# Distributed Spacecraft Autonomy for Earth Observation

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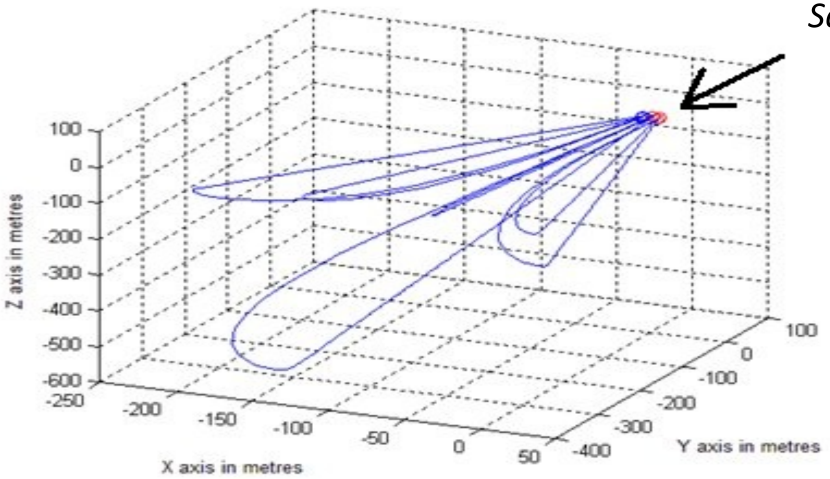
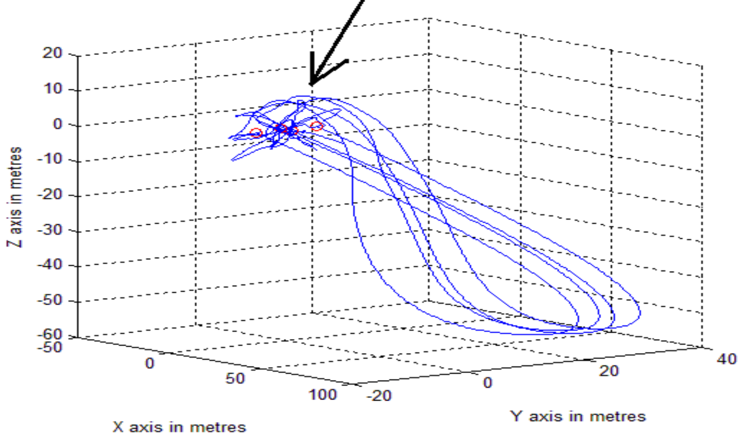
# Space Robotics Operations

- Scatter Maneuvering of Satellite Swarms using artificial potential fields
  - As an International Research Fellow in ESA ESTEC (Netherlands) in Summer 2010




*Scatter under directed threat:*




*S. Nag, L. Summerer, "Behavior-based, Autonomous and Distributed Scatter Manouevres for Satellite Swarms", Acta Astronautica 82 (2013) 95-109*

SPHERES onboard the International Space Station:


- SPHERES Zero Robotics
  - SM thesis Crowdsourcing and STEM Education + Program lead 2011
  - ~1800 users, ~180,000 simulations in the first 4 months
  - Collaborative competition in S/W development, inter-team as alliances and within the game
  - Embedded system -> API -> Game Code -> User Code
  - All obstacles and game items were virtual
  - Sim, Ground, Alliance ,ISS competitions with astronauts

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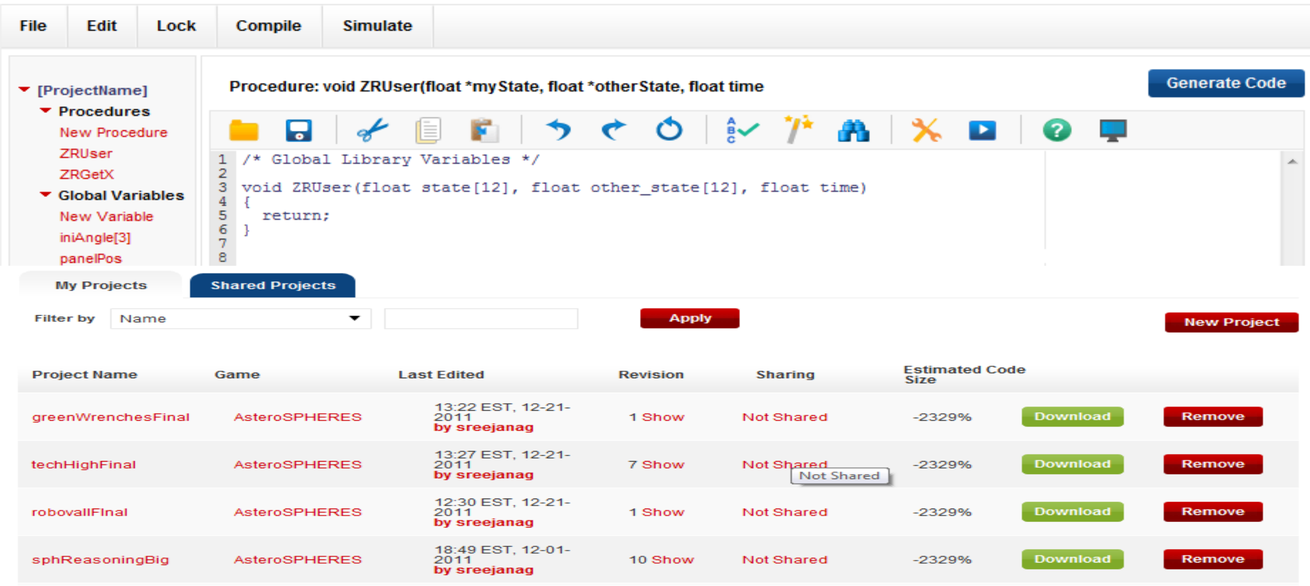
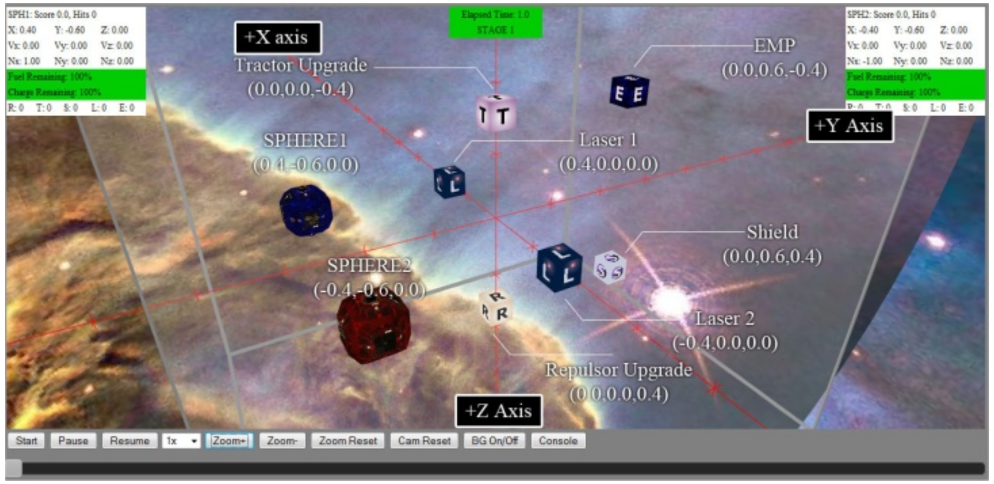
# Space Robotics Operations




Online gaming system for coding the SPHERES

Ground Competition at MIT




Example animation of an online SPHERES game

Finals broadcast from the ISS

*S. Nag, J.G. Katz, A. Saenz-Otero, "Collaborative Gaming and Competition for CS-STEM Education using SPHERES Zero Robotics", Acta Astronautica 83 (2013) 145-174*

*S. Nag, J.A. Hoffman, O.L. de Weck, "Collaborative and Educational Crowdsourcing of Spaceflight Software using SPHERES Zero Robotics", International Journal of Space Technology Management and Innovation (IJSTMI), vol 2, no. 2, 2012.*

*S. Nag, I. Heffan, A. Saenz-Otero, M. Lydon, "SPHERES Zero Robotics software development: Lessons on crowdsourcing and collaborative competition", IEEE Aerospace Conference, Montana, March 2012*

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# Better Science with Satellite Formation Agility

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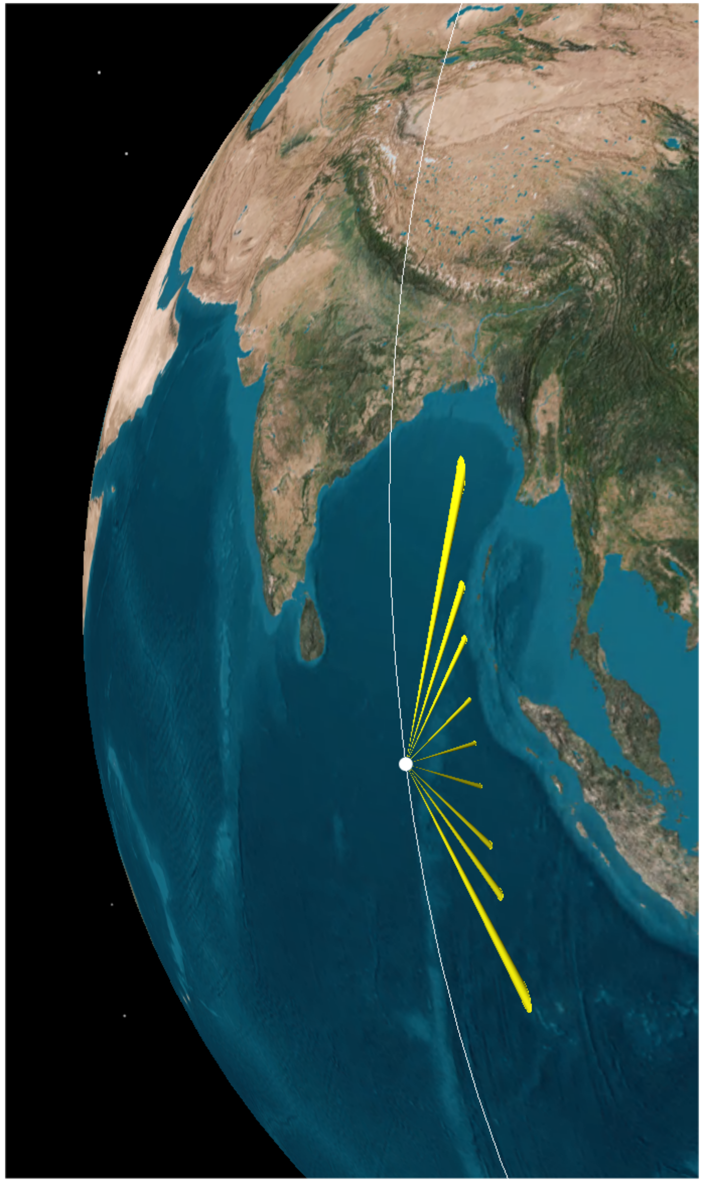
## *BRDF Estimation*

- Because reflectance values depend on the direction of solar illumination and direction of measured reflection
- Angular sampling is sparse using monolithic spacecrafts presenting an angular challenge
- Dependent products e.g. albedo, GPP

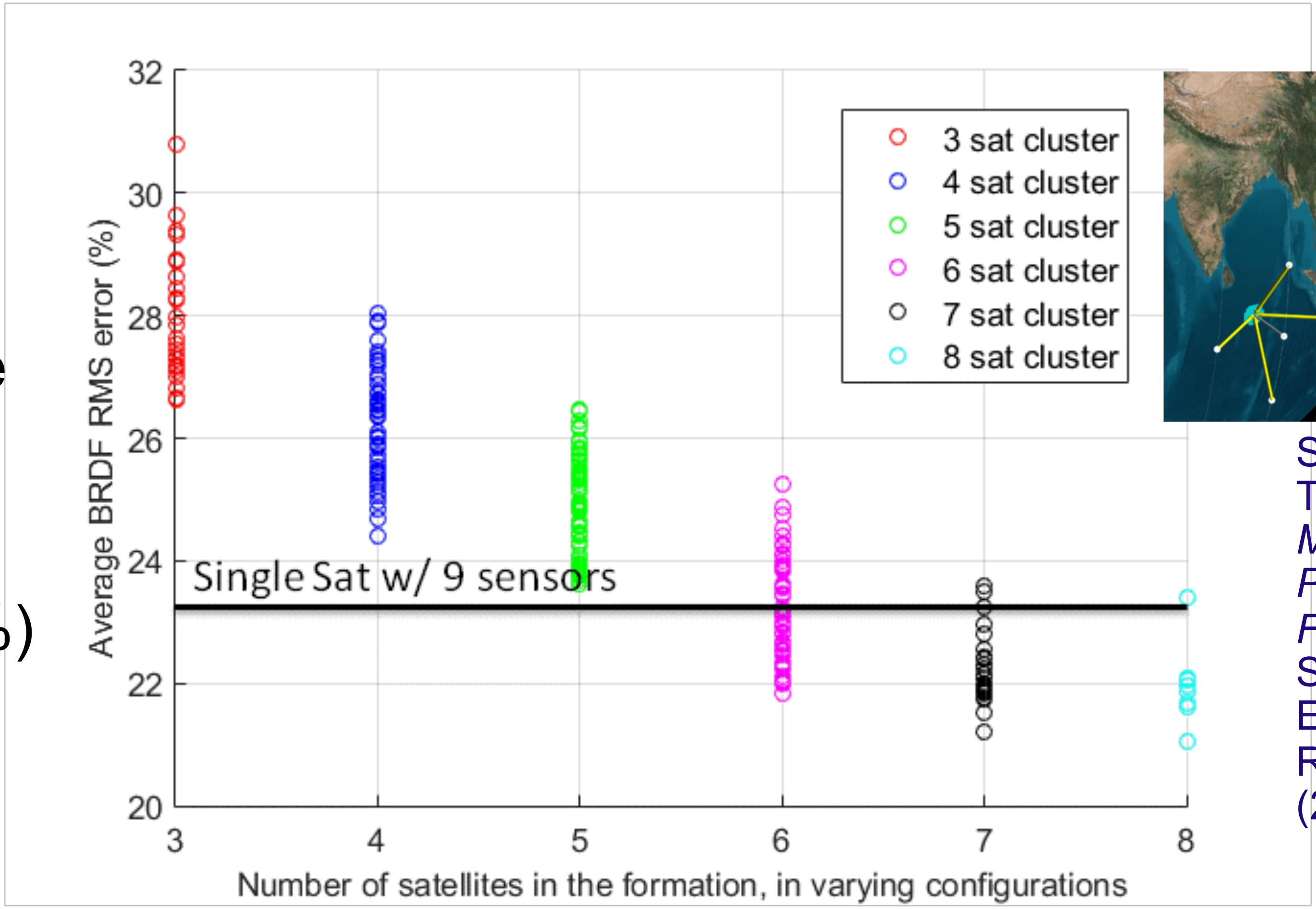


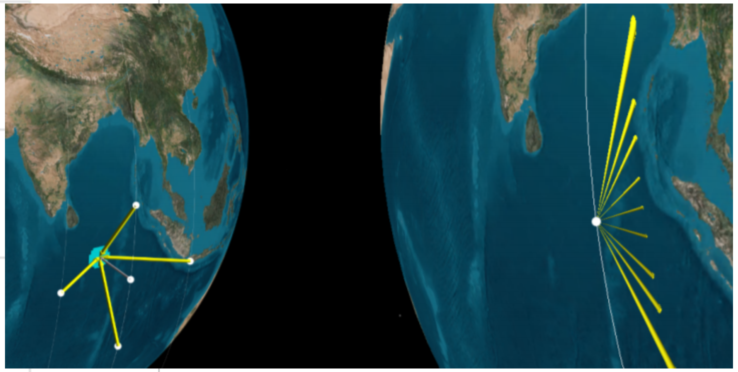
*S. Nag, C.K. Gatebe, O.L. de Weck, "Observing System Simulations for Small Satellite Formations Estimating Bidirectional Reflectance", International Journal of Applied Earth Observation and Geoinformation 43 (2015), 102-118*

# Better Science with Satellite Formation Agility

## *Estimation Errors*

- BRDF: 6 (or 8) single-sensor sats in some (or any) configurations give lower errors than 1 sat with 9 sensors
- Max Albedo: 3 (7) sats in absolute (%)
- Average NDVI: 3 (or 8) in some (or any) config beat
- PRI/GPP: Reflectance errors at 8 sats can cause 60-90% errors



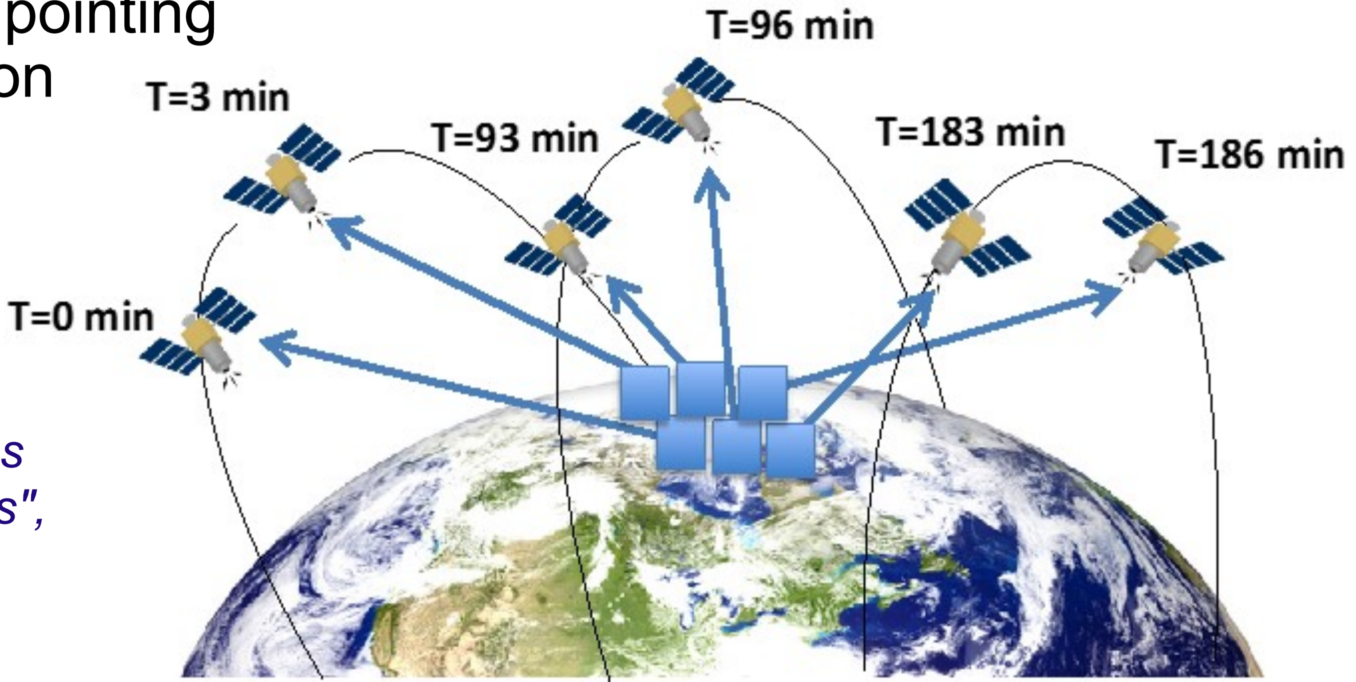
S. Nag, C.K. Gatebe, T.Hilker, *"Simulation of Multiangular Remote Sensing Products Using Small Satellite Formations"*, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 10, no. 2 (2017), *638-653*

*S. Nag , T. Hewagama, G. Georgiev, B. Pasquale, S. Aslam, C. K. Gatebe, "Multispectral Snapshot Imagers onboard Small Satellite Formations for Multi-Angular Remote Sensing", IEEE Sensors Journal 17, no. 16 (2017), 5252-5268*

*S. Nag, C.K. Gatebe, D.W. Miller, O.L. de Weck, "Effect of Satellite Formation Architectures and Imaging Modes on Global Albedo Estimation", Acta Astronautica 126 (2016), 77-97*

# Agile Spacecraft Constellations Maximizing Coverage and Revisit

- Small Sat constellation + Full-body reorientation agility + Ground scheduling autonomy = More Coverage, for any given number of satellites in any given orbits
- Using Landsat as first case study (710 km, SSO, 15 deg FOV) w/ a 14 day revisit. Daily revisit needs ~15 satellites or 4 satellites with triple the FOV.
- Assuming a 20 kg satellite platform for option of agile pointing
- Scheduling algorithm allows 2 sat constellation over 12 hours to observe 2.5x compared to the fixed pointing approach. 1.5x with a 4-sat constellation
- Extendable to monitoring applications (e.g. coral reefs)




*S. Nag, A.S. Li, J.H. Merrick, "Scheduling Algorithms for Rapid Imaging using Agile Cubesat Constellations", COSPAR Advances in Space Research - Astrodynamics 61, Issue 3 (2018), 891-913*

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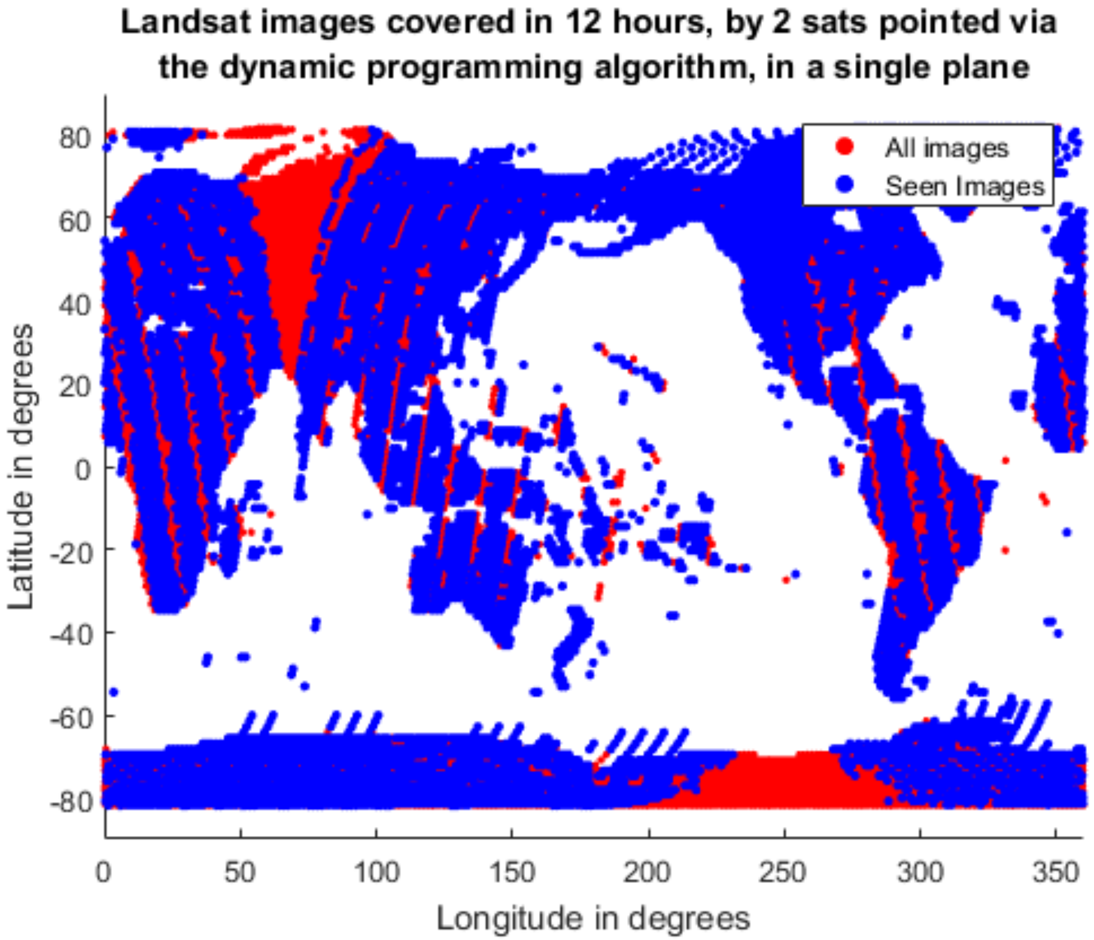
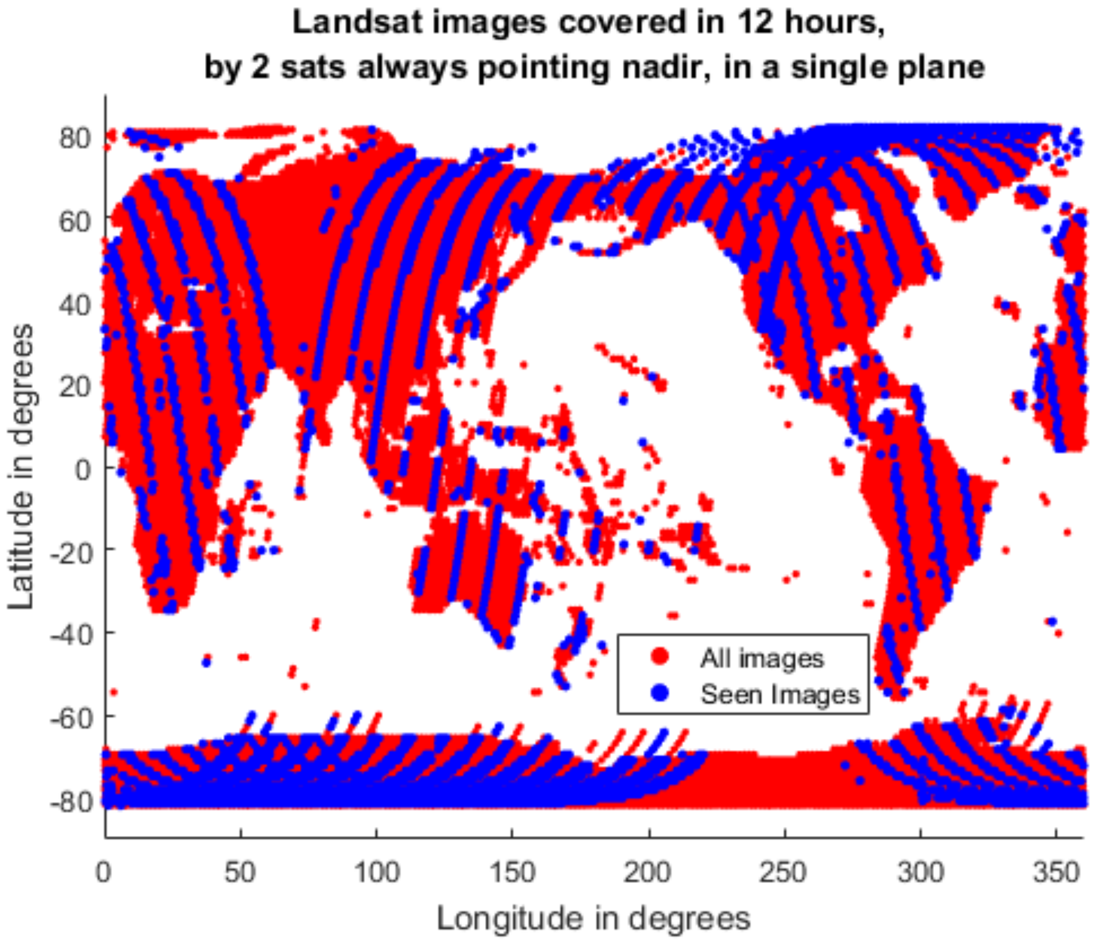
# Agile Spacecraft Constellations Maximizing Coverage and Revisit

*Over 12 hours of planning horizon using 2 satellites, 180 deg apart in the same plane :*

- Using our **proposed DP algorithm**




- Using a **fixed Landsat sensor**, as is




Adding onboard autonomy to flight software + inter-sat communication to the constellation can improve science-driven responsiveness?

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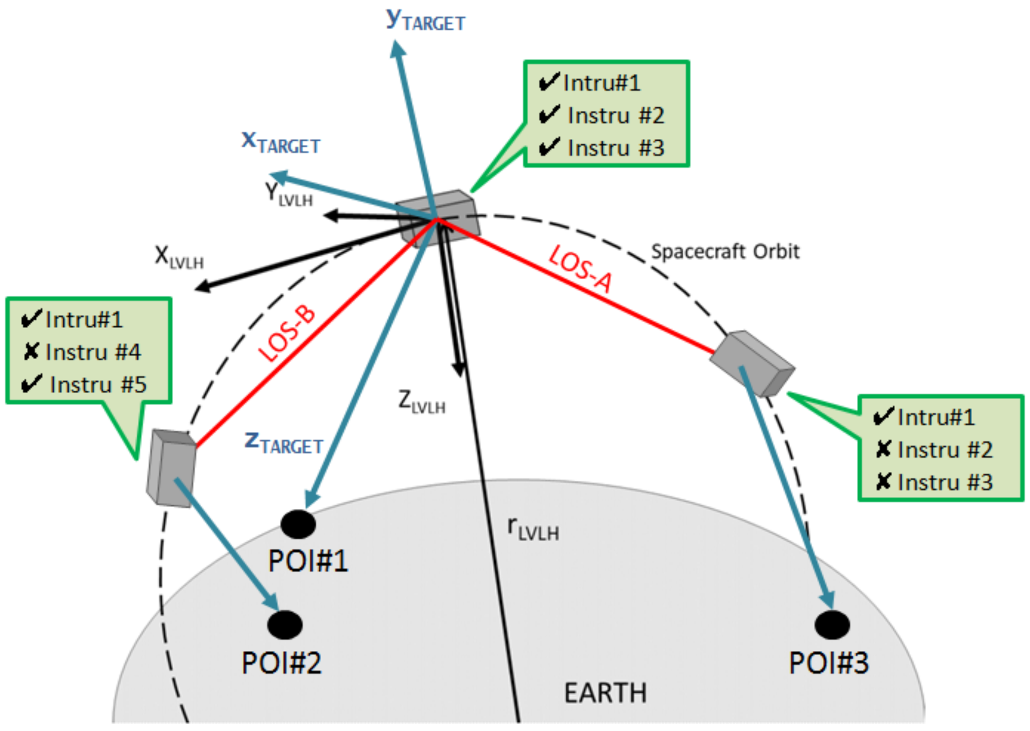
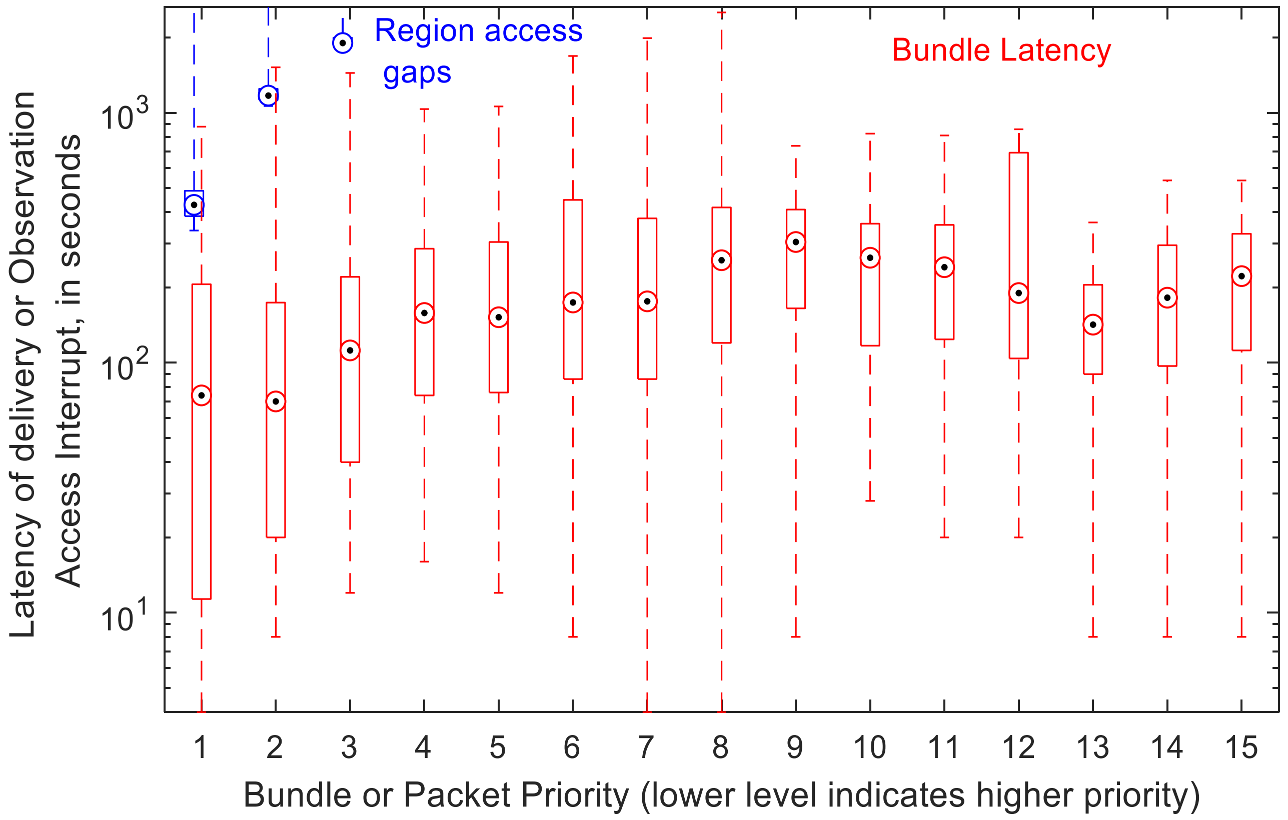
# Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Monitoring




*S. Nag, A. S. Li, V. Ravindra, M. Sanchez Net, K.M. Cheung, R. Lammers, B. Bledsoe, "Autonomous Scheduling of Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Imaging", International Conference on Automated Planning and Scheduling SPARK Workshop, Berkeley CA, July 2019*

If longest latency < shortest gap, for pairs with the same priority => each satellite can be considered fully updated with information from all others, i.e. perfect consensus is possible, in spite of distributed decisions made on a disjoint graph.

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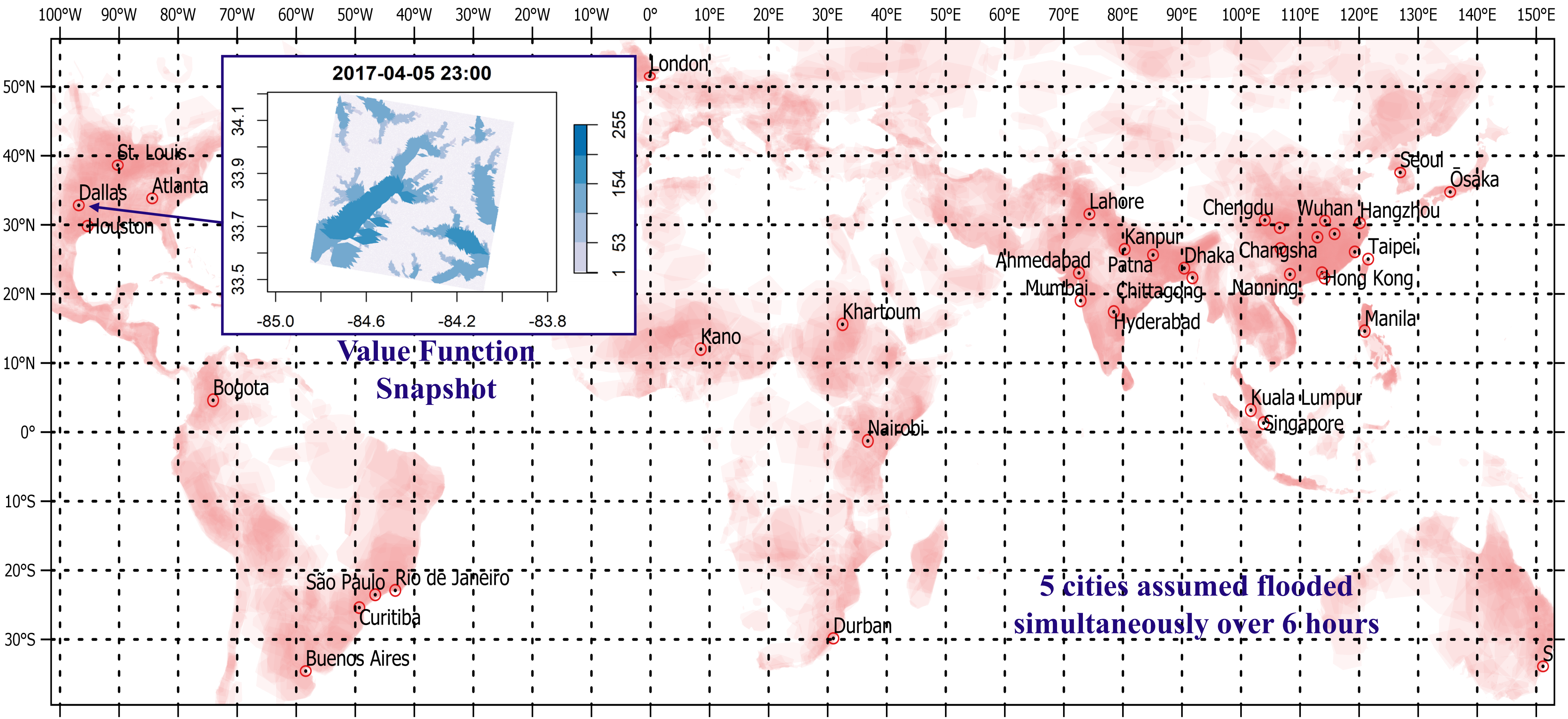
# Initial Use Case: Episodic Precipitation and Transient Floods




**Value Function Snapshot**

**5 cities assumed flooded simultaneously over 6 hours**



*Data: Dartmouth Flood Observatory (Brakenridge 2012)*

# D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions

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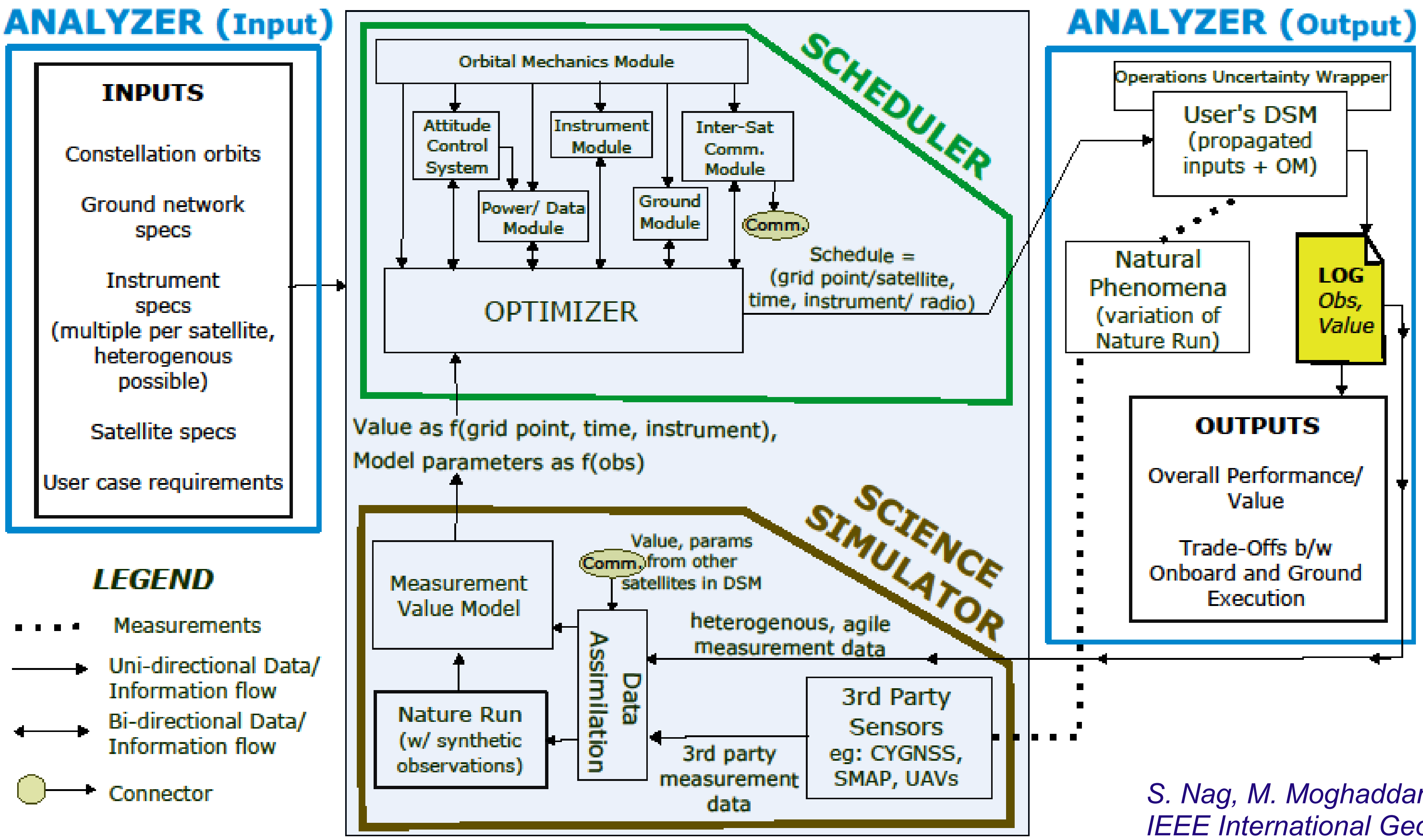



## *Initial results:*

Appropriately low latency in information exchange enables the onboard scheduler to observe ~7% more flood magnitude than a ground-based implementation.

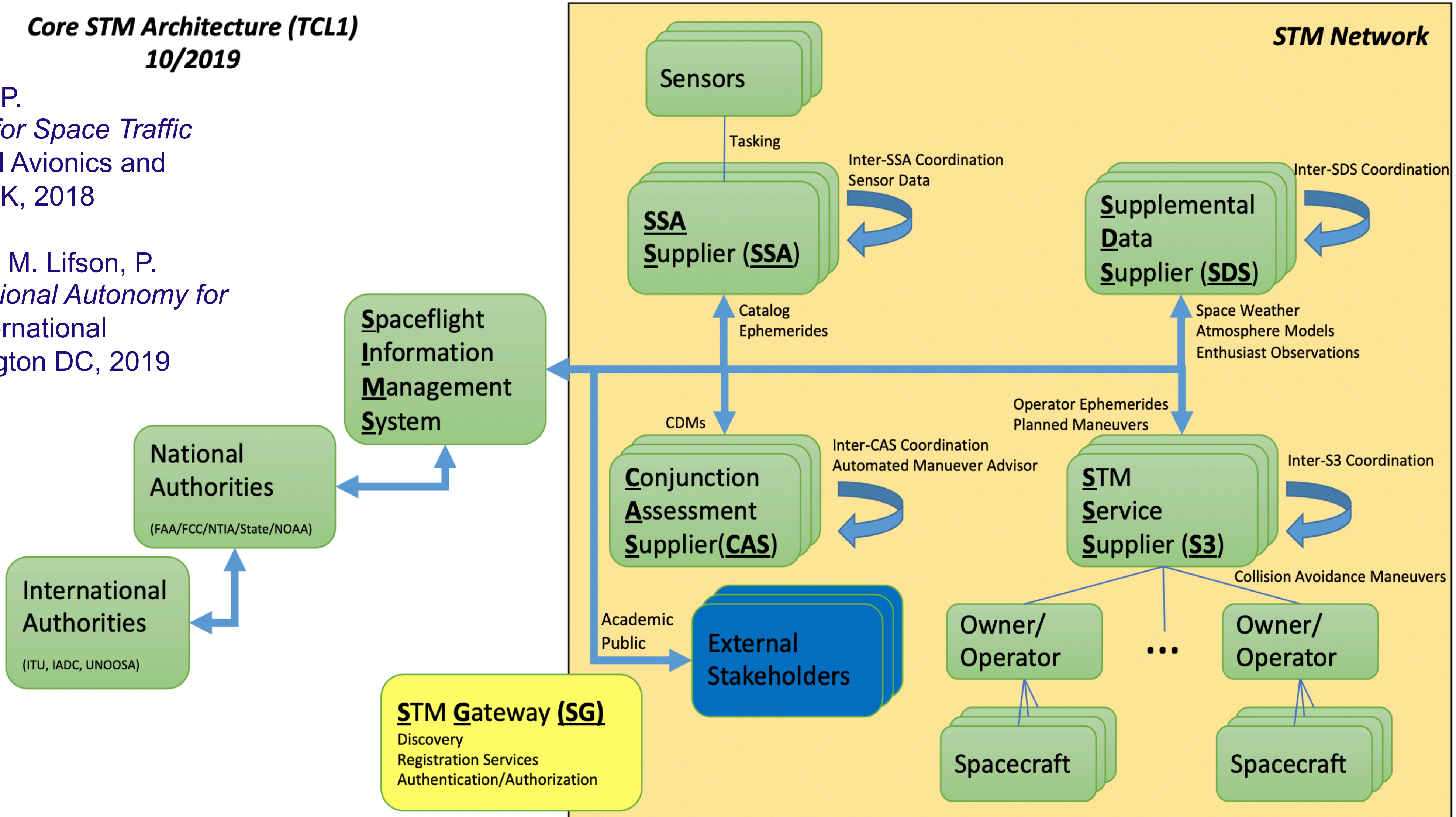
Both onboard and offline versions performed ~98% better than constellations without agility.


*S. Nag, M. Moghaddam, D. Selva, J. Frank, "D-SHIELD", IEEE International Geoscience and Remote Sensing Symposium, Hawaii, July 2020*

# Autonomating Spaceflight Traffic Management

S. Nag, D. Murakami, M. Lifson, P. Kopardekar *"System Autonomy for Space Traffic Management"*, IEEE/AIAA Digital Avionics and Systems Conference, London, UK, 2018

S. Nag, D. Murakami, N. Marker, M. Lifson, P. Kopardekar, *"Prototyping Operational Autonomy for Space Traffic Management"*, International Astronautical Congress, Washington DC, 2019



# Questions?

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# DP-based Onboard/Ground Scheduler

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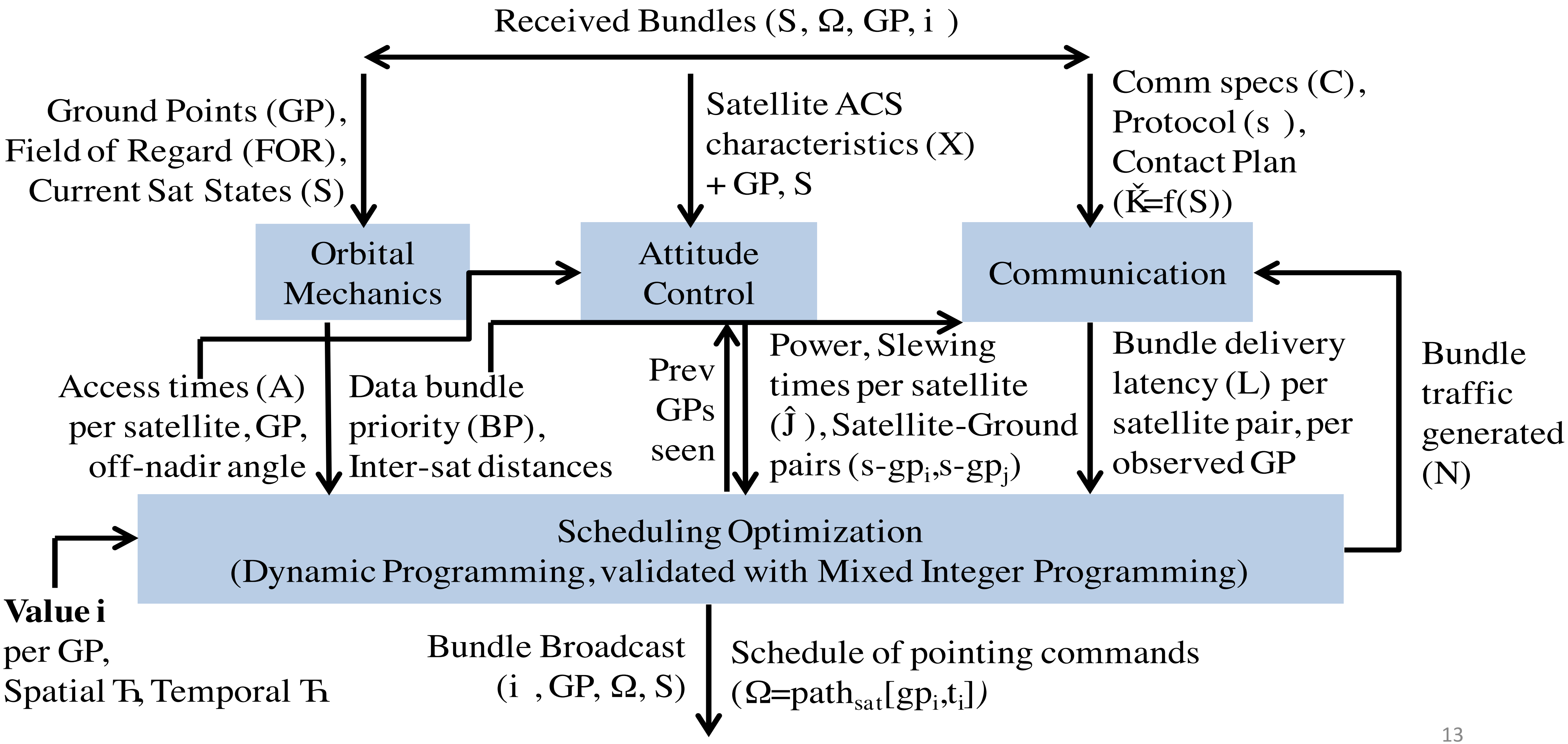
## Information Flow between Scheduler Modules:



# Distributed Spacecraft Autonomy Flight Experiment

**[0] Network Communication**

**[1] Ground Interaction through one swarm asset**

Swarm assets will be able to relay information/files to all other assets, such that any one asset can communicate the state of the swarm and all its information to the ground station/s.

**[2] Commanding of the swarm as one entity**

Humans in ground stations will be able to send their intent to the swarm as commands through a single swarm asset.

**[3] Coordination between multiple assets in the swarm**

Swarm assets will be able to coordinate decisions and make plans among themselves, w/o input from humans or ground automation, however accounting for all such external inputs if they were to arrive.

**[4] Closed-loop control by the Swarm**

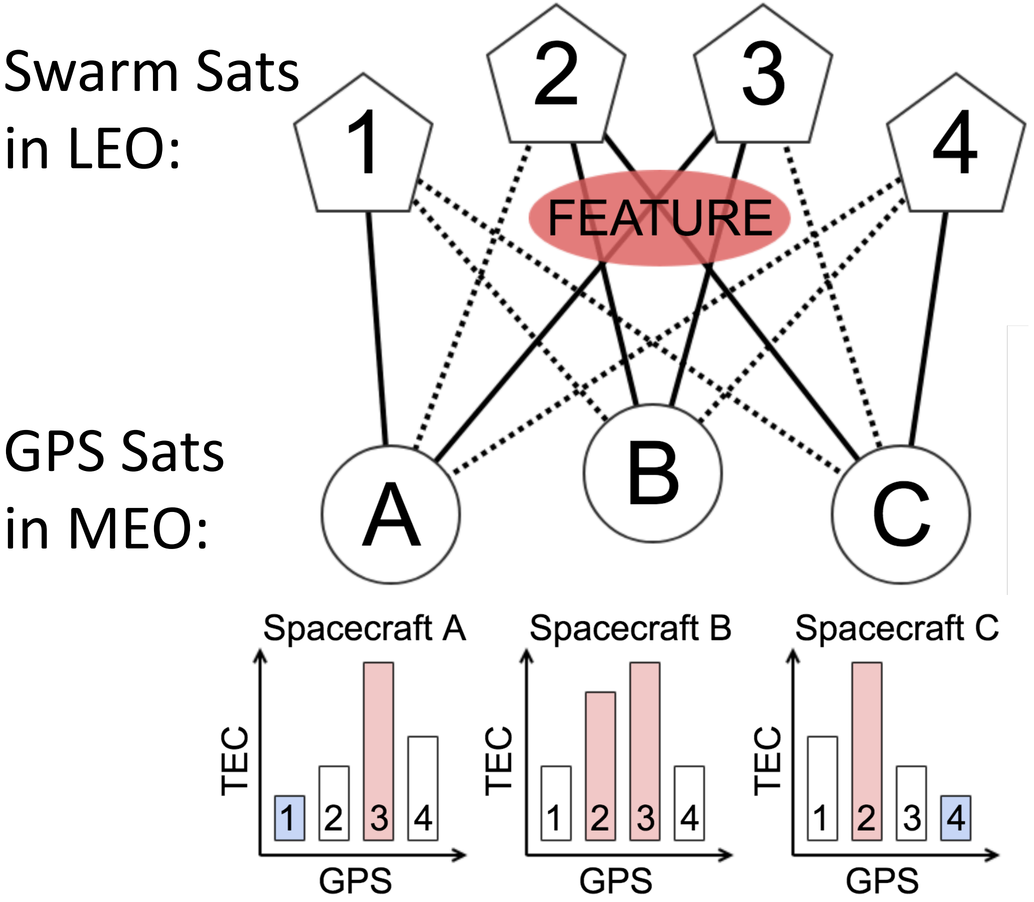
The swarm will be able to control its behavior by processing past observations, making predictions based on results, executing new observations, and repeating this process through the experiment.

**[5] Adaptive reconfiguration by distributed planning**

The swarm will be able to adapt its behavior to a change in the external environment (e.g. plasmasphere) and/or a change in the swarm itself (e.g. failed asset or asset component), by making new plans to replace old ones

**Case Study: GPS Channel Selection/Allocation**

Spacecraft perform live channel selection to identify features of interest and reduce data volume without compromising performance



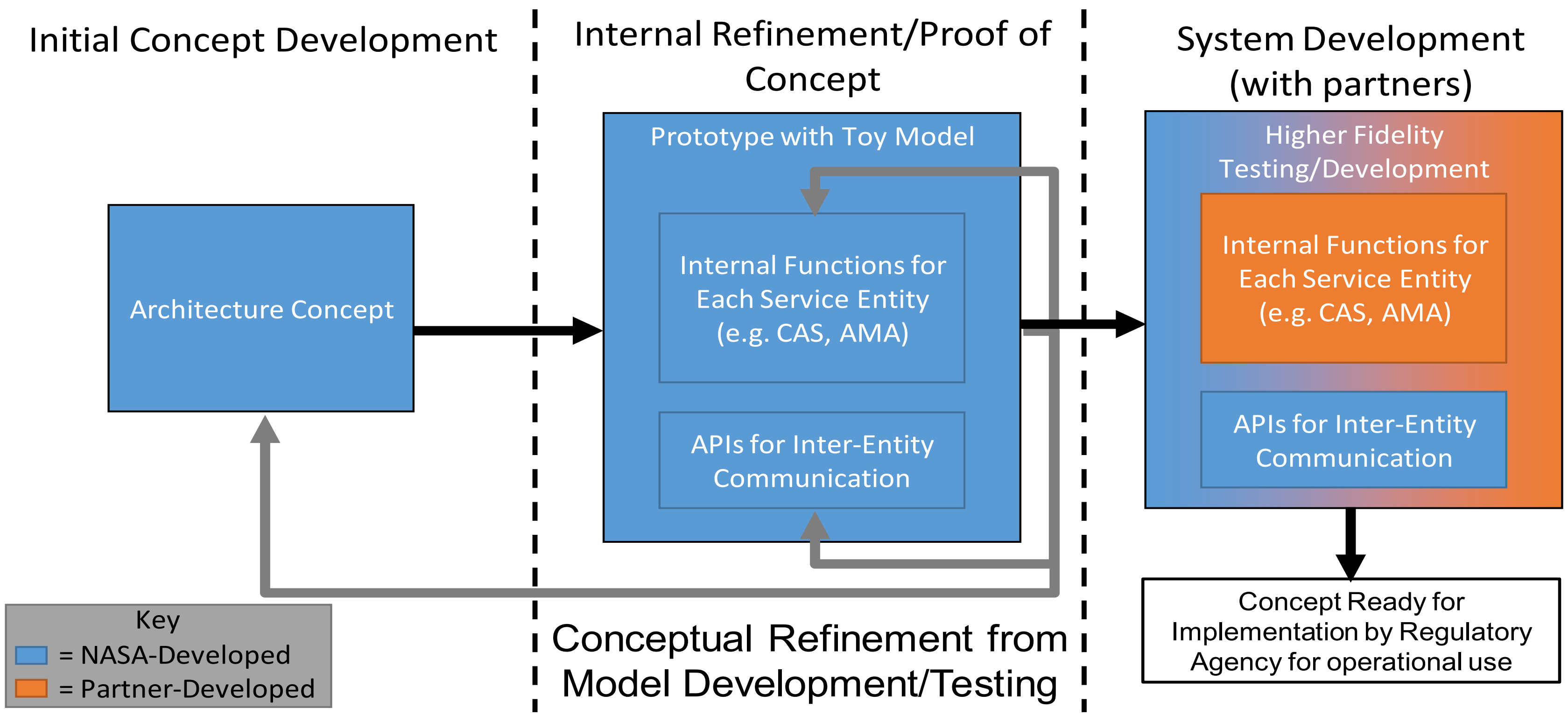

*Funded by NASA STMD Game Changing Development Grant*

# STM Roadmap

- Proposed an STM architecture + software prototyped it with example service providers (e.g. CAS, AMA, SSA) and in-house toy models or publicly available algorithms for internal functions of the services. Will be natured over Tech Capability Levels like UTM

- Presented a maneuver planner and reward function as a strawman for future STM services.
- The STM architecture and standardization of interaction between entities paves the way for a research ecosystem similar to other AI/autonomy fields

*Development cycle of the STM prototype per Technical Capability Level:*



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# STM Use Case: Collision Avoidance Maneuvering