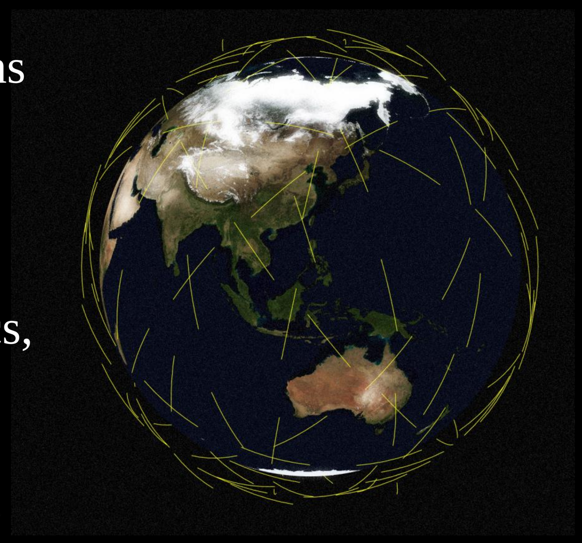
Proliferated LEO Orchestration and Data Assimilation with the Collective Space Tasking and Assimilation Reasoning System (CoSTARS*)

Traditional Ground Systems Unable to Scale to p-LEO

New proliferated Low Earth Orbit (p-LEO) constellations are rapidly expanding in scale and sensitivity while also diversifying to include broader, multi-modal sensing capabilities. Payload orchestration, control, data analytics, and information dissemination on short, relevant timescales is key to fully enabling p-LEO constellations.

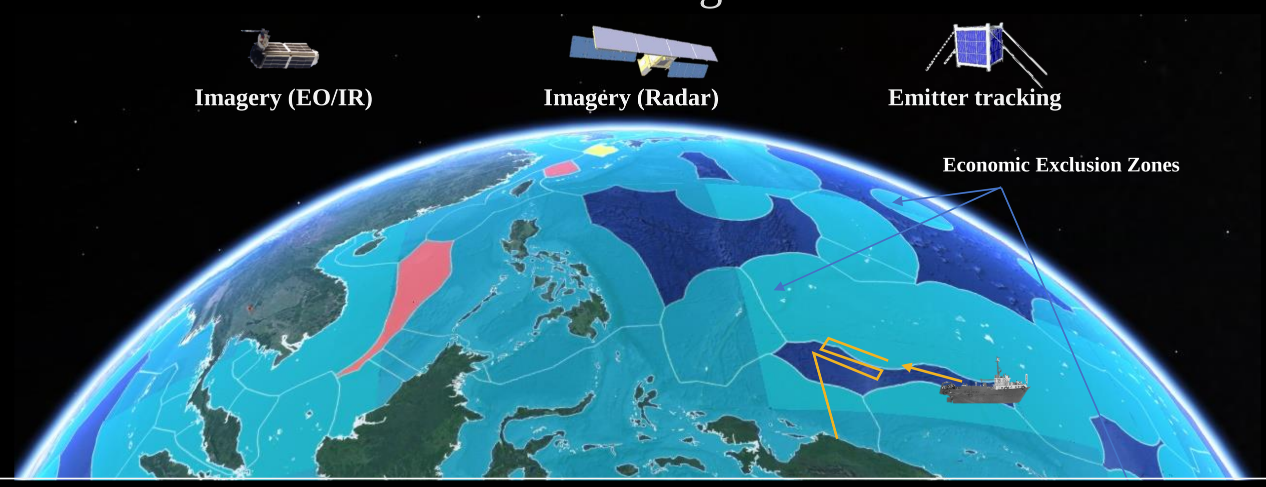


Measurement	Description
Response Time	Inefficient Re-planning time scales
Cost	Storage, analytics, and transport of large data volumes
Staffing	Heavy man-in-the-loop needs for command, control, processing, and exploitation
Adaptability	Ability to respond to new satellite systems and user needs

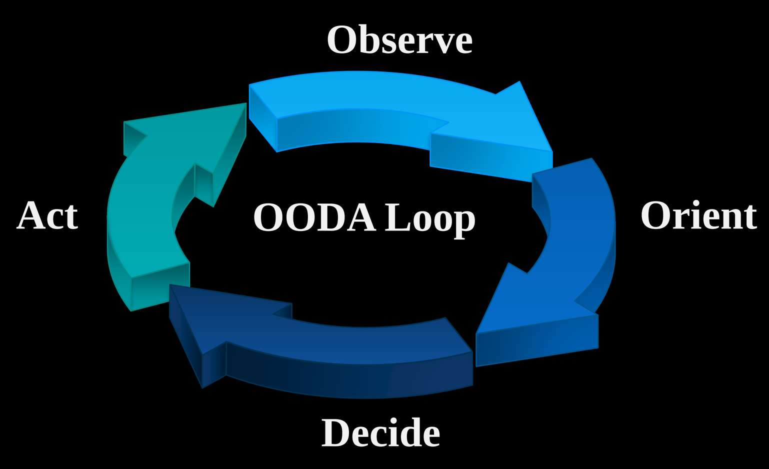
Space-based sensors needed for large area, responsive custody operations

Illegal fishing activities alone estimated to cost $36.4 billion per year to the world economy. Space-based geospatial intelligence systems able to monitor the maritime domain and enable fishery protection. Space systems able to monitor ships in a variety of modes including Electro-Optical (EO) imagery, Synthetic Aperture radar (SAR) imagery, and radio frequency (RF) emissions such as Automatic Identification System (AIS) transponders. Commercial companies addressing these sensing modalities include Spire, Capella Space, Umbra, ICEEYE, Planet, Maxar, and many others.

Multi-modal satellites to identify and respond to Illegal Fishing



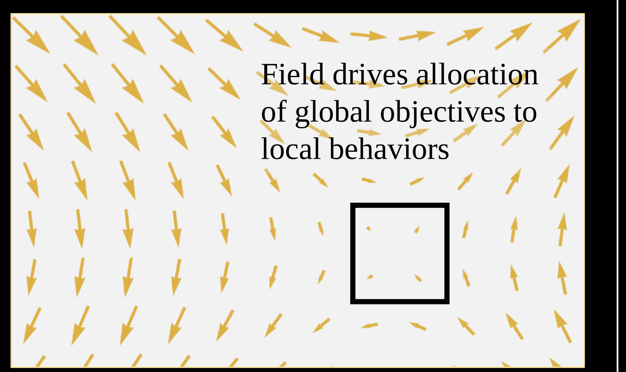
Edge-processing AI enables rapid response times

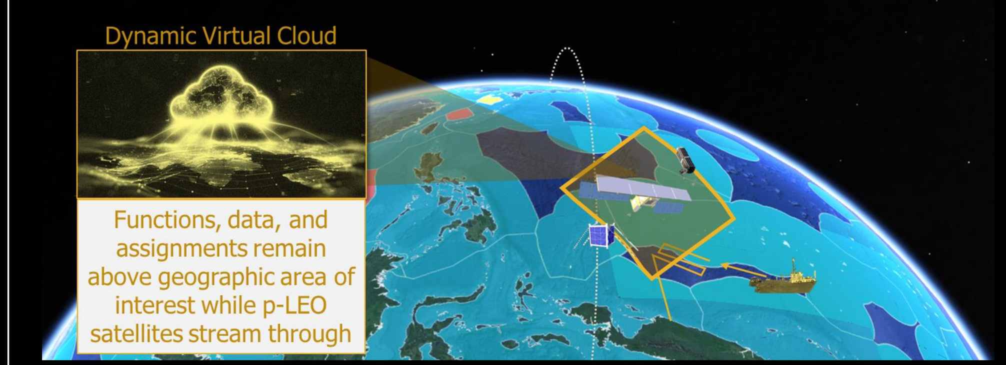


Integrated p-LEO constellations need to execute OODA loop on fast timescales. Satellite edge-processing required for many necessary OODA-loop timescales. CoSTARS focuses on solving problems on the integrated satellite system to solve traditional ground station limitations.

Collective Functions

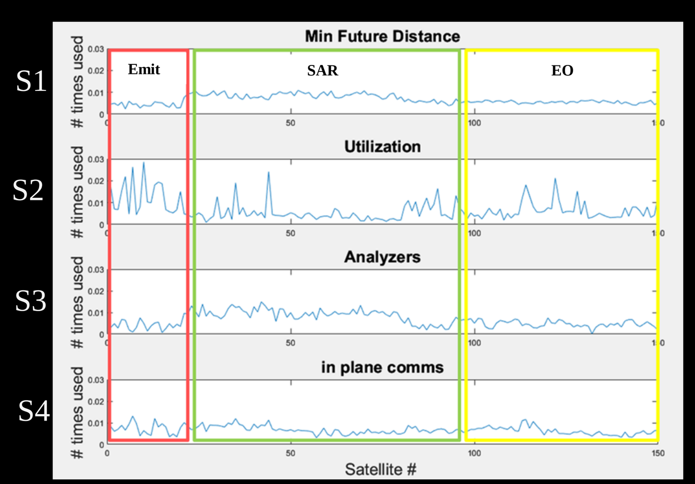
Large scale, heterogenous p-LEO systems well matched to Swarm control theories. While orbits are well determined, locations, capabilities, and mission objectives are locally driven while meeting global objectives. CoSTARS leverages field theory for allocation of functions and ownership to specific edge nodes (on minute timescales).

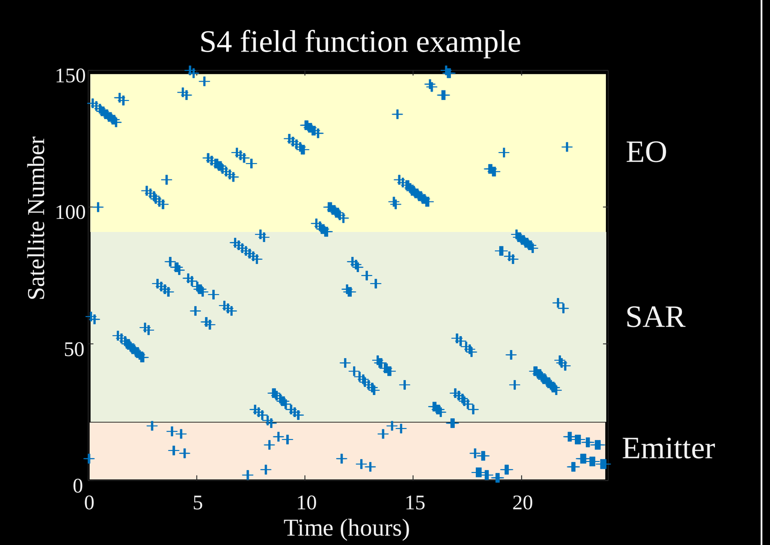




Regional focus create natural organization function based on geographic objectives. Virtual clouds over geographic regions create natural field function as satellites flow in and out of access region.

Field Function	Description	Result
S1. Minimum future distance	Next satellite over Area of Interest (AoI)	Spreads resource utilization evenly while smartly moving data from sense to analyze, underutilizes higher orbits (rarer access).
S2. Resource cost	Next satellite with resource (power) cost factor.	Hard to tune as resource utilization eventually pushes analysis tasks to small number of satellites used rarely
S3. Analyze or sense	A satellite can not be picked if it will be sensing in next few cycles	Worst results. Pushes data for analysis far from sensing satellites (50% worse)
S4. In-plane comms preferred	Next satellite, resource cost factor, and short data path preference	Maximizes in-plane transfers as expected. Good utilization of high-altitude satellites. Preferred option



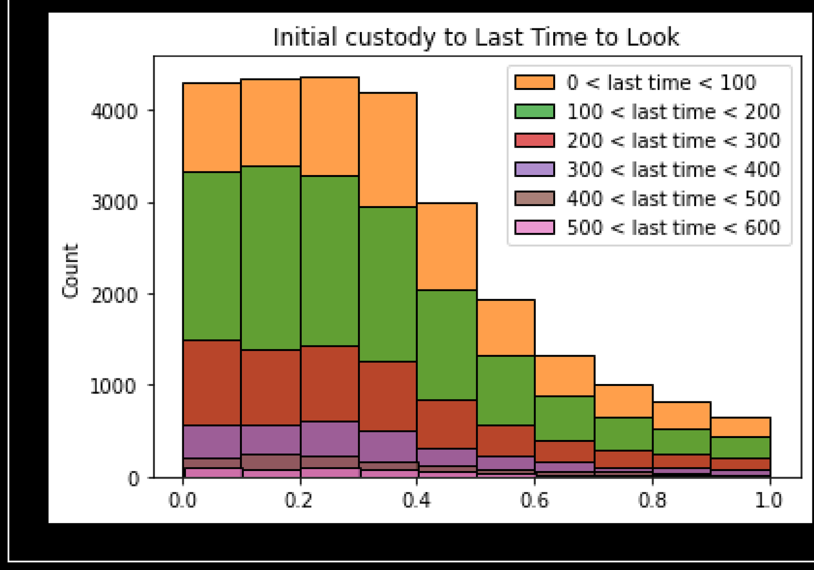


Decentralized Functions

Function	Description
Collective Organization	• **Dynamic ownership selection and agreement** across edge nodes to assign capability leadership • Selection based on resource cost and status
Task Learning	• Creates tasks sets based on initial subject matter expert inputs • **Learns and improves tasking** leveraging Koopman learning techniques and system feedback
Task Allocation	• Auction algorithms allocate and orchestrate tasks • **Enables rapid scalability** across heterogenous satellites as unit response based on likely success of request
Resource Management	• High fidelity **resource scheduling** focused on sensor timing and constraints • Feeds task allocation to align costs across tasking
Data Assimilation	• Flexible fusion of multi-domain sensing • AI/ML mechanisms for signal processing
Understand	• Maps current system status to initial objectives
Mission Learning	• Extensible sets of **prediction and learning algorithms**
Data Management	• **Prioritization and routing flexibility** across long latency links and variable bandwidths • Extensible across link types and domains

Data-Efficient Model-based Task Decomposition (Small Sat paper by Dr. Cooper)

CoSTARS uses a data-efficient two-part system, modeled after the Actor-Critic architecture to generate optimized tasking and assignments. We leverage Koopman operator theory approach to predict satellite availability, observation capabilities, and resource utilization. We also use the Hierarchical Bayesian Program Learning (HBPL) paradigm to formulate and learn a task decomposition and generation 'program'. Tasks are constructed and defined probabilistically while guided by expert informed structure and bounds, enabling efficient search and optimization of the task space. During execution, the HBPL component proposes sets of tasks (serving as the 'actor') which are scored by the Koopman model. The two methods described above are notable due to their low data requirements and speed of model training or updating, making them a stellar pairing for on-orbit applications.



Custody error of 0 indicates high confidence, whereas custody error of 1 is complete loss of custody. The data generating experiments reveal the frequency at which custody is maintained for later observation times.

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Summary and Next Steps

- CoSTARS integrated system implements edge-processing capabilities across heterogenous satellites to improve system response, maintenance costs, manning requirements, and system adaptability.
- Capabilities includes wide range of autonomy functionality from rule based to Koopman operator theory. Implementation enables plug and play functionality as new capabilities advance (S/W and H/W).
- Focused on creating space deployable software system to support 100-1000 satellites

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