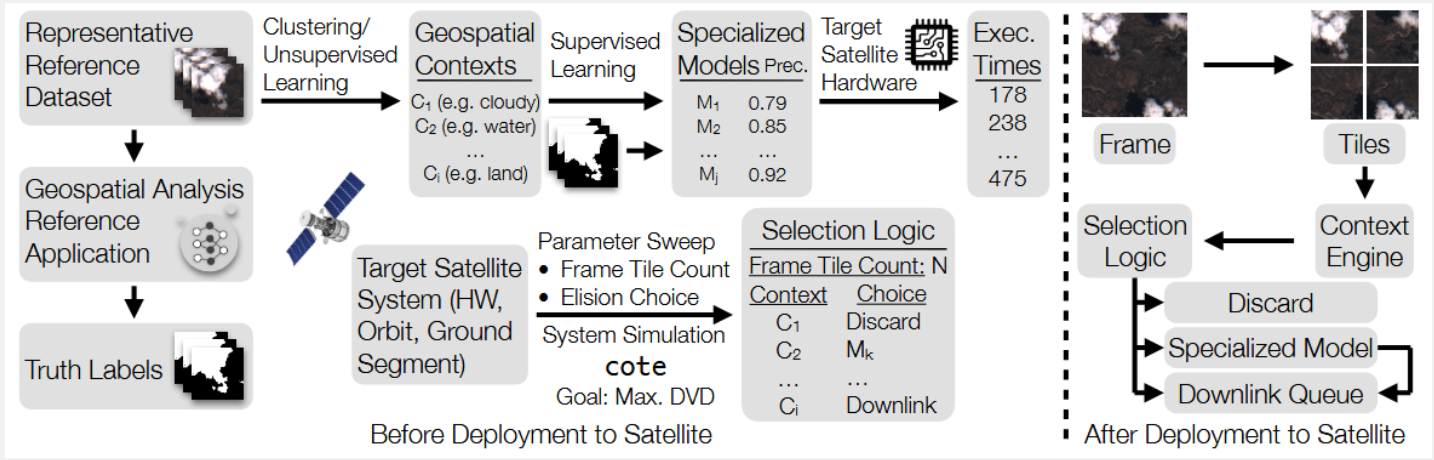
Transmission Coding | Image Compression | Orbital Edge Computing

[1] X. Delaunay, et al. Signal Processing, 2010.

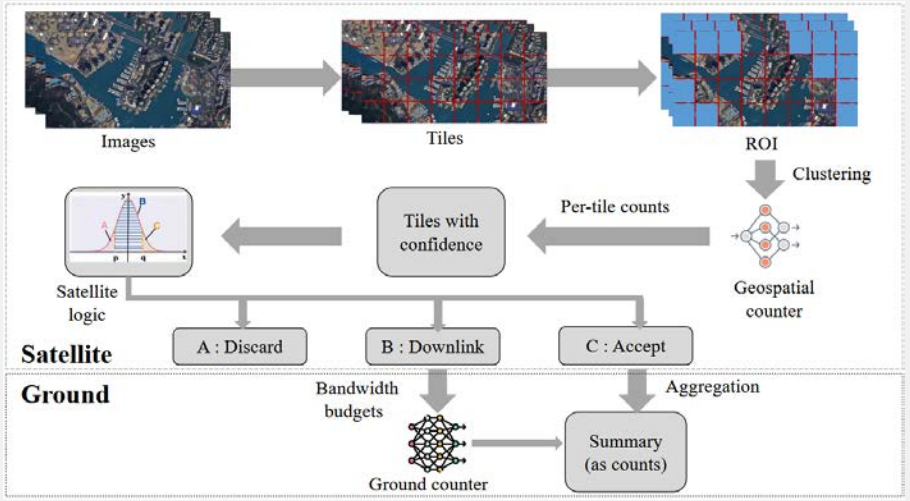
[2] Mohammadreza Bayat, et al. AeroConf, 2020.

A Short Review of Satellite Downlink

Researchers Pursued Diverse Approaches in Related Fields



Kodan: Solving Computational Bottleneck via Hardware-aware Modifications of Satellite Applications[1]



TargetFuse: Collaborative Satellite-Ground System [2]

Transmission Coding | Image Compression | Orbital Edge Computing

[1] Bradley Denby, et al. ASPLOS, 2023.

[2] Qiyang Zhang, et al. INFOCOM, 2024.

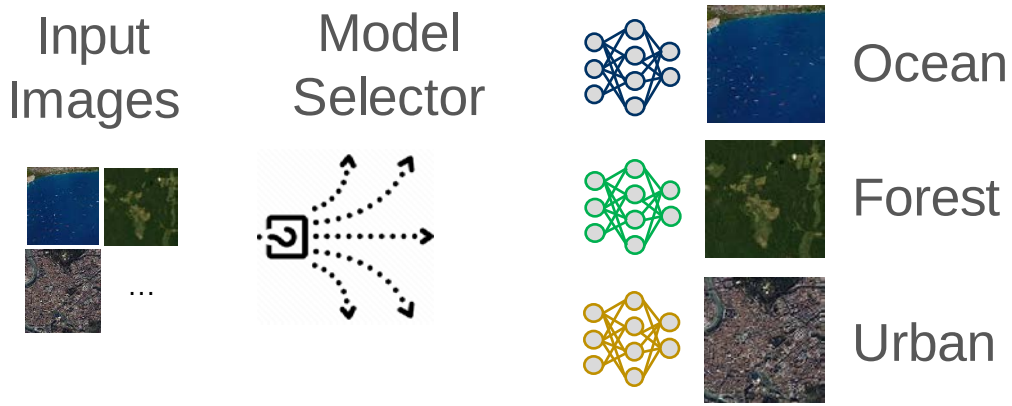
Motivation: Dynamic Scene Complexity

Satellites Encounter Dynamic Scene Complexity

Satellite-Specific Environment

- Severe Thermal Conditions
  e.g. -22°C to +77°C[1]
- Dynamic Communication Bandwidth
  e.g. 0 to 220 Mbps[2]
- Varying Complexity Workload
  e.g. ocean to urban scenes[3]

Multi-model System



Select Appropriate Models
Based on Geospatial Context[4]

Static multi-model system handles dynamic scenes.

[1] Casper Versteeg, et al. 2018.
[2] Starlink specifications – starlink [Online].
[3] Changhao Wu, et al. arXiv, 2023
[4] Denby Bradley, et al. ASPLOS, 2023

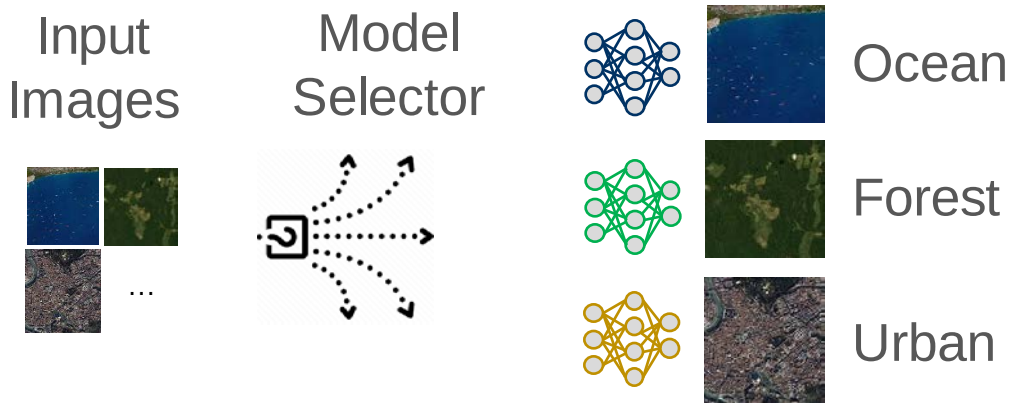
Motivation: Dynamic Scene Complexity

Satellites Encounter Dynamic Scene Complexity

Satellite-Specific Environment

- Severe Thermal Conditions
  e.g. -22°C to +77°C[1]
- Dynamic Communication Bandwidth
  e.g. 0 to 220 Mbps[2]
- Varying Complexity Workload
  e.g. ocean to urban scenes[3]

Multi-model System



Select Appropriate Models
Based on Geospatial Context[4]

Static multi-model system handles dynamic scenes.

[1] Casper Versteeg, et al. 2018.
[2] Starlink specifications – starlink [Online].
[3] Changhao Wu, et al. arXiv, 2023
[4] Denby Bradley, et al. ASPLOS, 2023

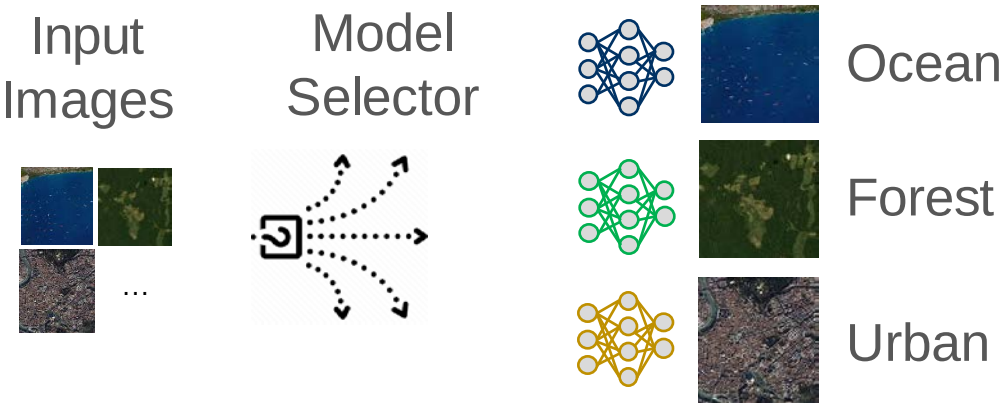
Motivation: Dynamic Scene Complexity

Satellites Encounter Dynamic Scene Complexity

Satellite-Specific Environment

- Severe Thermal Conditions
  e.g. -22°C to +77°C[1]
- Dynamic Communication Bandwidth
  e.g. 0 to 220 Mbps[2]
- Varying Complexity Workload
  e.g. ocean to urban scenes[3]

Multi-model System



Select Appropriate Models
Based on Geospatial Context[4]

Static multi-model system handles dynamic scenes.

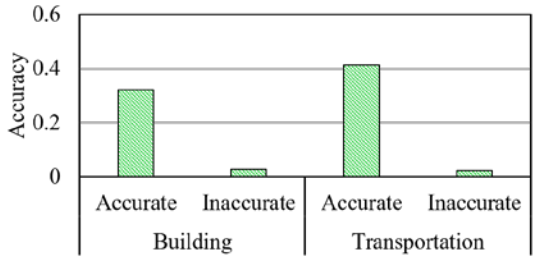
[1] Casper Versteeg, et al. 2018.
[2] Starlink specifications – starlink [Online].
[3] Changhao Wu, et al. arXiv, 2023
[4] Denby Bradley, et al. ASPLOS, 2023

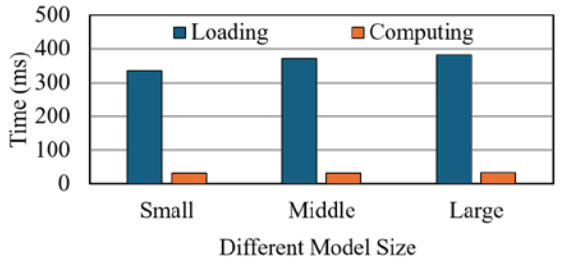
Motivation: Dynamic Scene Complexity

Static Methods may Falter with Complex Scene

Drawbacks of Static Method

Use Static Multi-model System





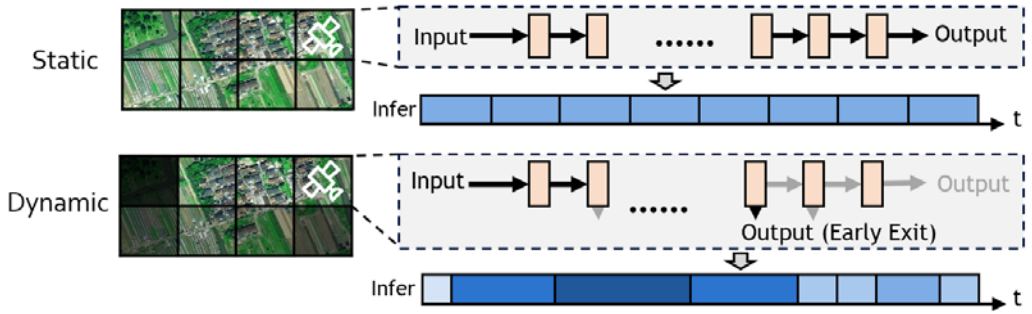
Vulnerability of reliance on prior knowledge

Long loading time

How Adaptive Method Work

Performing Early Exit for Simple Images

Full Processing for Complex Images



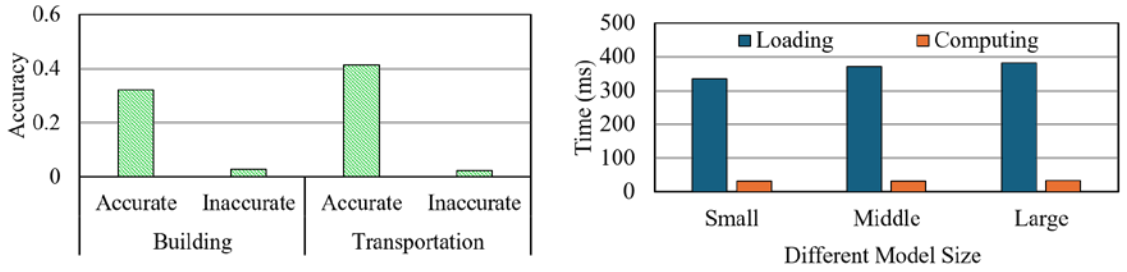
We need adaptive OEC for rapid changing environment.

Motivation: Dynamic Scene Complexity

Static Methods may Falter with Complex Scene

Drawbacks of Static Method

Use Static Multi-model System



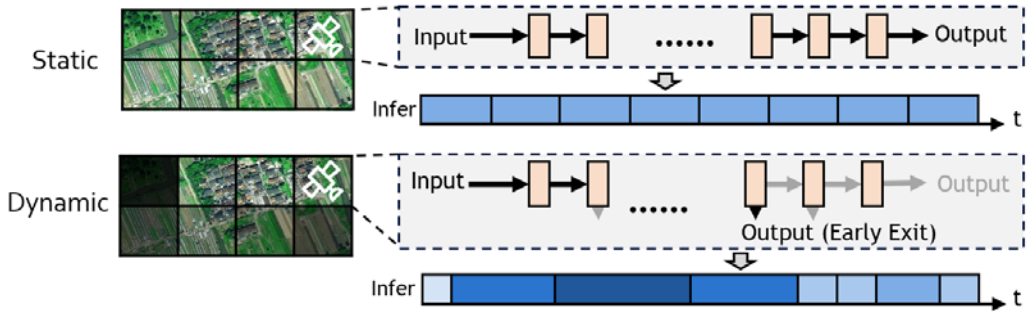
Vulnerability of reliance on prior knowledge

Long loading time

How Adaptive Method Work

Performing Early Exit for Simple Images

Full Processing for Complex Images



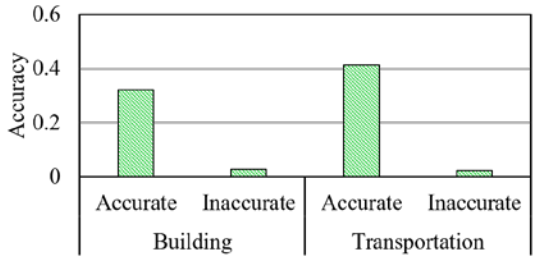
We need adaptive OEC for rapid changing environment.

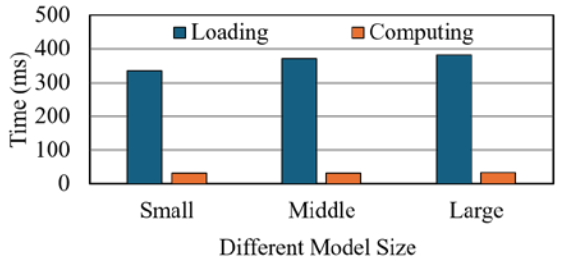
Motivation: Dynamic Scene Complexity

Static Methods may Falter with Complex Scene

Drawbacks of Static Method

Use Static Multi-model System





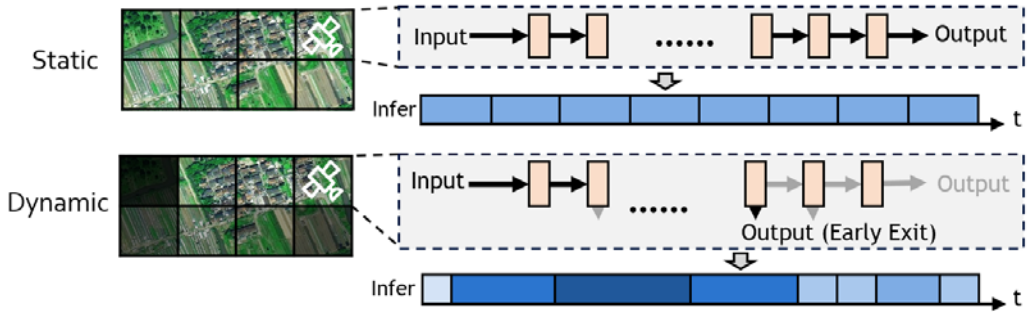
Vulnerability of reliance on prior knowledge

Long loading time

How Adaptive Method Work

Performing Early Exit for Simple Images

Full Processing for Complex Images



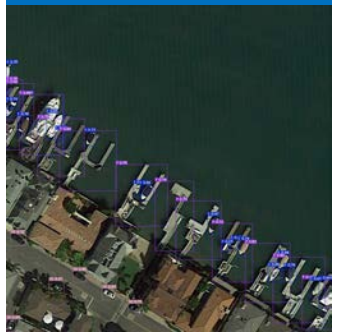
We need adaptive OEC for rapid changing environment.

Challenge: From Algorithm to System

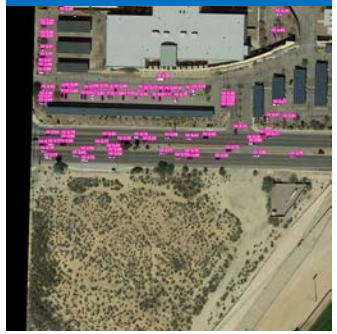
Algorithm and System Challenges in Adaptive Implementation

Multi-scale info. & Geo. context

Ocean(easy)



Land(hard)



Visual and geospatial context influence complexity.

Hetero. devices

Jetson Nano

472GFLOPS/10W

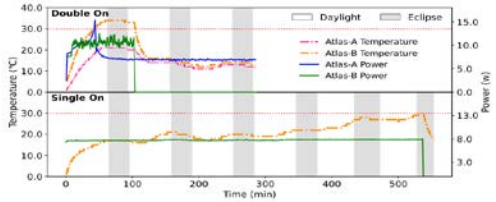
Jetson Xavier NX

21TFLOPS/20W

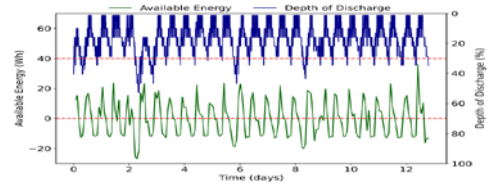
Task scheduling is crucial in heterogeneous system.

Runtime resource

Sensitive Thermal Condition



Limited Power Budget



Power and thermal budget impact processing system.[1]

We need an algorithm-system co-design to tackle challenges.

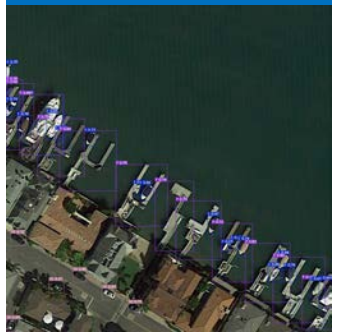
[1] Ruolin Xing et al. ACM MobiCom '24: 30th Annual International Conference on Mobile Computing and Networking, 2024.

Challenge: From Algorithm to System

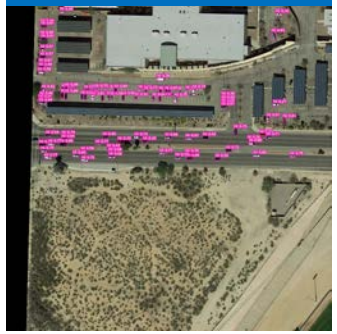
Algorithm and System Challenges in Adaptive Implementation

Multi-scale info. & Geo. context

Ocean(easy)



Land(hard)



Visual and geospatial context influence complexity.

Hetero. devices

Jetson Nano

472GFLOPS/10W

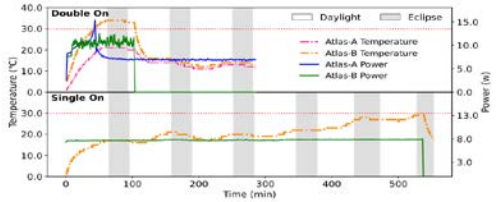
Jetson Xavier NX

21TFLOPS/20W

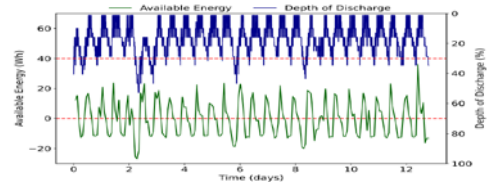
Task scheduling is crucial in heterogeneous system.

Runtime resource

Sensitive Thermal Condition



Limited Power Budget



Power and thermal budget impact processing system.[1]

We need an algorithm-system co-design to tackle challenges.

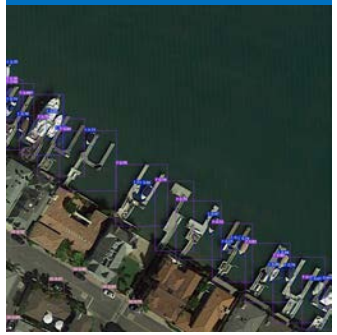
[1] Ruolin Xing et al. ACM MobiCom '24: 30th Annual International Conference on Mobile Computing and Networking, 2024.

Challenge: From Algorithm to System

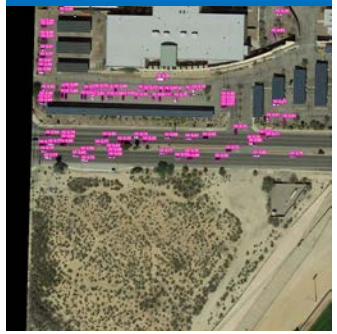
Algorithm and System Challenges in Adaptive Implementation

Multi-scale info. & Geo. context

Ocean(easy)



Land(hard)



Visual and geospatial context influence complexity.

Hetero. devices

Jetson Nano

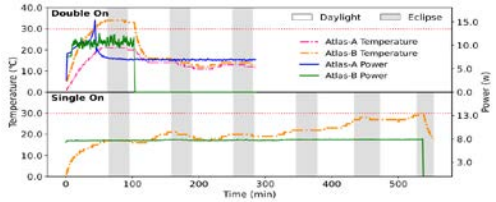
Jetson Xavier NX

472GFLOPS/10W 21TFLOPS/20W

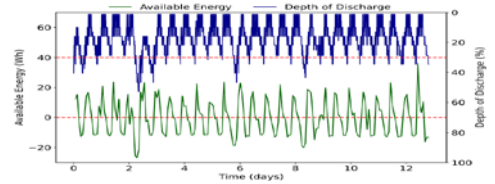
Task scheduling is crucial in heterogeneous system.

Runtime resource

Sensitive Thermal Condition



Limited Power Budget



Power and thermal budget impact processing system.[1]

We need an algorithm-system co-design to tackle challenges.

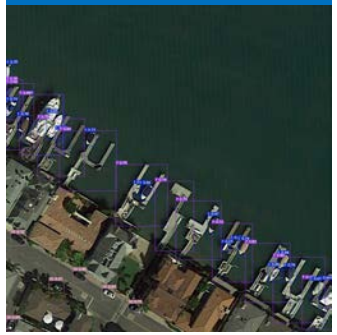
[1] Ruolin Xing et al. ACM MobiCom '24: 30th Annual International Conference on Mobile Computing and Networking, 2024.

Challenge: From Algorithm to System

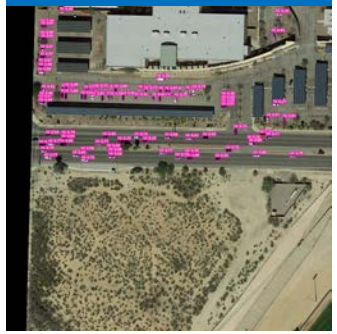
Algorithm and System Challenges in Adaptive Implementation

Multi-scale info. & Geo. context

Ocean(easy)



Land(hard)



Visual and geospatial context influence complexity.

Hetero. devices

Jetson Nano

472GFLOPS/10W

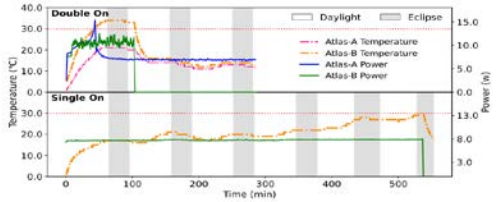
Jetson Xavier NX

21TFLOPS/20W

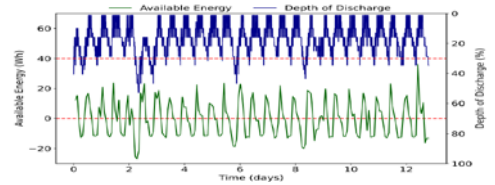
Task scheduling is crucial in heterogeneous system.

Runtime resource

Sensitive Thermal Condition



Limited Power Budget



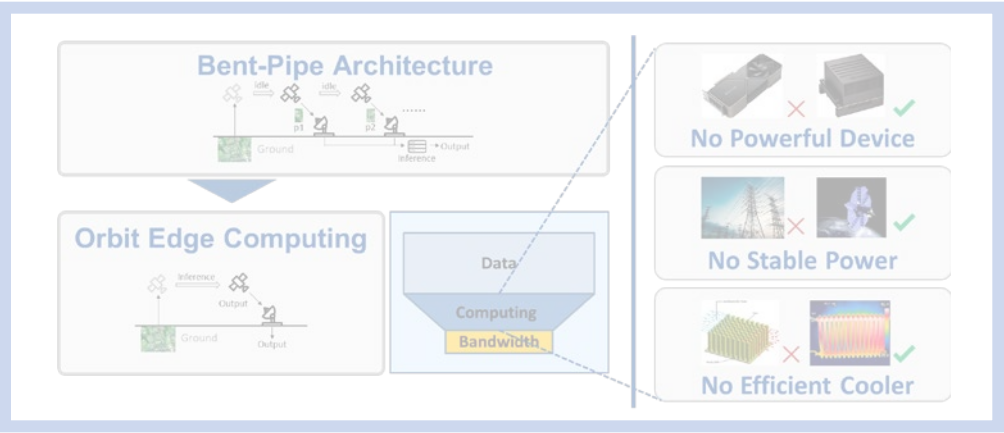
Power and thermal budget impact processing system.[1]

We need an algorithm-system co-design to tackle challenges.

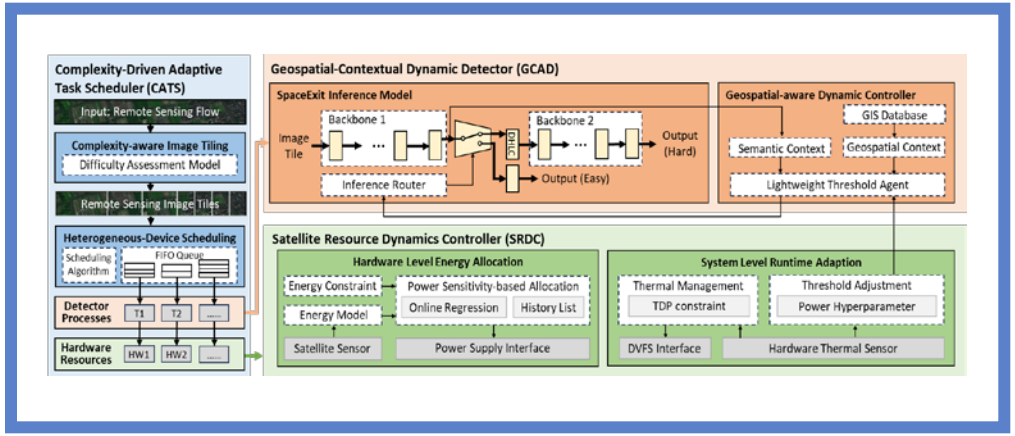
[1] Ruolin Xing et al. ACM MobiCom '24: 30th Annual International Conference on Mobile Computing and Networking, 2024.

Content

1. Background & Motivation



2. System Design



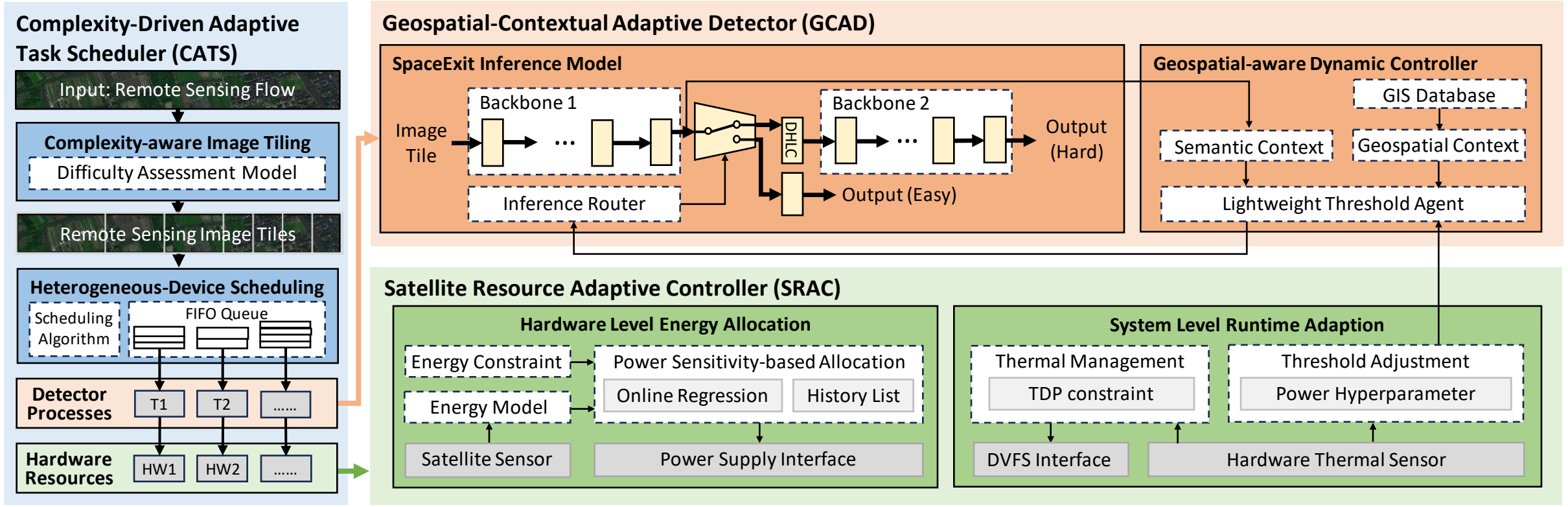
3. Workflow & Evaluation

5.2%-37.6% improvement

4. Conclusion

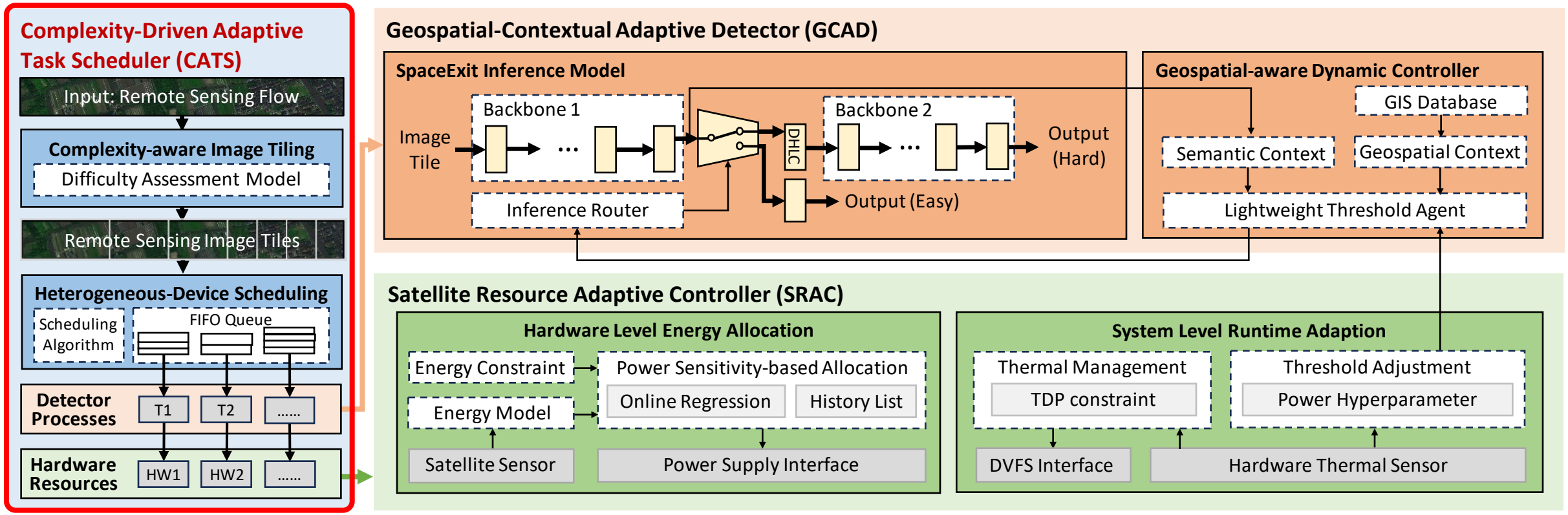
- We embrace OEC (Orbit Edge Computing), which is emerging as a solution to imbalanced data-bandwidth growth.
- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.
- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

SpaceExit Overview



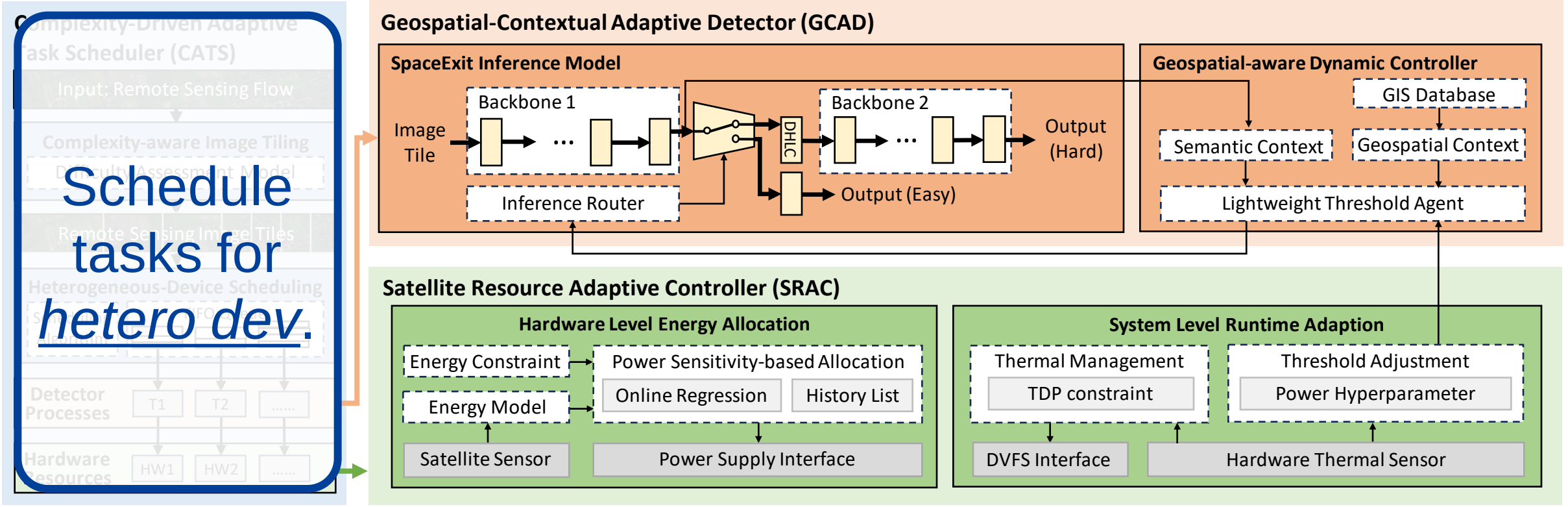
***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview



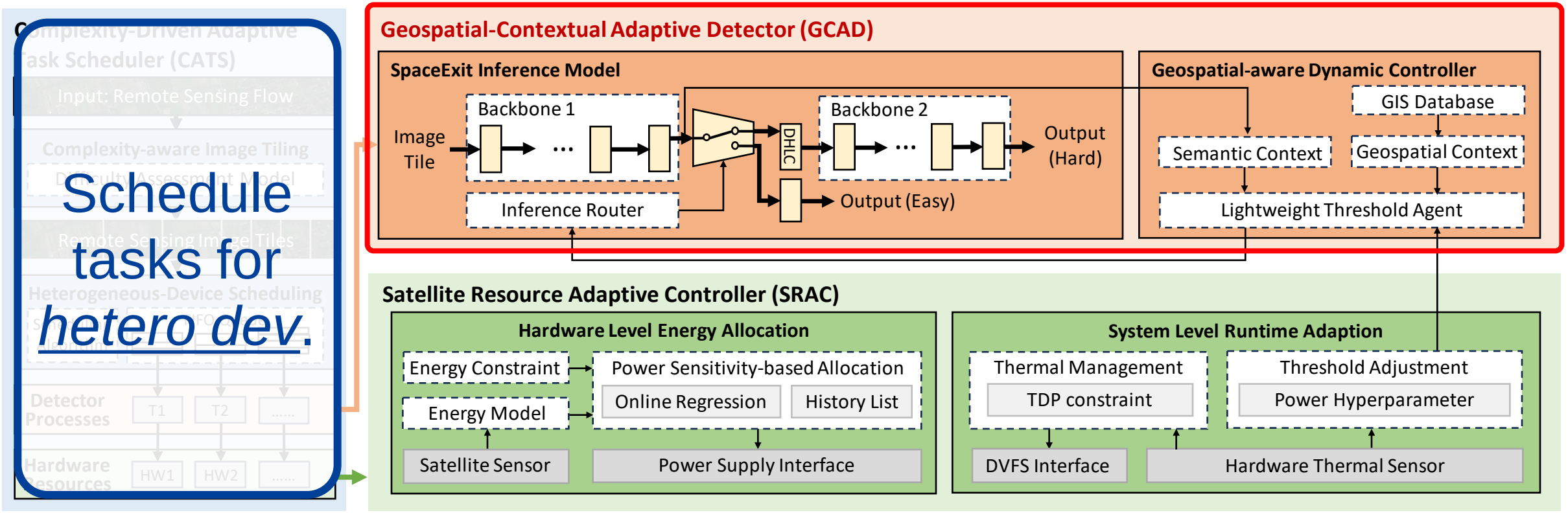
***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview



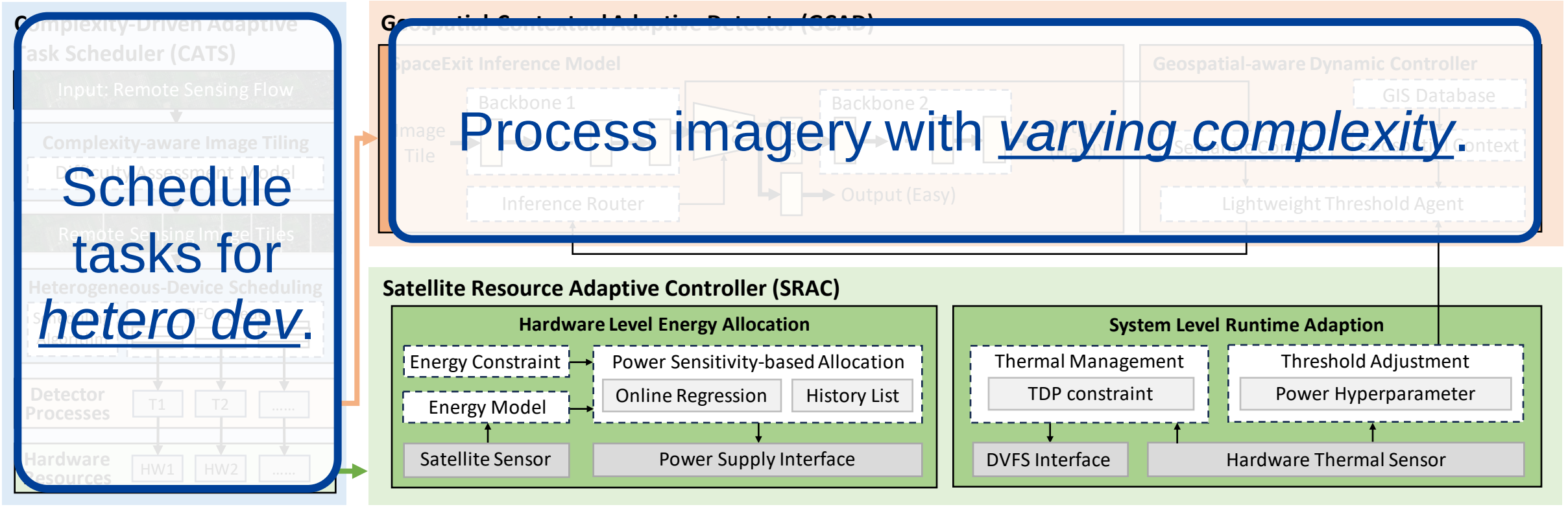
***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview



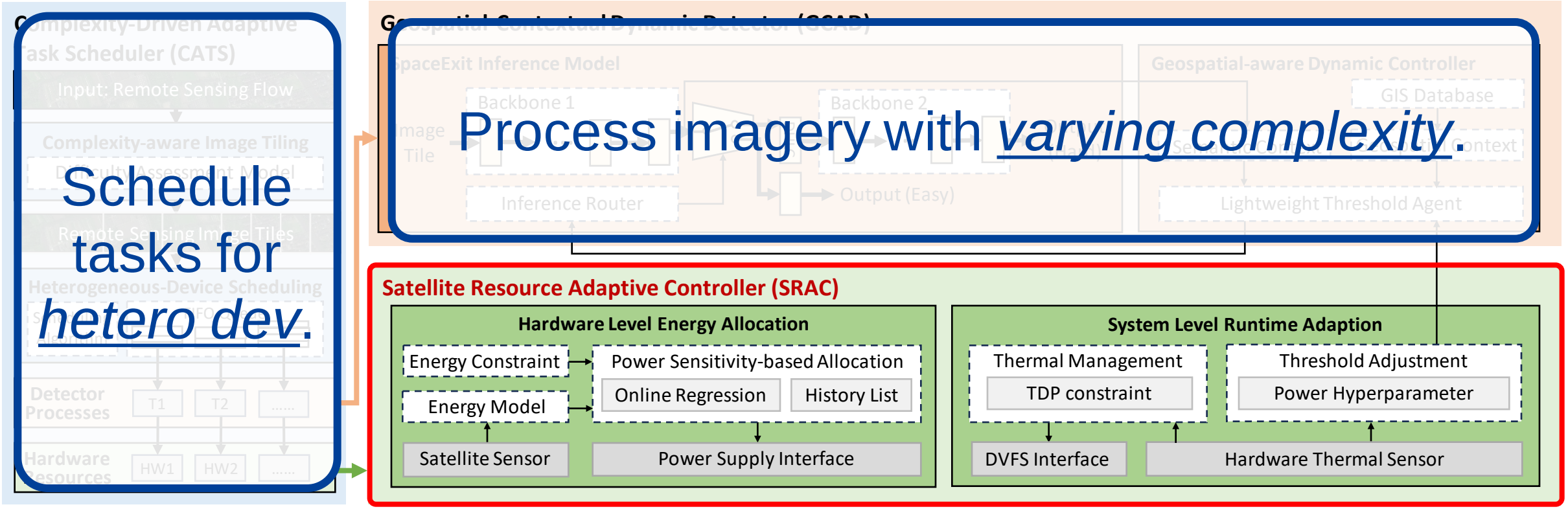
***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview



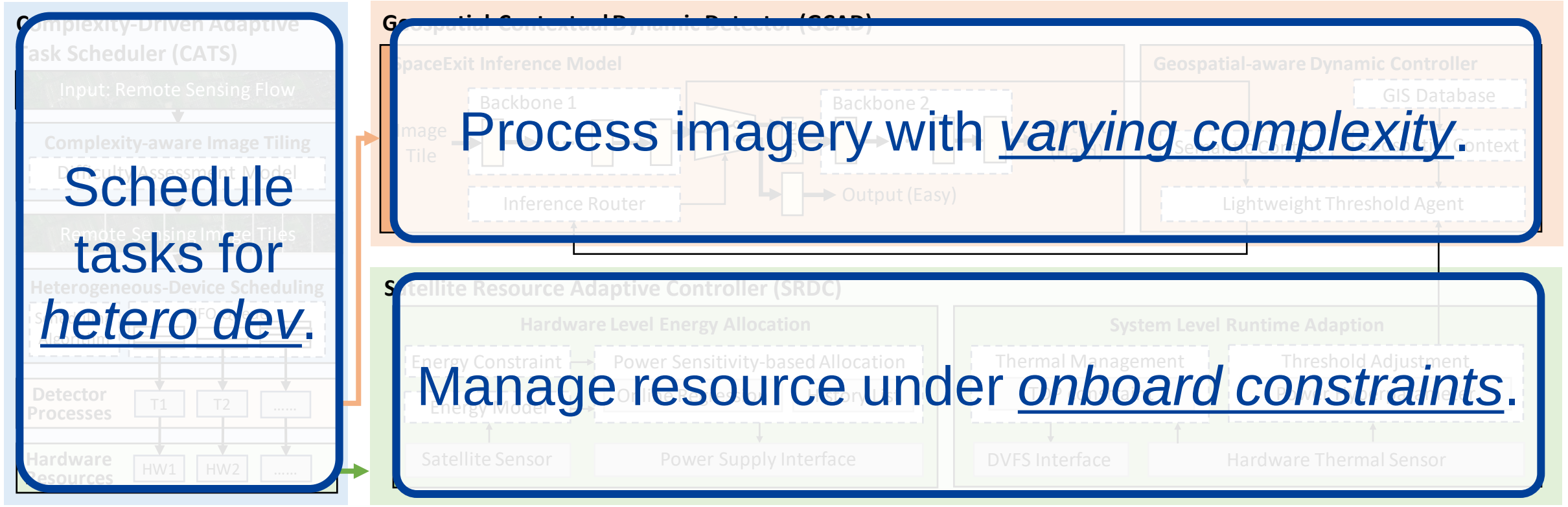
***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview



***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Overview

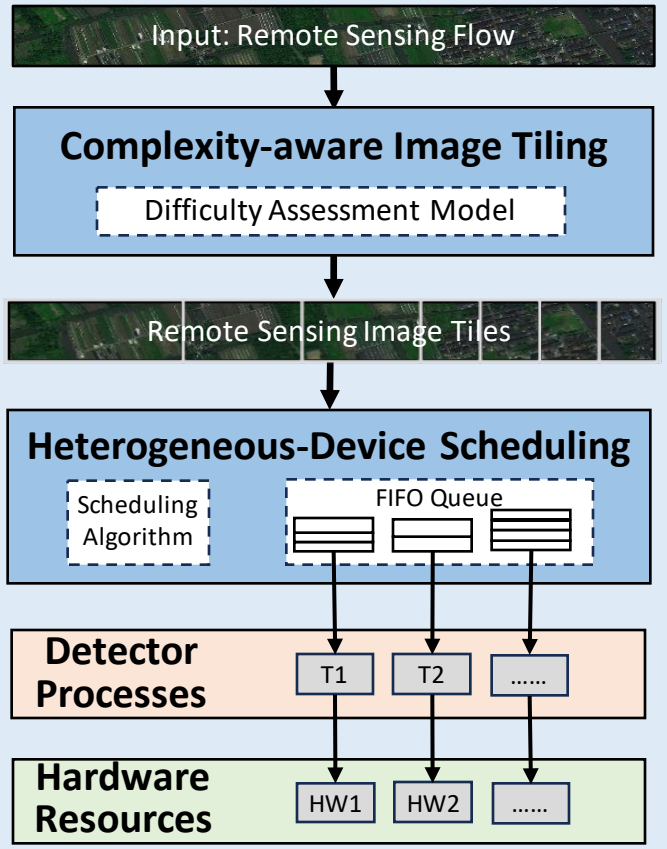


***SpaceExit* Optimize Detection Pipeline via Algo-System Co-design**

SpaceExit Subsystem: CATS

Schedule tasks for heterogeneous devices: CATS

Complexity-Driven Adaptive Task Scheduler (CATS)



Simple Network to Assess Difficulty

Input image → difficulty d_t

Complexity-aware Image Tiling Module Output Tiles

$$w_t = h_t = \frac{w_{base}}{\sqrt{d_t}}$$

Scheduling Module Assign Tiles to Hetero Devices

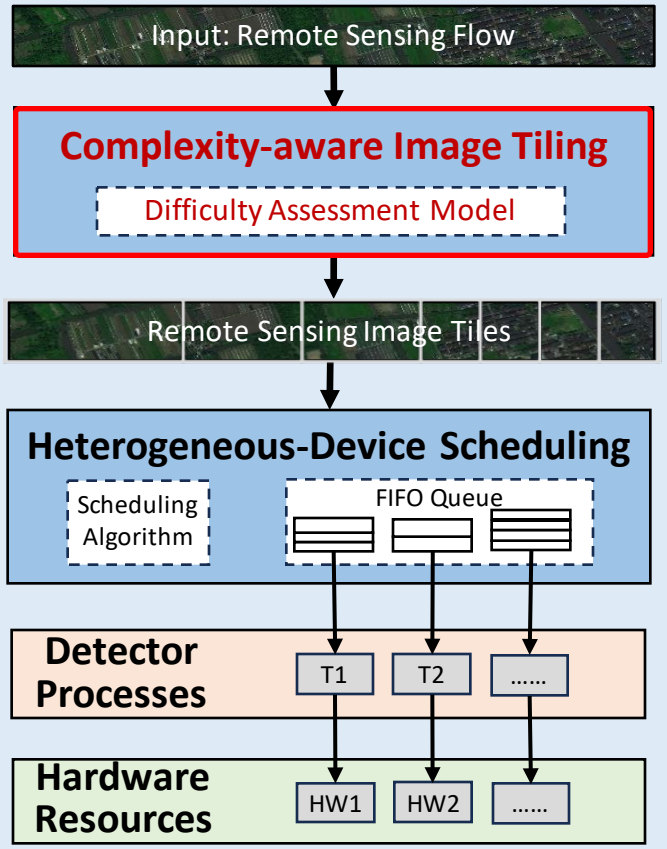
$$Q_{\sigma(i)} = Q_{\sigma(i)} \cup \{r\}$$

$$\sigma(i) = \arg\min_j \left\{ \frac{n_j}{v_j} \mid j \in [1, N], |Q_j| < K_j \right\}$$

SpaceExit Subsystem: CATS

Schedule tasks for heterogeneous devices: CATS

Complexity-Driven Adaptive Task Scheduler (CATS)



Simple Network to Assess Difficulty

Input image → difficulty d_t

Complexity-aware Image Tiling Module Output Tiles

$$w_t = h_t = \frac{w_{base}}{\sqrt{d_t}}$$

Scheduling Module Assign Tiles to Hetero Devices

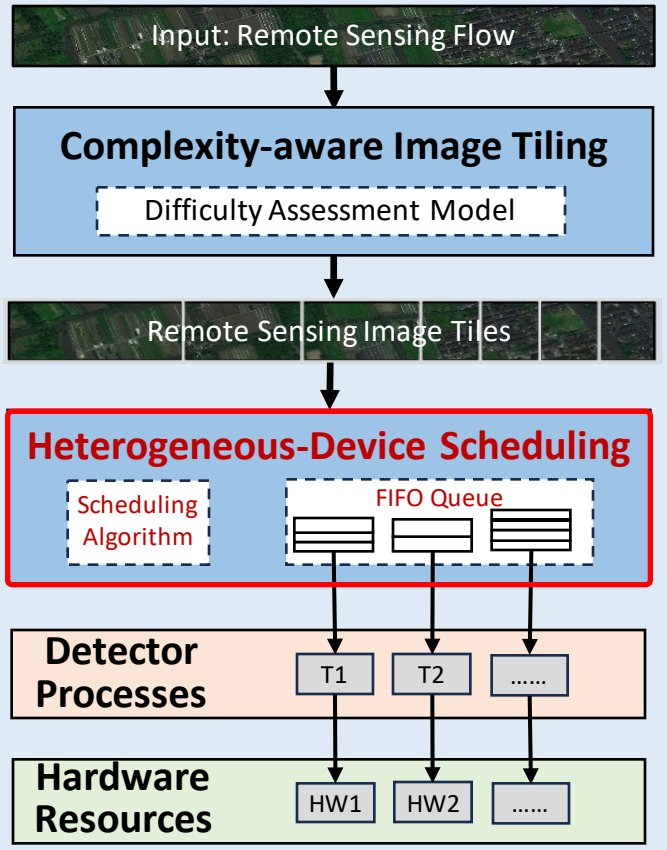
$$Q_{\sigma(i)} = Q_{\sigma(i)} \cup \{r\}$$

$$\sigma(i) = \arg\min_j \left\{ \frac{n_j}{v_j} \mid j \in [1, N], |Q_j| < K_j \right\}$$

SpaceExit Subsystem: CATS

Schedule tasks for heterogeneous devices: CATS

Complexity-Driven Adaptive Task Scheduler (CATS)



Simple Network to Assess Difficulty

Input image → difficulty d_t

Complexity-aware Image Tiling Module Output Tiles

$$w_t = h_t = \frac{w_{base}}{\sqrt{d_t}}$$

Scheduling Module Assign Tiles to Hetero Devices

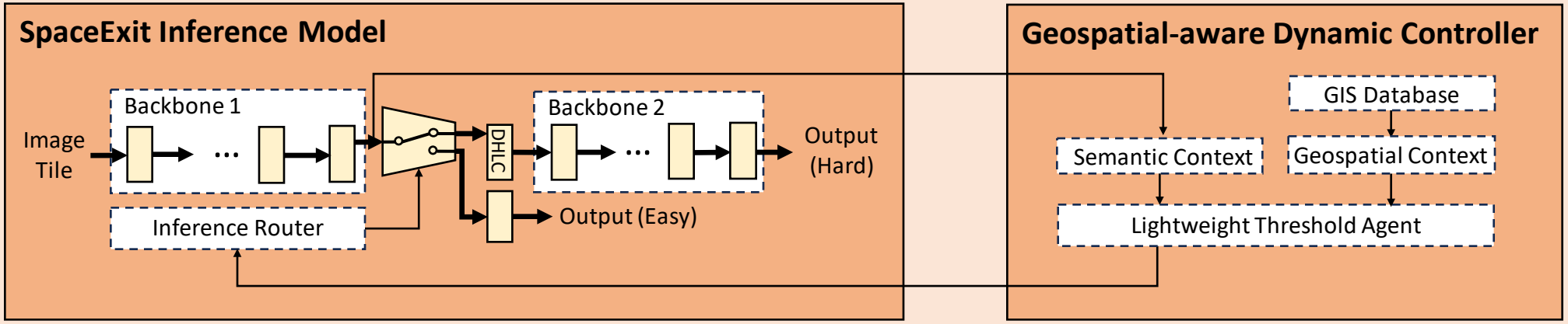
$$Q_{\sigma(i)} = Q_{\sigma(i)} \cup \{r\}$$

$$\sigma(i) = \arg\min_j \left\{ \frac{n_j}{v_j} \mid j \in [1, N], |Q_j| < K_j \right\}$$

SpaceExit Subsystem: GCAD

Process imagery with varying complexity: GCAD

Geospatial-Contextual Adaptive Detector (GCAD)



Multiscale Backbone to Capture Features

$$f_{\mathbf{x}}^{L} = \mathcal{F}_L(\ldots \mathcal{F}_2(\mathcal{F}_1(\mathbf{x}))) \qquad \widetilde{F} = \|_{i=1}^{L} \mathcal{P}(f^i)$$

Inference Router to Decide Whether to Exit

$$u = \sigma\left(W_2\left(\delta\left(W_1 \widetilde{F} + b_1\right)\right) + b_2\right) \sim \tau_{val}$$

Agent to Fine-tune Threshold

semantic feature r

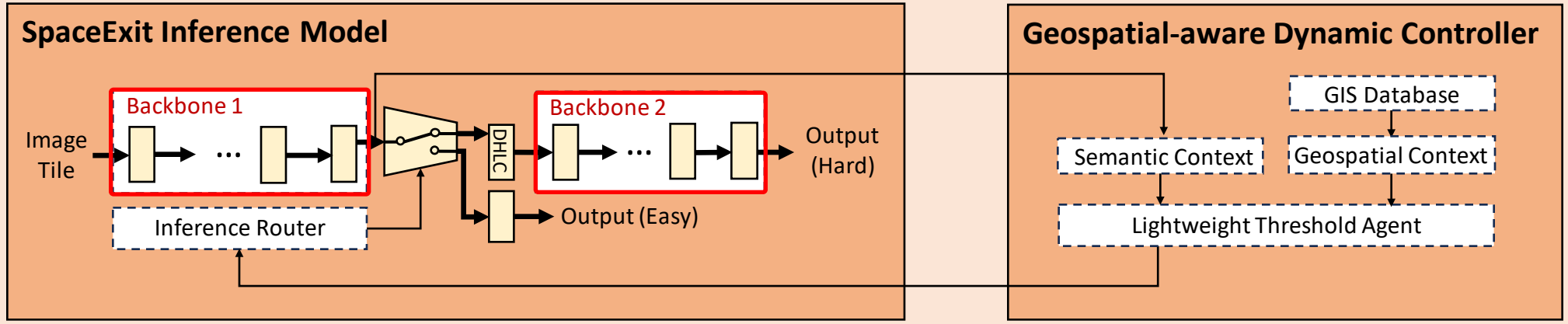
geospatial embedding g

$$\tau_{val} = \mathcal{P}(\mathcal{S}_{val}, k) + \Delta\tau$$

SpaceExit Subsystem: GCAD

Process imagery with varying complexity: GCAD

Geospatial-Contextual Adaptive Detector (GCAD)



Multiscale Backbone to Capture Features

$$f_{\mathbf{x}}^{L} = \mathcal{F}_L(\ldots \mathcal{F}_2(\mathcal{F}_1(\mathbf{x}))) \qquad \widetilde{F} = \|_{i=1}^{L} \mathcal{P}(f^i)$$

Inference Router to Decide Whether to Exit

$$u = \sigma\left(W_2\left(\delta\left(W_1 \widetilde{F} + b_1\right)\right) + b_2\right) \sim \tau_{val}$$

Agent to Fine-tune Threshold

semantic feature r

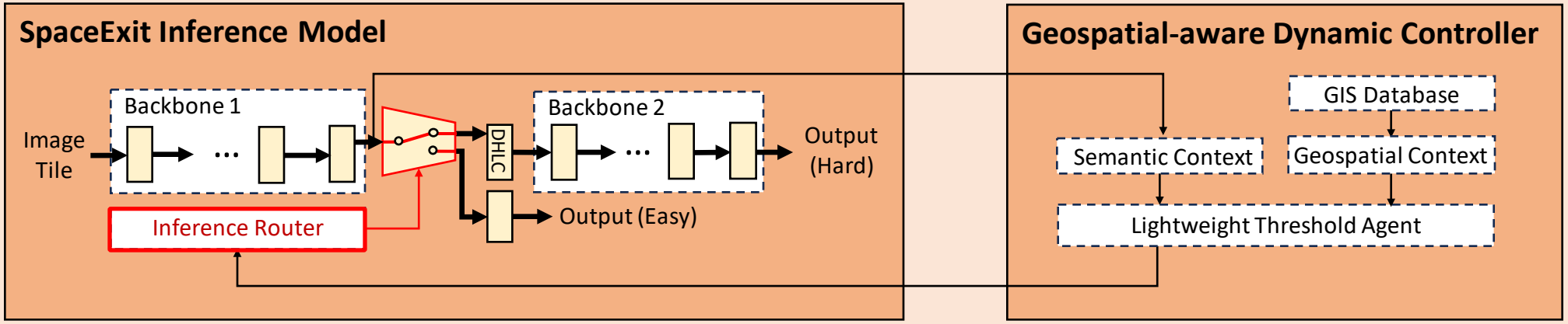
geospatial embedding g

$$\tau_{val} = \mathcal{P}(\mathcal{S}_{val}, k) + \Delta\tau$$

SpaceExit Subsystem: GCAD

Process imagery with varying complexity: GCAD

Geospatial-Contextual Adaptive Detector (GCAD)



Multiscale Backbone to Capture Features

$$f_{\mathbf{x}}^{L} = \mathcal{F}_L(\ldots \mathcal{F}_2(\mathcal{F}_1(\mathbf{x}))) \qquad \widetilde{F} = \|_{i=1}^{L} \mathcal{P}(f^i)$$

Inference Router to Decide Whether to Exit

$$u = \sigma\left(W_2\left(\delta\left(W_1 \widetilde{F} + b_1\right)\right) + b_2\right) \sim \tau_{val}$$

Agent to Fine-tune Threshold

semantic feature r

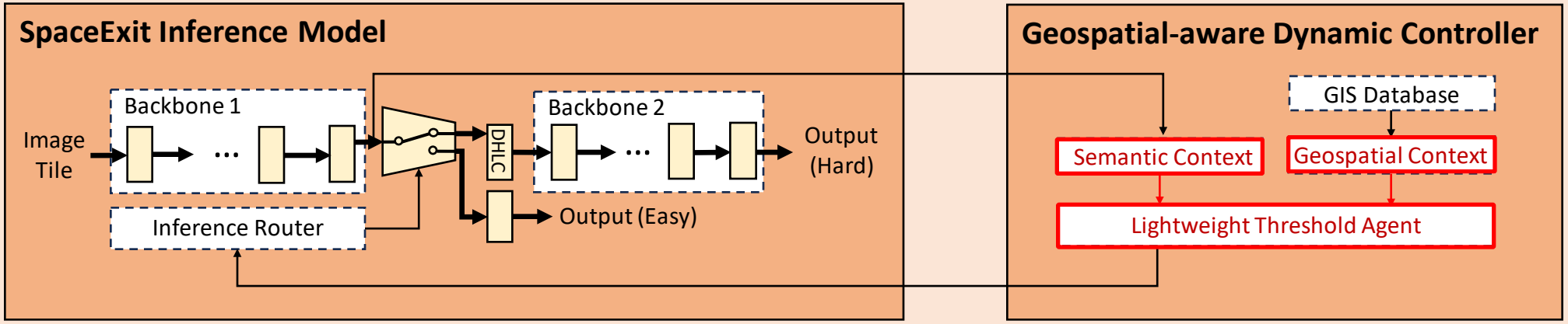
geospatial embedding g

$$\tau_{val} = \mathcal{P}(\mathcal{S}_{val}, k) + \Delta\tau$$

SpaceExit Subsystem: GCAD

Process imagery with varying complexity: GCAD

Geospatial-Contextual Adaptive Detector (GCAD)



Multiscale Backbone to Capture Features

$$f_{\mathbf{x}}^{L} = \mathcal{F}_L(\ldots \mathcal{F}_2(\mathcal{F}_1(\mathbf{x}))) \qquad \widetilde{F} = \|_{i=1}^{L} \mathcal{P}(f^i)$$

Inference Router to Decide Whether to Exit

$$u = \sigma\left(W_2\left(\delta\left(W_1 \widetilde{F} + b_1\right)\right) + b_2\right) \sim \tau_{val}$$

Agent to Fine-tune Threshold

semantic feature r

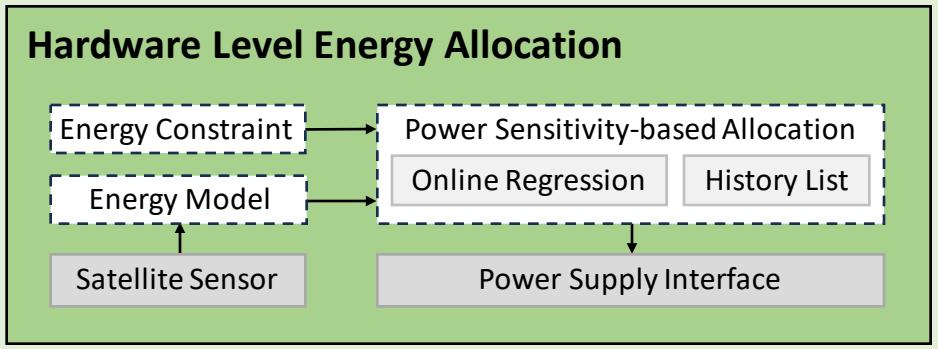
geospatial embedding g

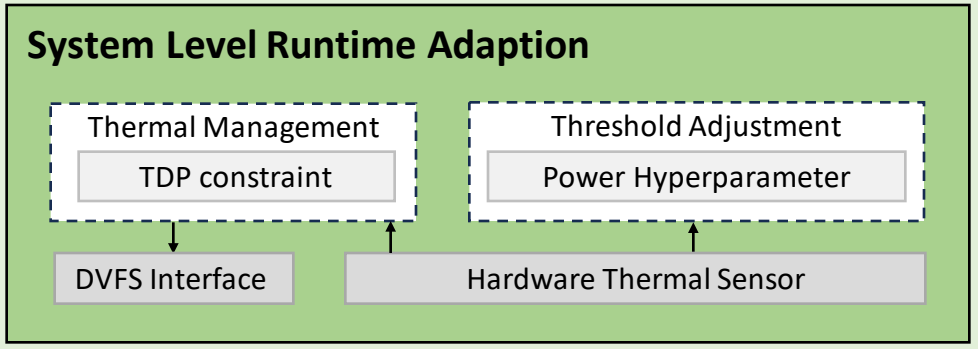
$$\tau_{val} = \mathcal{P}(\mathcal{S}_{val}, k) + \Delta\tau$$

SpaceExit Subsystem: SRAC

Manage resource under onboard constraints: SRAC

Satellite Resource Adaptive Controller (SRAC)





Energy Constraint for Allocation

$$\sum_{i=1}^{N} P_i(t) \le I(t)$$

Power Sensitivity-based Allocation

$$P_i(t) = P_{base,i} + (I(t) - P_{base}) \cdot \frac{\partial X_i / \partial P_i}{\sum_{j=1}^{N} \partial X_j / \partial P_j}$$

Thermal Management under TDP Constraint

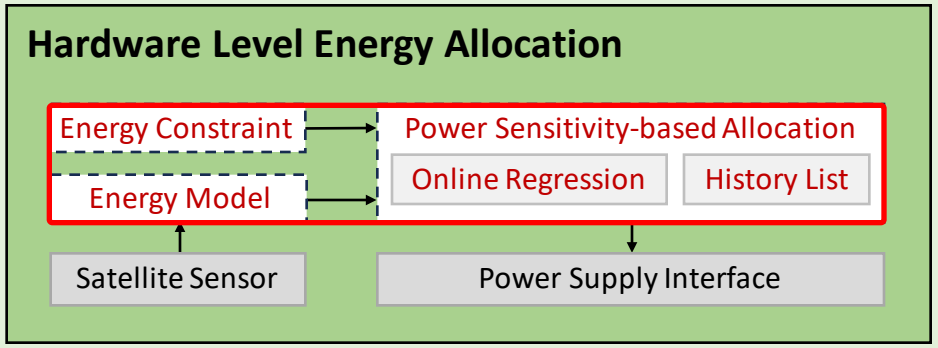
$$\Delta P = \frac{1}{\alpha}[T_{max} - T_i(t)] - [P_i(t) - \beta(T_i^4(t) - T_{amb}^4)]$$

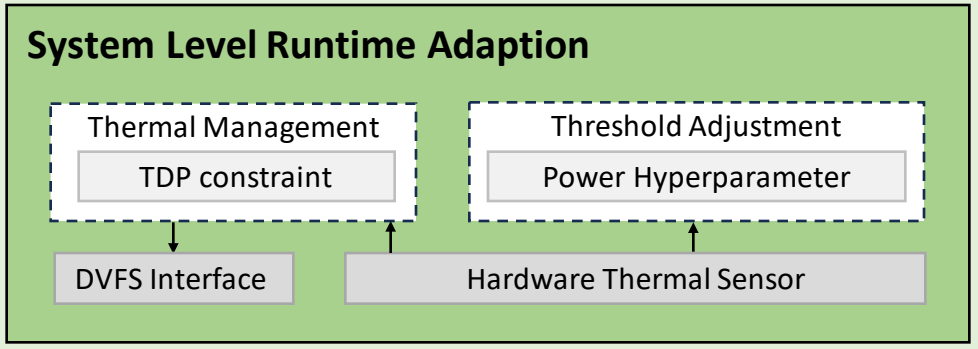
Threshold Adjustment for GCAD module

$$\tau = \tau_{base} \cdot \frac{\gamma P_{current}}{P_{nominal}}$$

Manage resource under onboard constraints: SRAC

Satellite Resource Adaptive Controller (SRAC)





Energy Constraint for Allocation

$$\sum_{i=1}^{N} P_i(t) \le I(t)$$

Power Sensitivity-based Allocation

$$P_i(t) = P_{base,i} + (I(t) - P_{base}) \cdot \frac{\partial X_i / \partial P_i}{\sum_{j=1}^{N} \partial X_j / \partial P_j}$$

Thermal Management under TDP Constraint

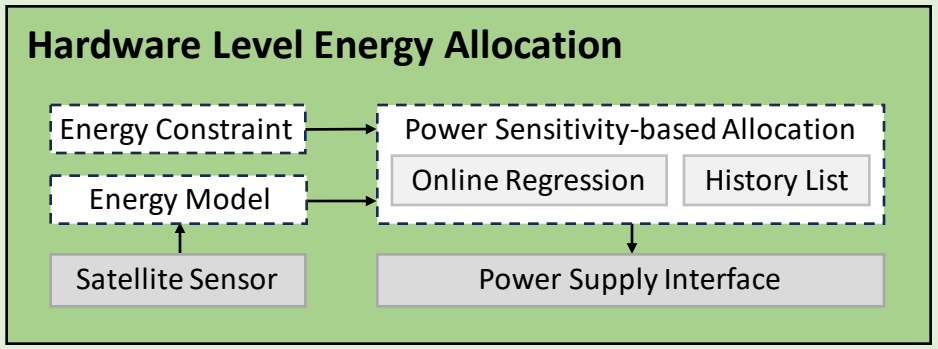
$$\Delta P = \frac{1}{\alpha}[T_{max} - T_i(t)] - [P_i(t) - \beta(T_i^4(t) - T_{amb}^4)]$$

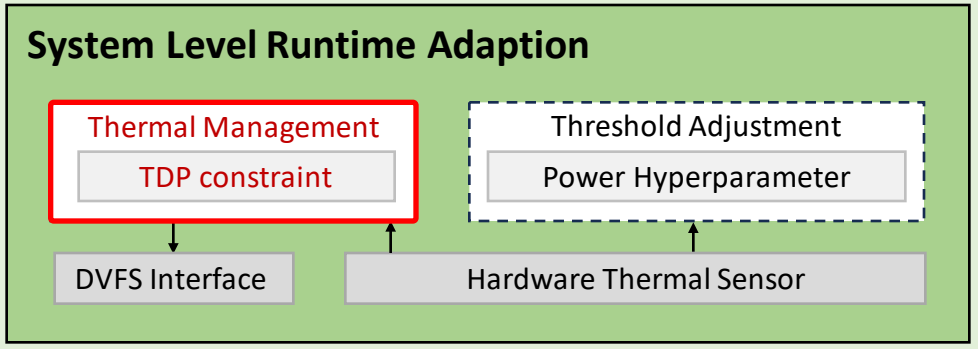
Threshold Adjustment for GCAD module

$$\tau = \tau_{base} \cdot \frac{\gamma P_{current}}{P_{nominal}}$$

Manage resource under onboard constraints: SRAC

Satellite Resource Adaptive Controller (SRAC)





Energy Constraint for Allocation

$$\sum_{i=1}^{N} P_i(t) \le I(t)$$

Power Sensitivity-based Allocation

$$P_i(t) = P_{base,i} + (I(t) - P_{base}) \cdot \frac{\partial X_i / \partial P_i}{\sum_{j=1}^{N} \partial X_j / \partial P_j}$$

Thermal Management under TDP Constraint

$$\Delta P = \frac{1}{\alpha}[T_{max} - T_i(t)] - [P_i(t) - \beta(T_i^4(t) - T_{amb}^4)]$$

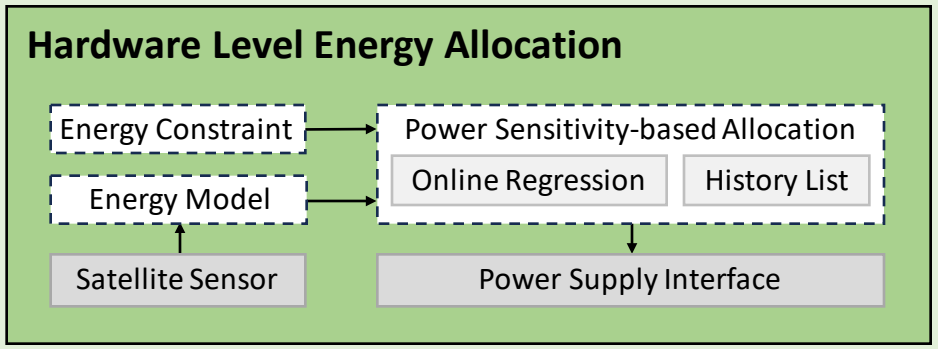
Threshold Adjustment for GCAD module

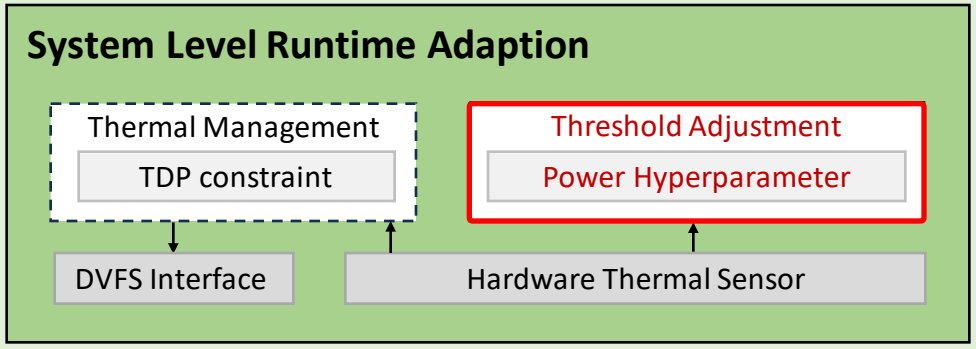
$$\tau = \tau_{base} \cdot \frac{\gamma P_{current}}{P_{nominal}}$$

SpaceExit Subsystem: SRAC

Manage resource under onboard constraints: SRAC

Satellite Resource Adaptive Controller (SRAC)





Energy Constraint for Allocation

$$\sum_{i=1}^{N} P_i(t) \le I(t)$$

Power Sensitivity-based Allocation

$$P_i(t) = P_{base,i} + (I(t) - P_{base}) \cdot \frac{\partial X_i / \partial P_i}{\sum_{j=1}^{N} \partial X_j / \partial P_j}$$

Thermal Management under TDP Constraint

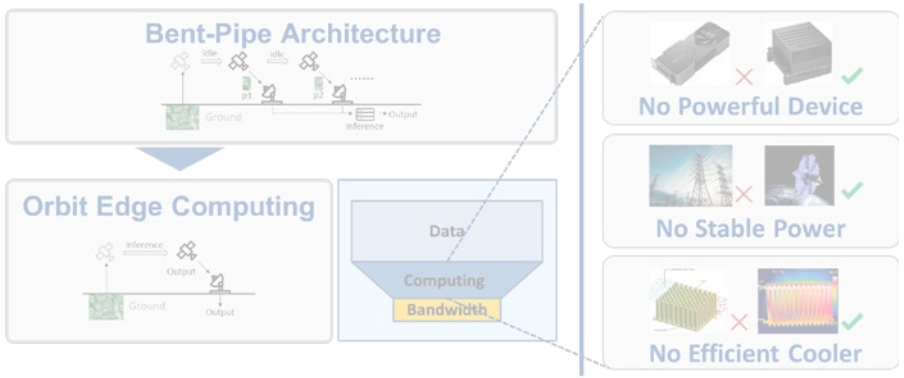
$$\Delta P = \frac{1}{\alpha}[T_{max} - T_i(t)] - [P_i(t) - \beta(T_i^4(t) - T_{amb}^4)]$$

Threshold Adjustment for GCAD module

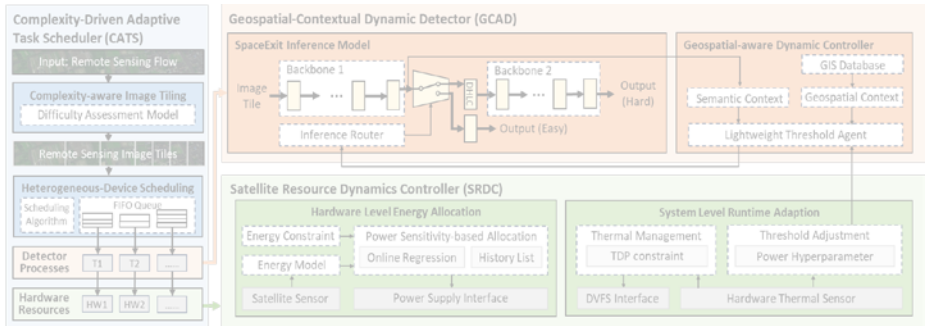
$$\tau = \tau_{base} \cdot \frac{\gamma P_{current}}{P_{nominal}}$$

Content

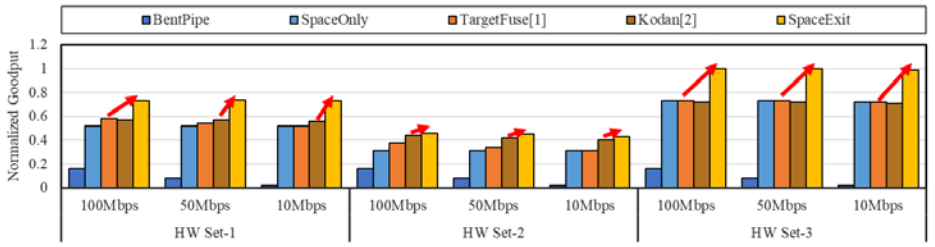
1. Background & Motivation



2. System Design



3. Workflow & Evaluation

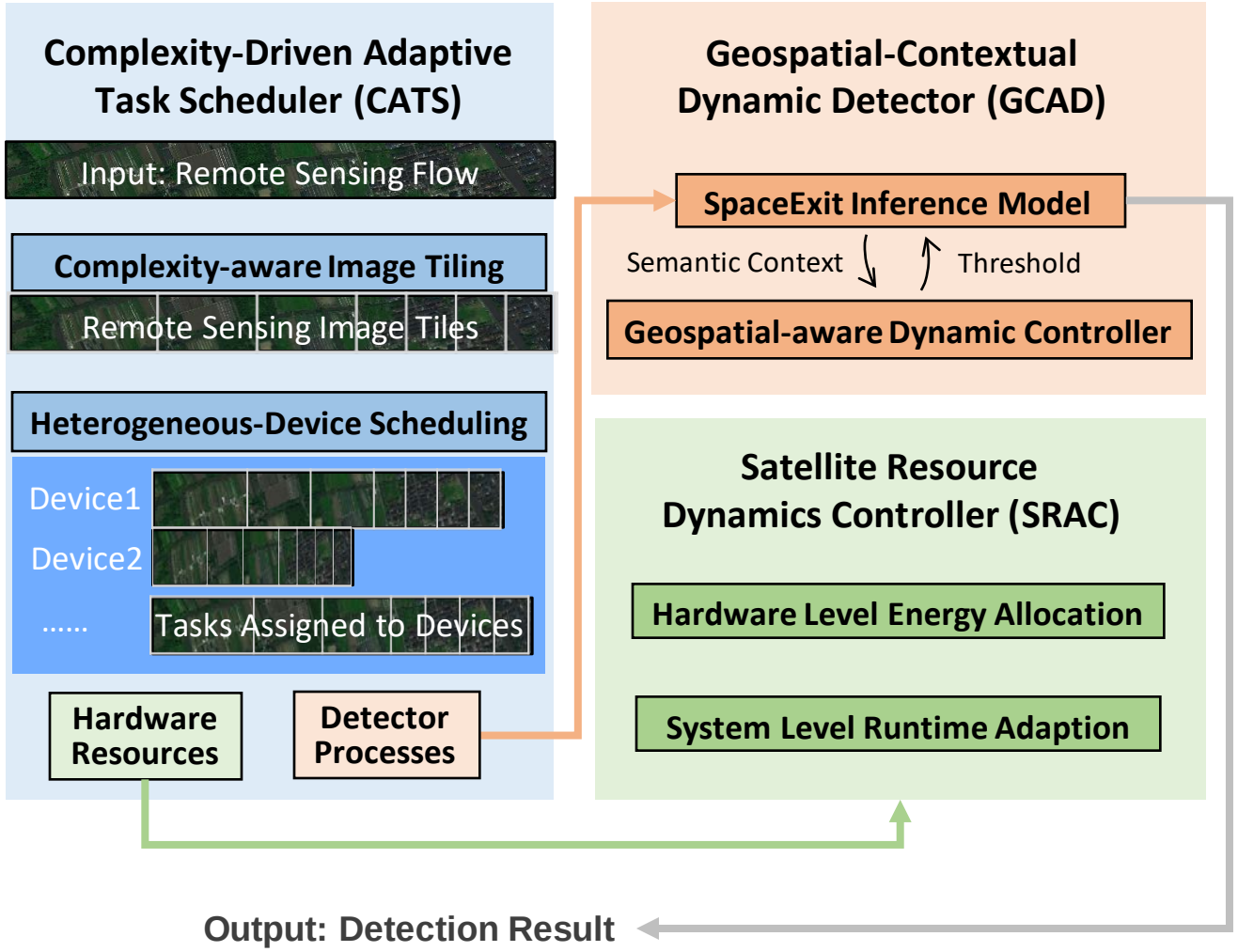


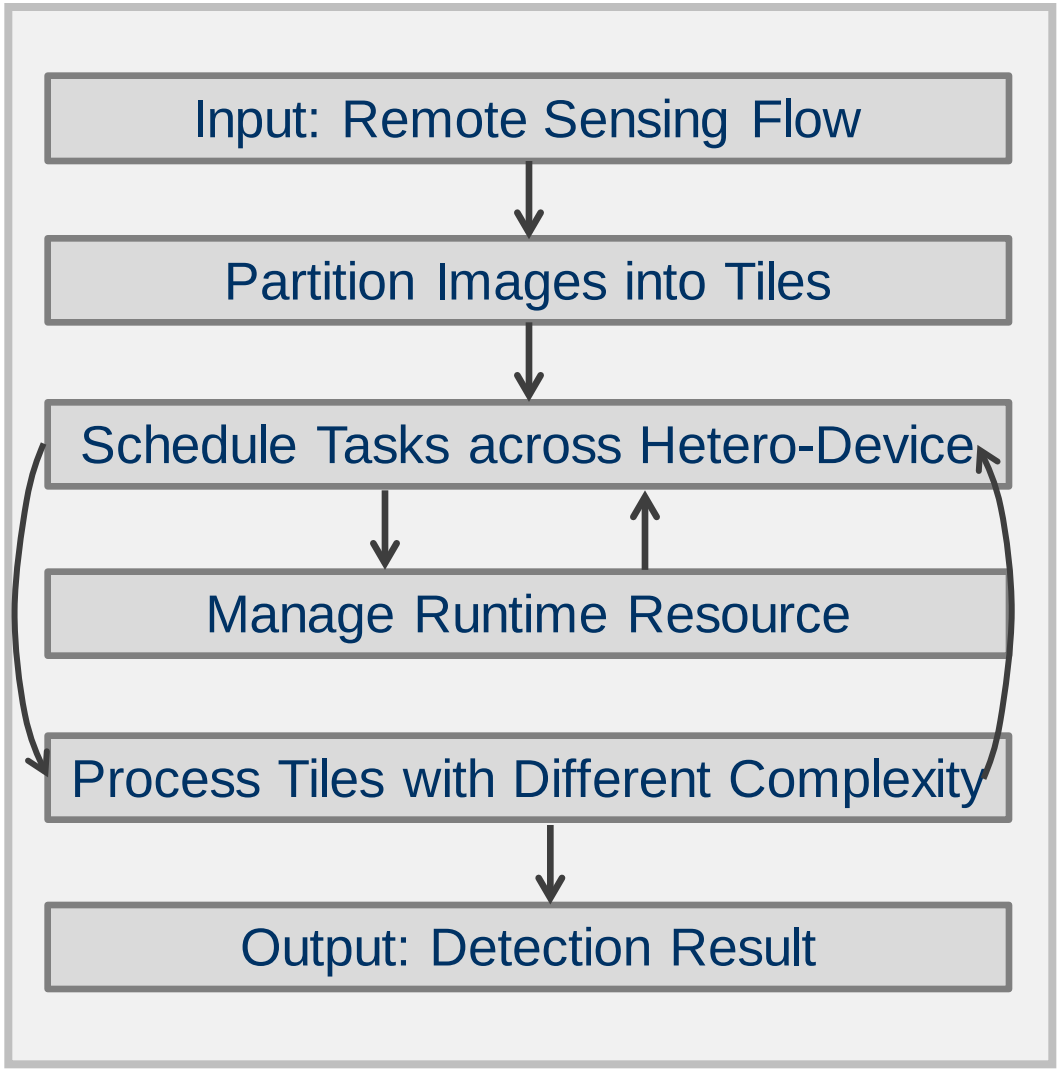
5.2%-37.6% improvement

4. Conclusion

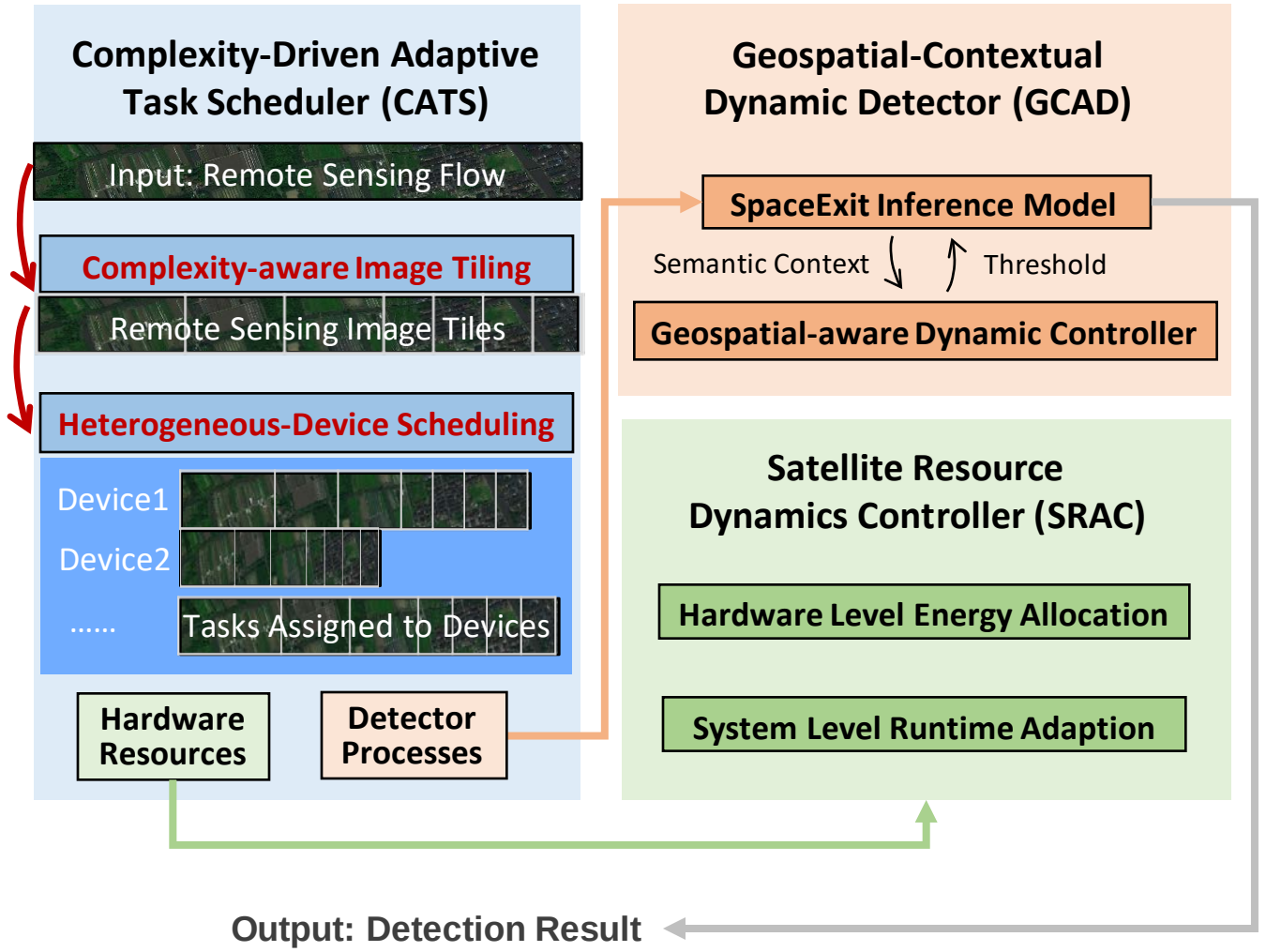
- We embrace OEC (Orbit Edge Computing), which is emerging as a solution to imbalanced data-bandwidth growth.
- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.
- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

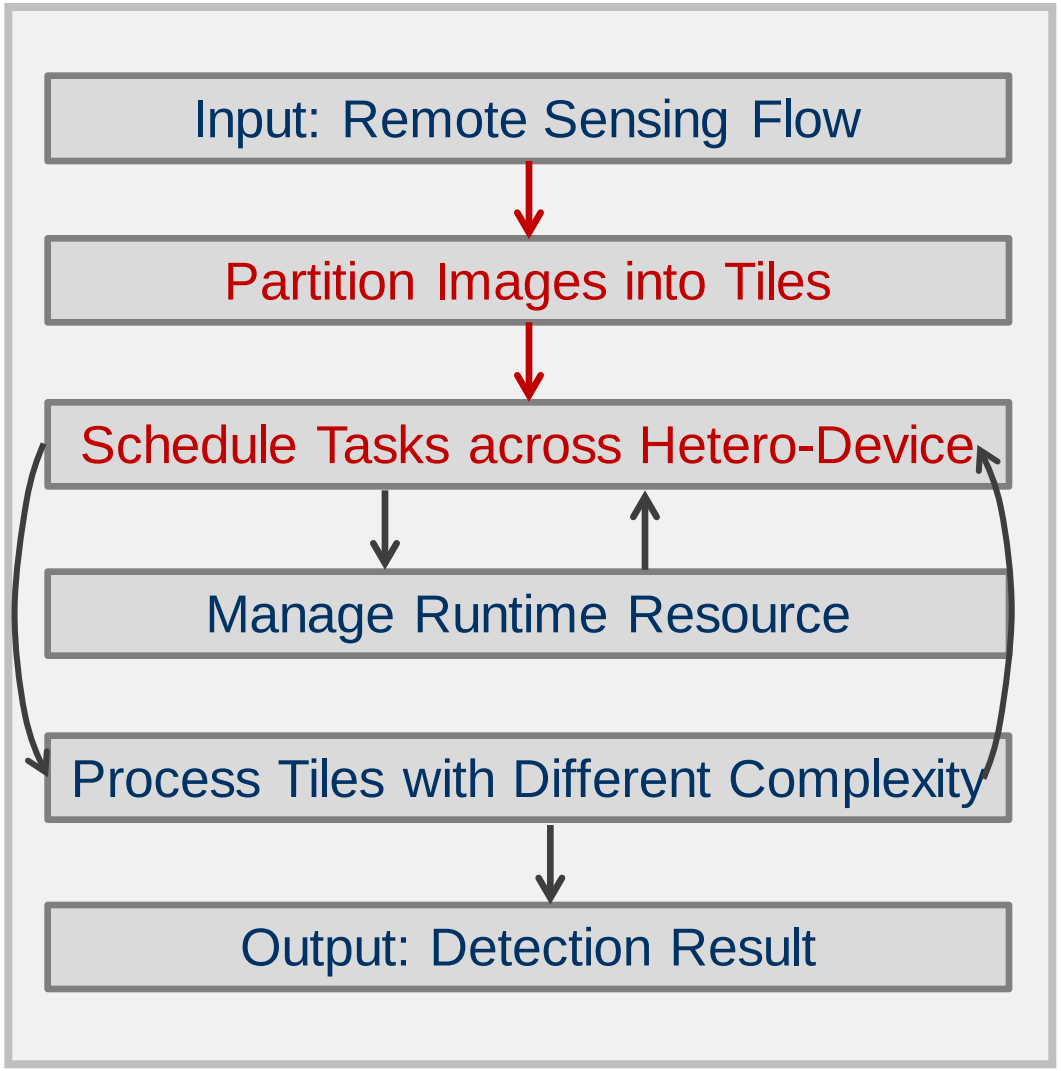
SpaceExit: Detailed Working Steps



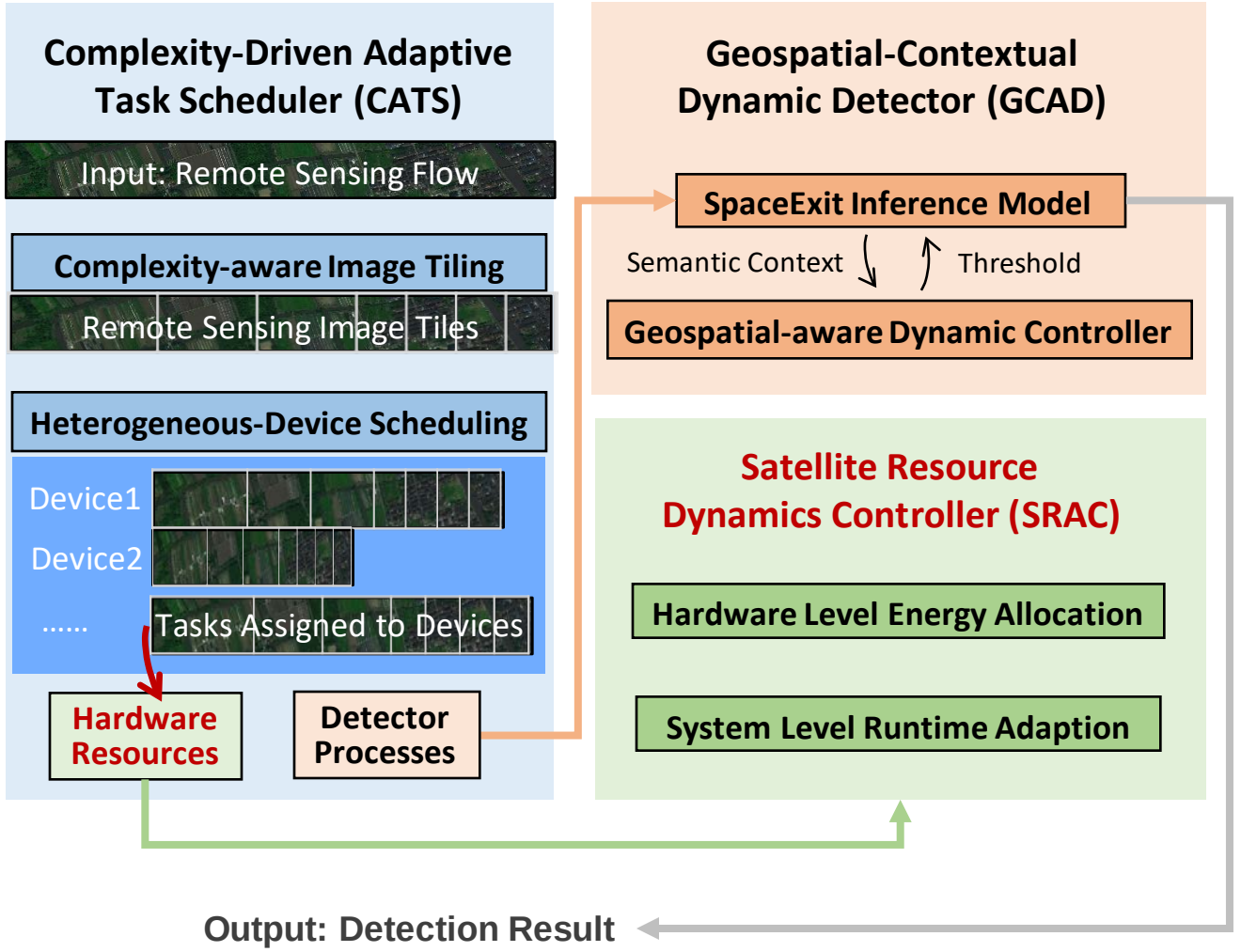


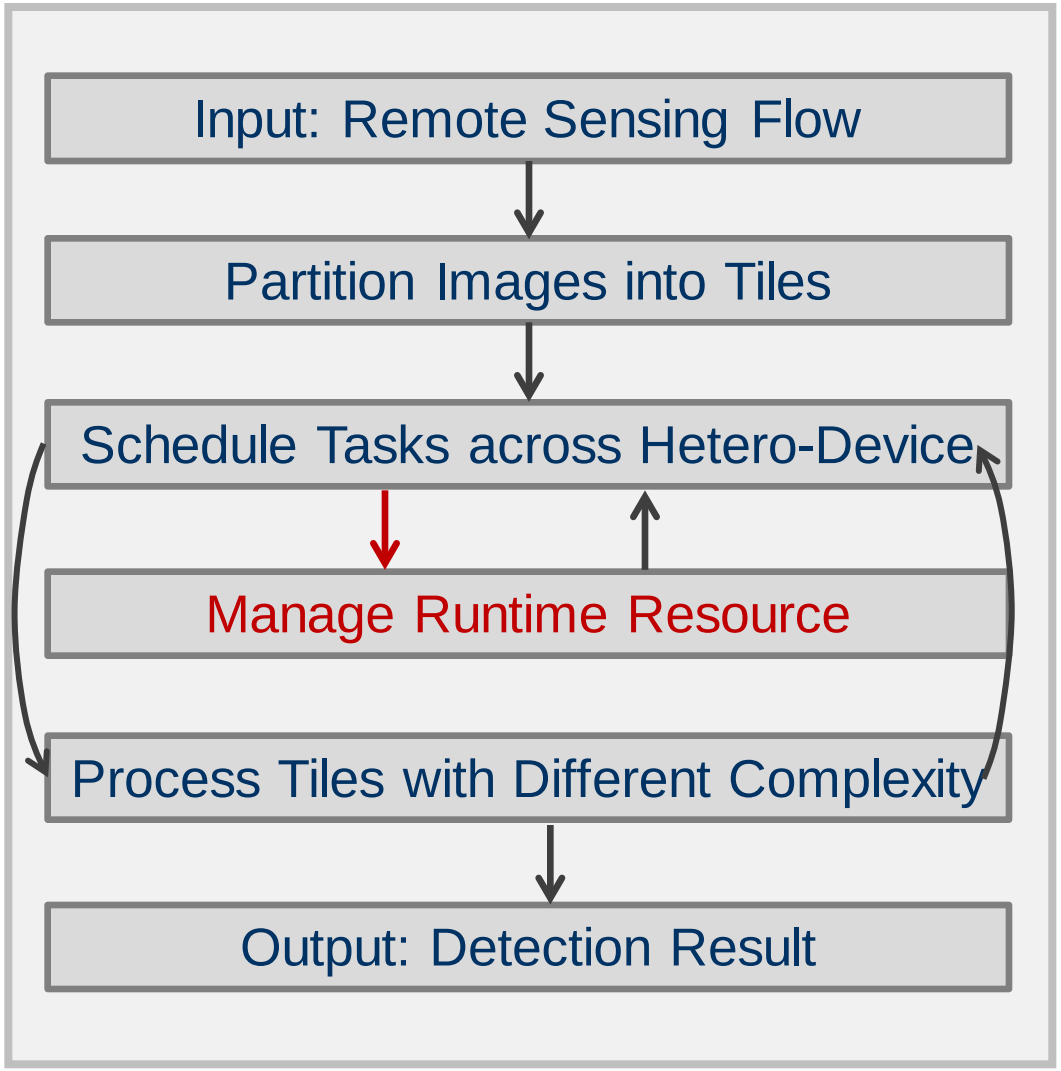
SpaceExit: Detailed Working Steps



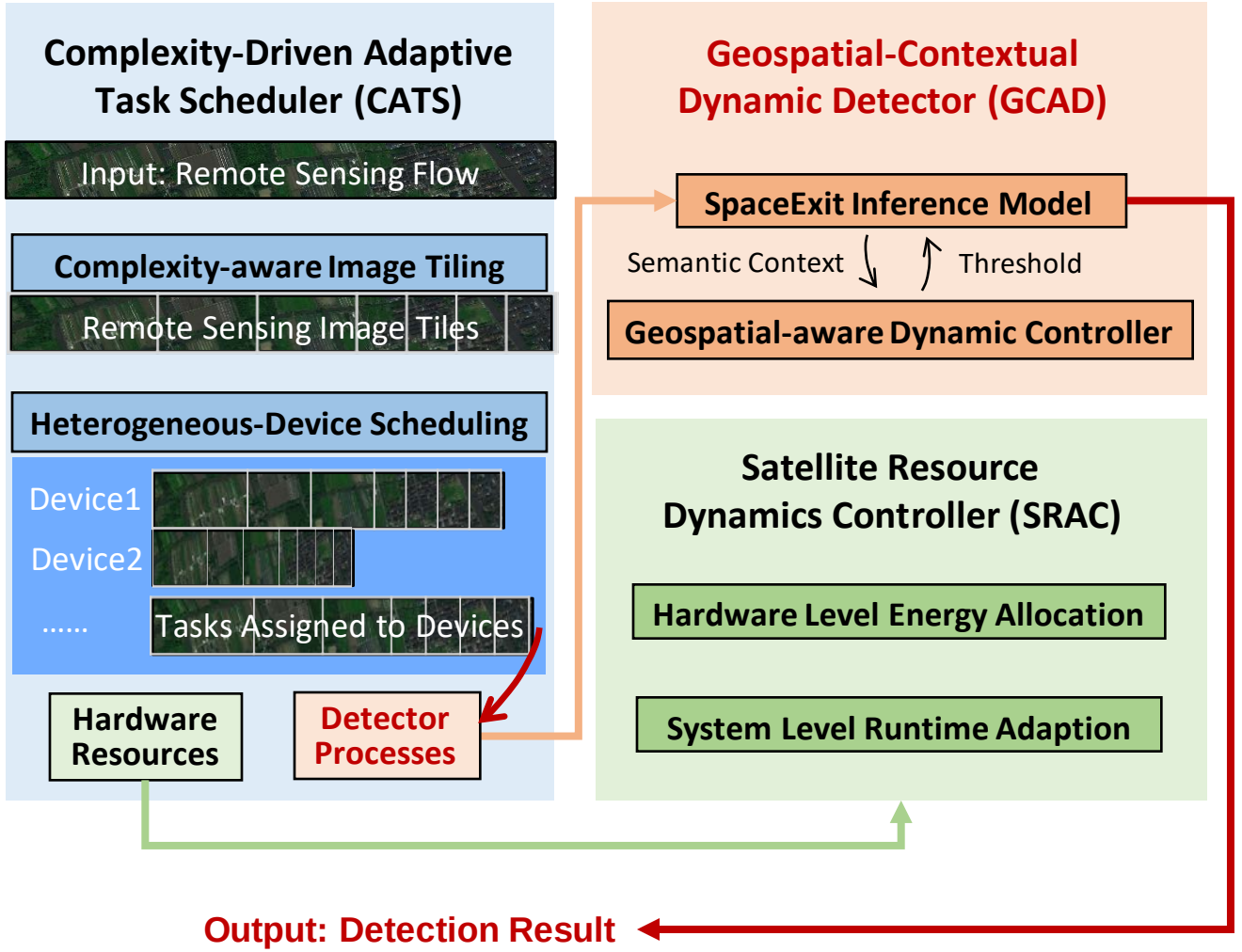


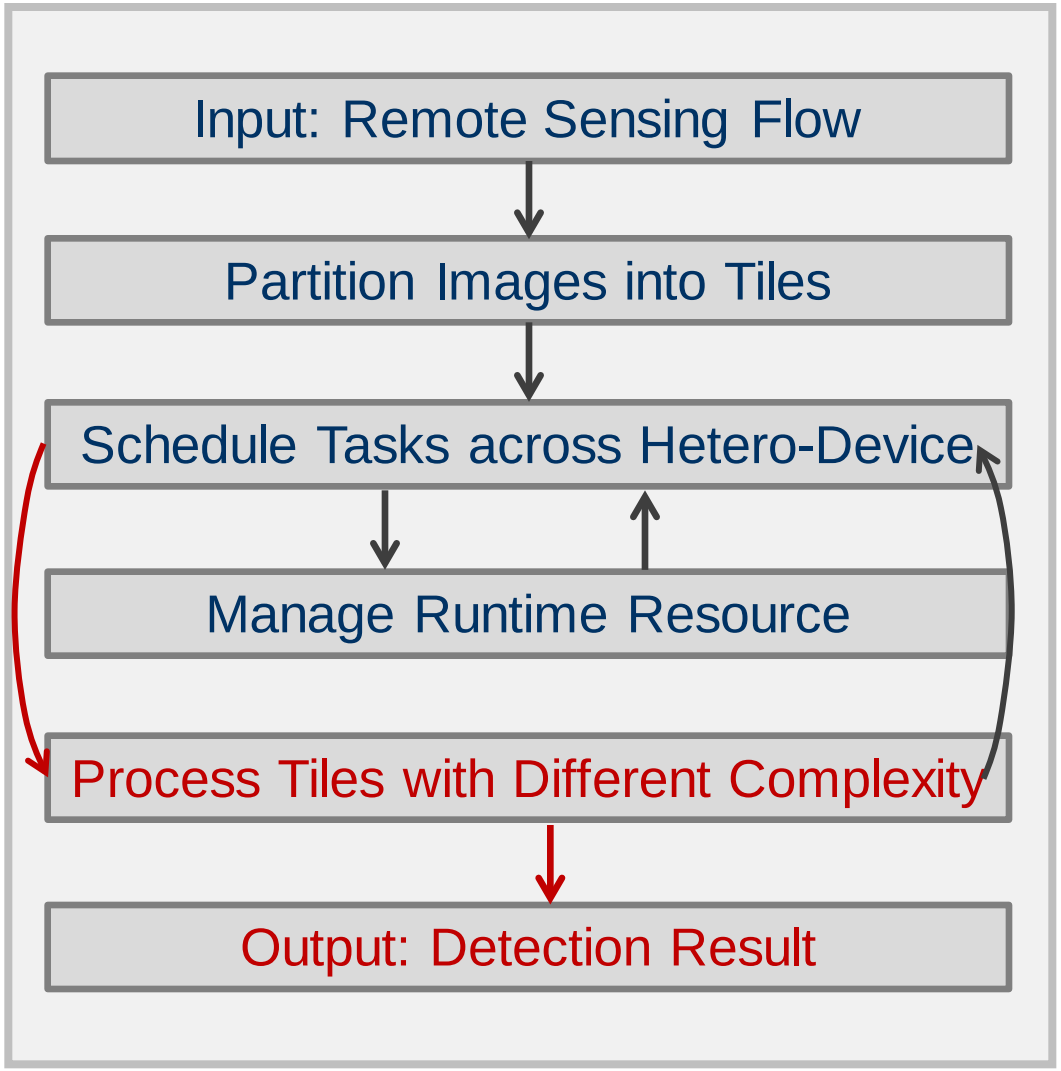
SpaceExit: Detailed Working Steps



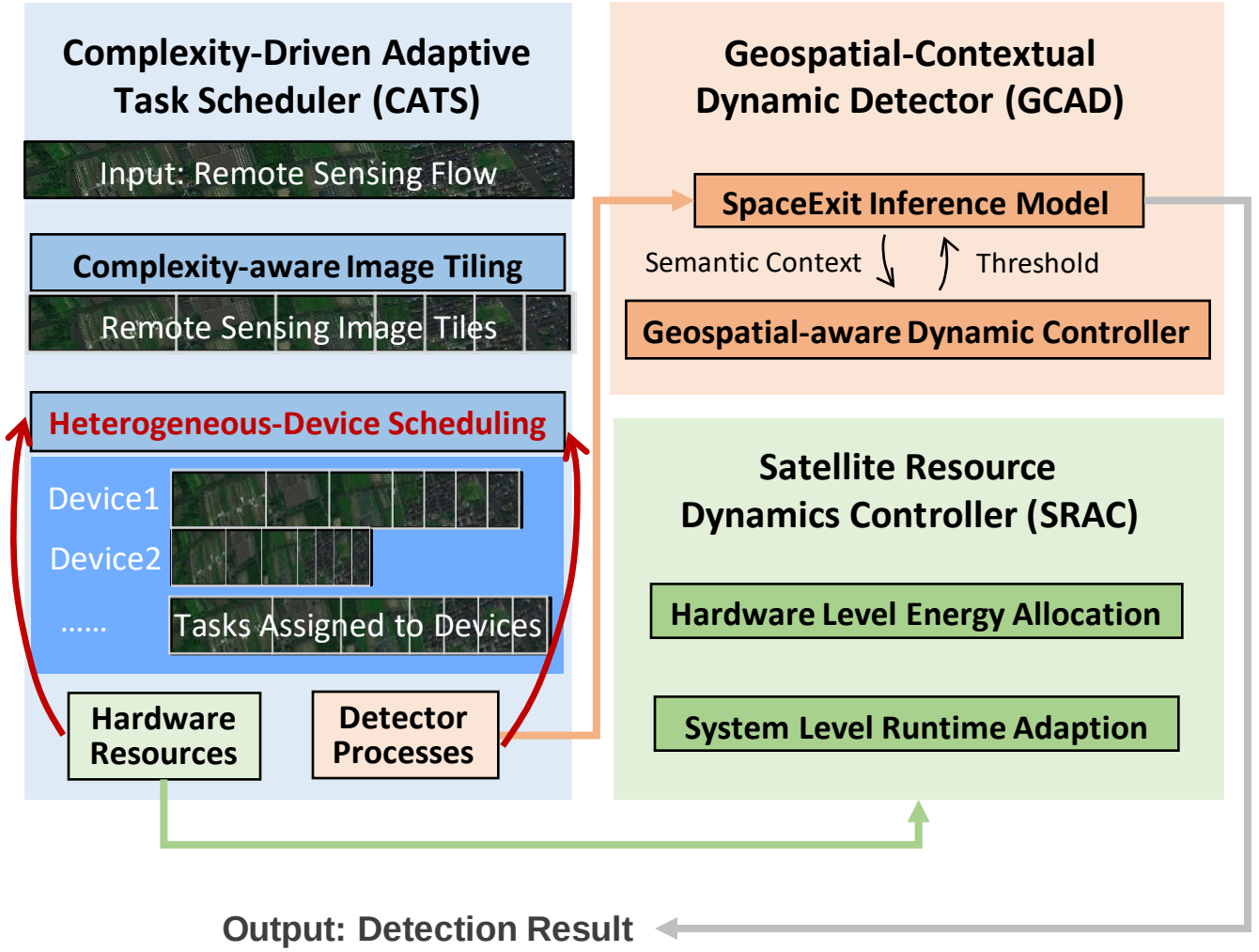


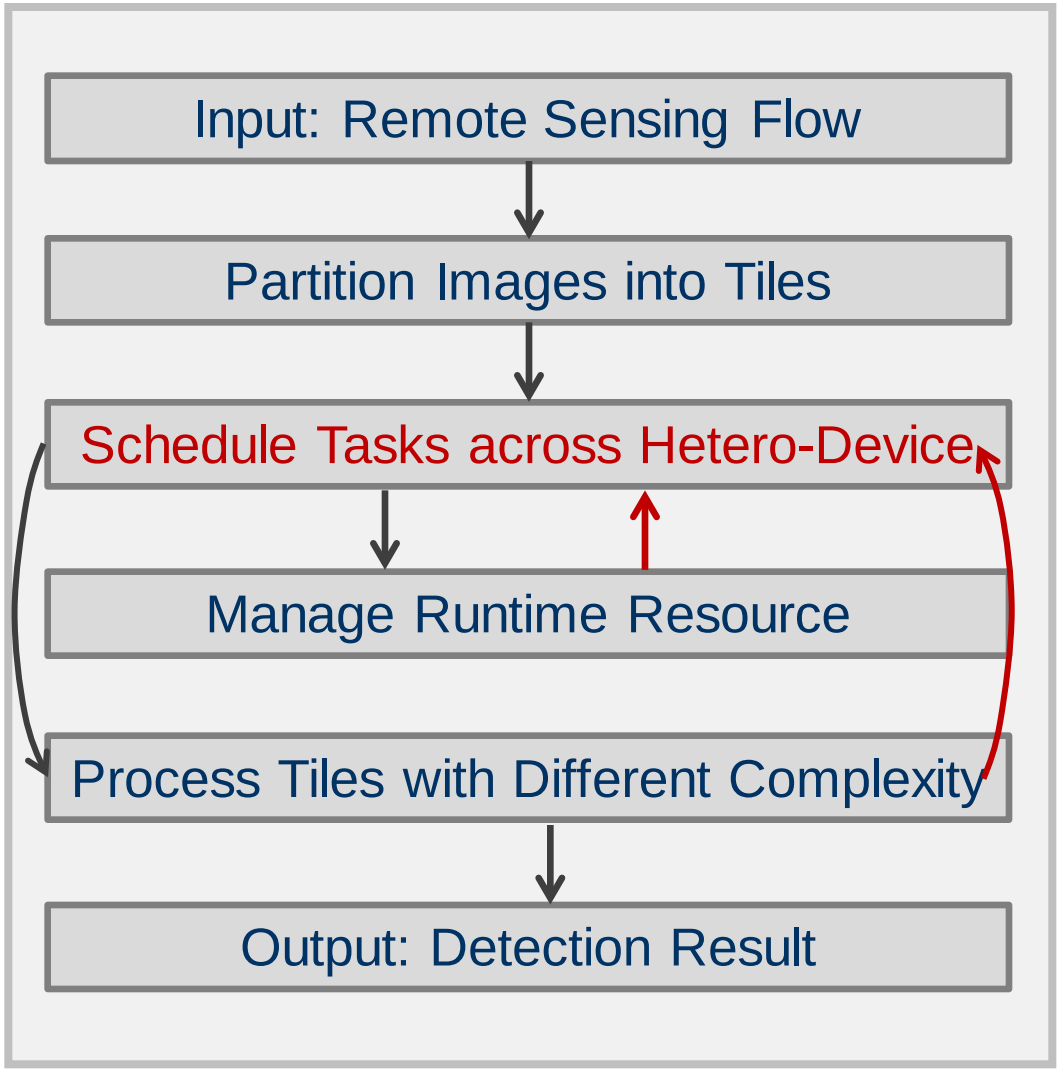
SpaceExit: Detailed Working Steps





SpaceExit: Detailed Working Steps





Experiment: Setup

Dataset, Baseline and Configurations in Experiment

Dataset	*Description*
DOTA	Satellite dataset for object detection

Baseline	*Description*
BentPipe[1]	Traditional ground-centric approach
SpaceOnly[1]	Performs all computations onboard
Kodan[2]	Leverages specialized models selected based on prior knowledge
TargetFuse[3]	Combines adaptive tiling, object clustering, and bandwidth schedulin

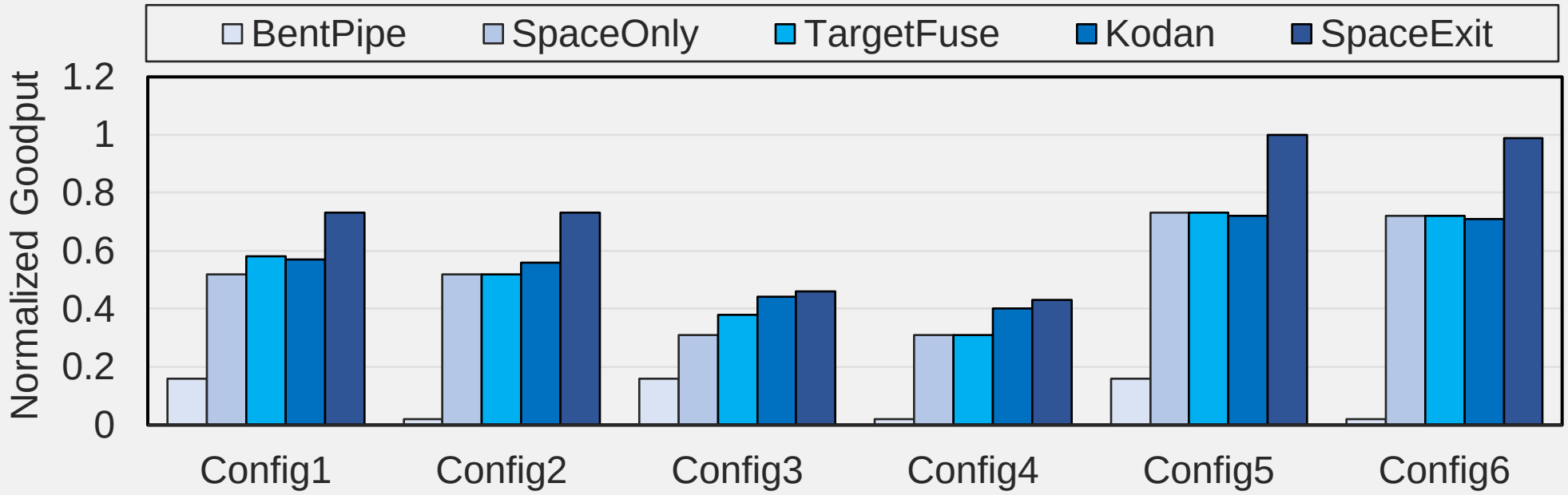
Config	Hardware Set	Bandwidth
Config1	Jetson Xavier NX+ Jetson Nano	100Mbps
Config2	Jetson Xavier NX×2	100Mbps
Config3	Jetson Nano×2	100Mbps
Config4	Jetson Xavier NX+ Jetson Nano	10Mbps
Config5	Jetson Xavier NX×2	10Mbps
Config6	Jetson Nano×2	10Mbps

SpaceExit is Evaluated in Various Configurations

[1] Bradley Denby et al. ASPLOS, 2020
[2] Bradley Denby et al. ASPLOS, 2023.
[3] Qiyang Zhang et al. INFOCOM, 2024.

Experiment: Goodput Evaluation

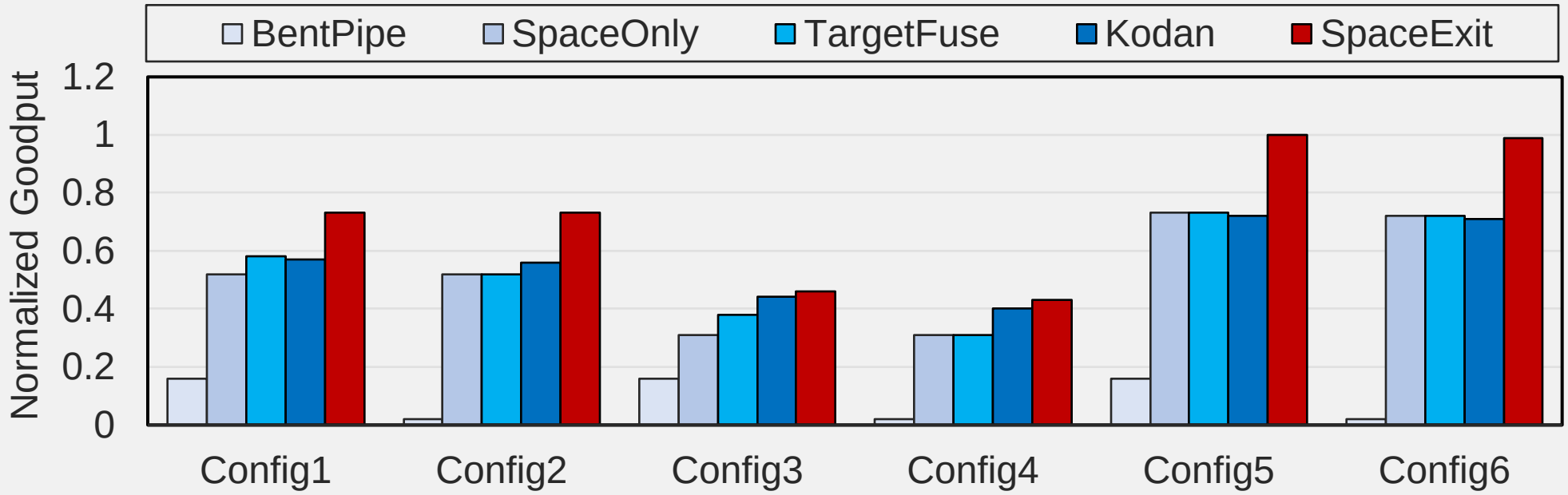
Comparative Evaluation of Goodput: SpaceExit and Baselines



SpaceExit Improves Goodput(5.2%~37.6%) in All Configuration

Experiment: Goodput Evaluation

Comparative Evaluation of Goodput: SpaceExit and Baselines

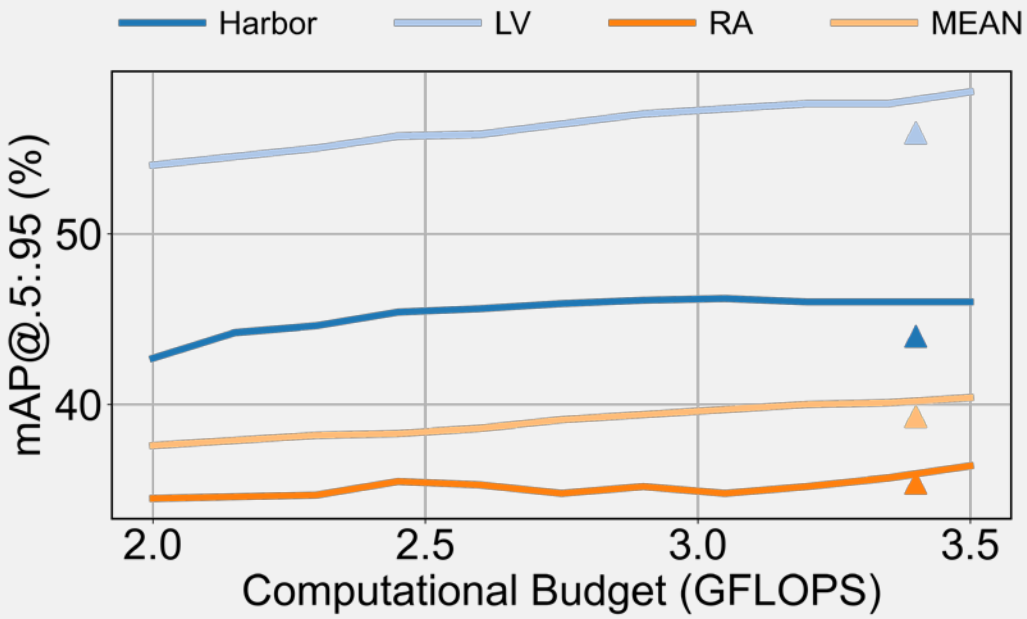


SpaceExit Improves Goodput(5.2%~37.6%) in All Configuration

Experiment: mAP Evaluation

mAP Comparison: Static Methods vs. GCAD

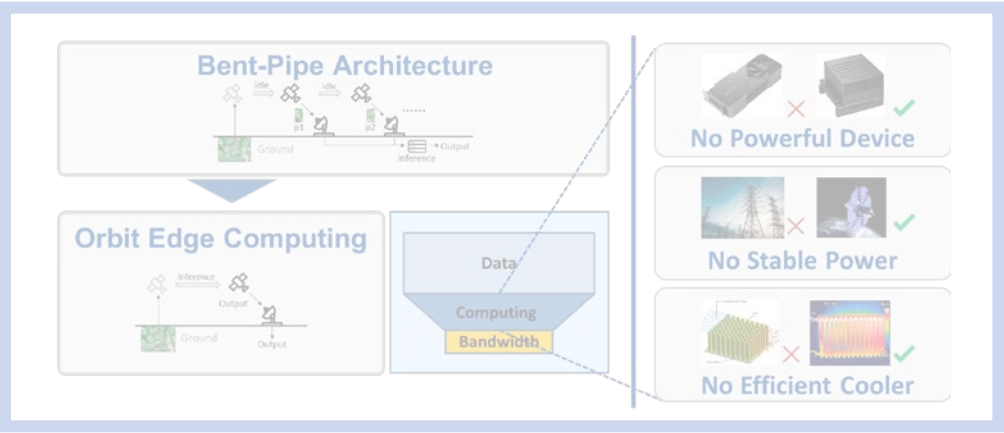
Class	Static		GCAD	
	mAP@.5	mAP@.5:.95	mAP@.5	mAP@.5:.95
Plane	0.911	0.643	0.918	0.666
Ship	0.866	0.577	0.872	0.598
ST	0.732	0.427	0.764	0.464
Harbor	0.815	0.440	0.836	0.460
LV	0.800	0.559	0.814	0.583
...	...	...	...	...
MEAN	**0.635**	**0.394**	**0.640**	**0.404**



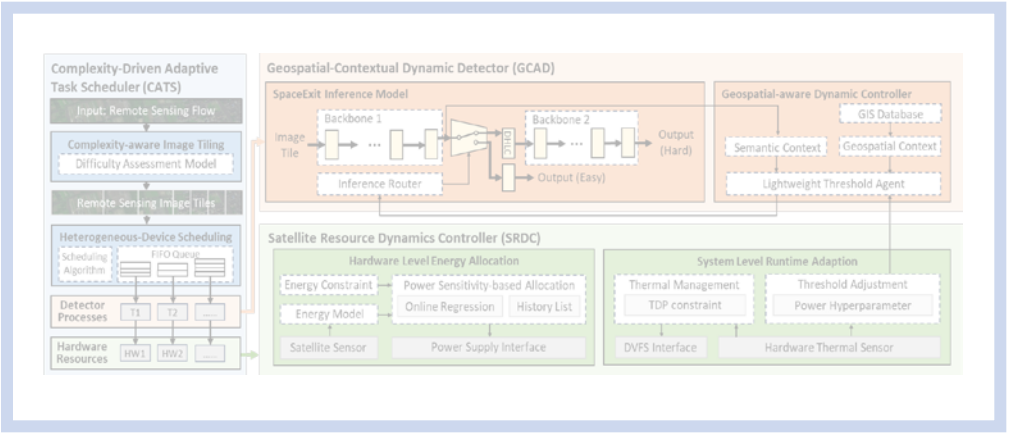
GCAD Outperforms Static Methods & Supports Flexible Compute

Content

1. Background & Motivation



2. System Design

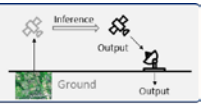


3. Workflow & Evaluation

5.2%-37.6% improvement

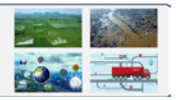
4. Conclusion

- We embrace OEC (Orbit Edge Computing), which is emerging as a solution to imbalanced data-bandwidth growth.



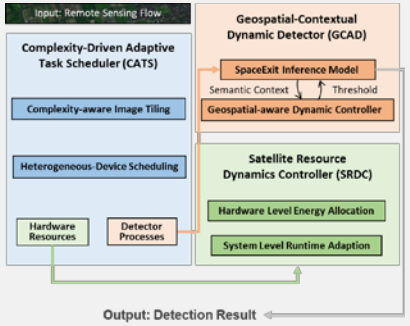
- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.

- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

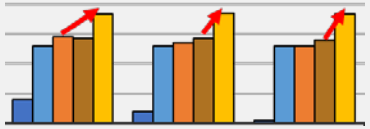


Conclusion

- SpaceExit is an integrated system that enables efficient adaptive Earth observation on satellites via algorithm-system co-design.
- SpaceExit tackles OEC challenges: multi-scale geospatial adaptation, cross-device scheduling & dynamic onboard constraints.



- Our evaluations across diverse satellite settings demonstrate that SpaceExit significantly outperforms existing methods.



- SpaceExit enhances Earth observation constellations' data delivery capacity, strengthening their role as platforms for diverse applications.

Available on Github: https://github.com/zhuxz0299/ATC-artifact-submission

Thank You! Q & A

SpaceExit: Enabling Efficient Adaptive Computing in Space with Early Exits

Discussion: Dr. Jiacheng Liu, liujiacheng@ieee.org
Xiaozhi Zhu (presenter), zhuxiaozhi@sjtu.edu.cn
Dr. Xiaofeng Hou, hou-xf@cs.sjtu.edu.cn

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY