ESTF2020

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

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Program: AIST-18

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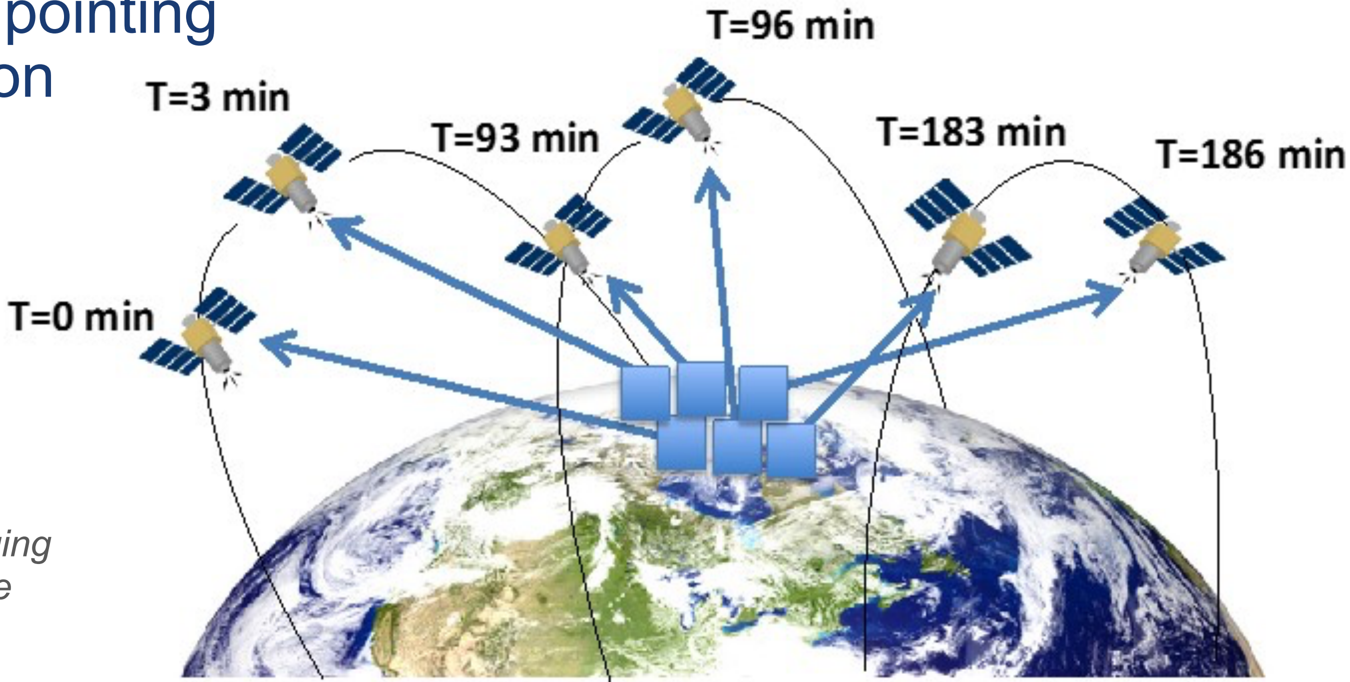
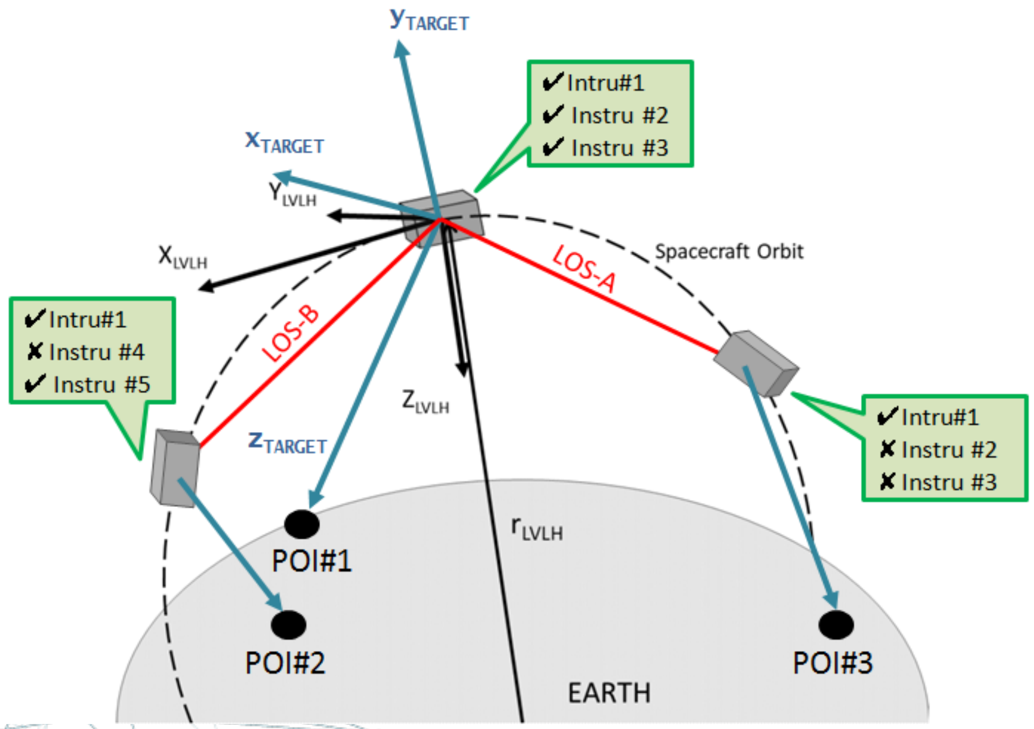
Tech: Agile Spacecraft Constellations Maximizing Coverage and Revisit

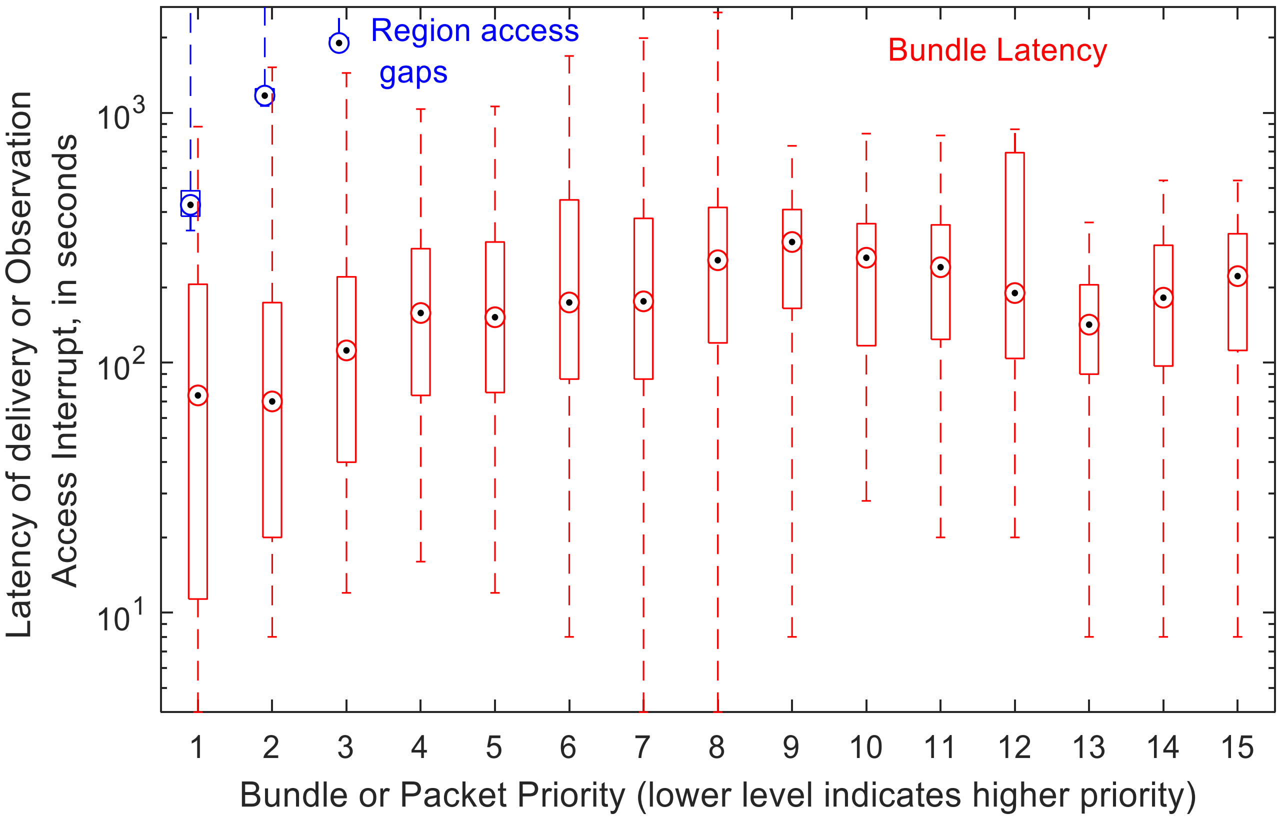
- Small Sat constellation + Full-body reorientation agility + Ground scheduling autonomy = More Coverage, for any given number of satellites in any given orbits
- Using Landsat as first case study w/ a 14 day revisit. Daily revisit needs ~15 satellites or 4 satellites with triple the FOV.
- Assuming 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

Tech: Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Monitoring

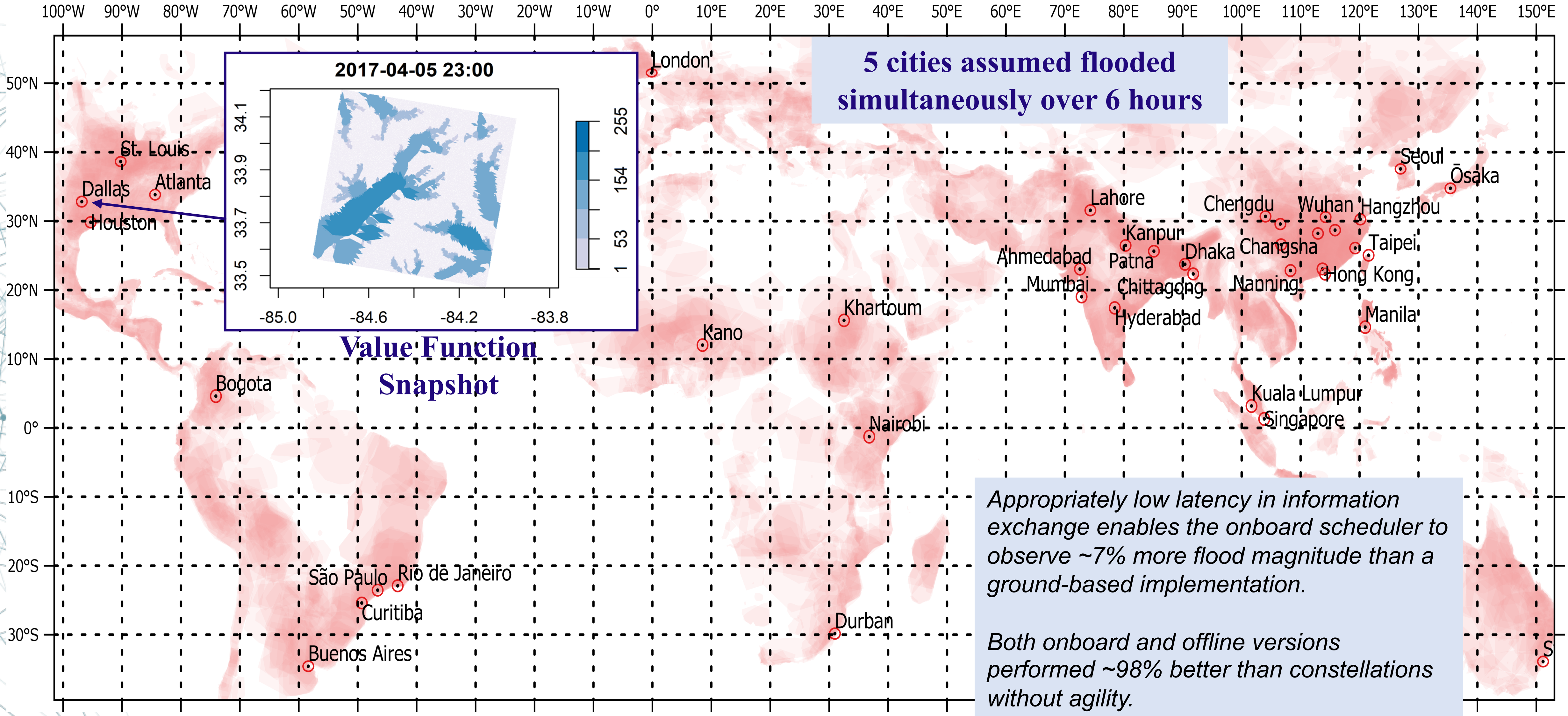




S. Nag, A. S. Li, V. Ravindra, M. Sanchez Net, K.M. Cheung, R. Lammers, B. Bledsoe, "Autonomous Scheduling of Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Imaging", International Conference on Automated Planning and Scheduling SPARK Workshop, Berkeley CA, July 2019

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.

Tech: Add science-in-the loop as lightweight Simulator
Example Use Case: Urban Flood Monitoring



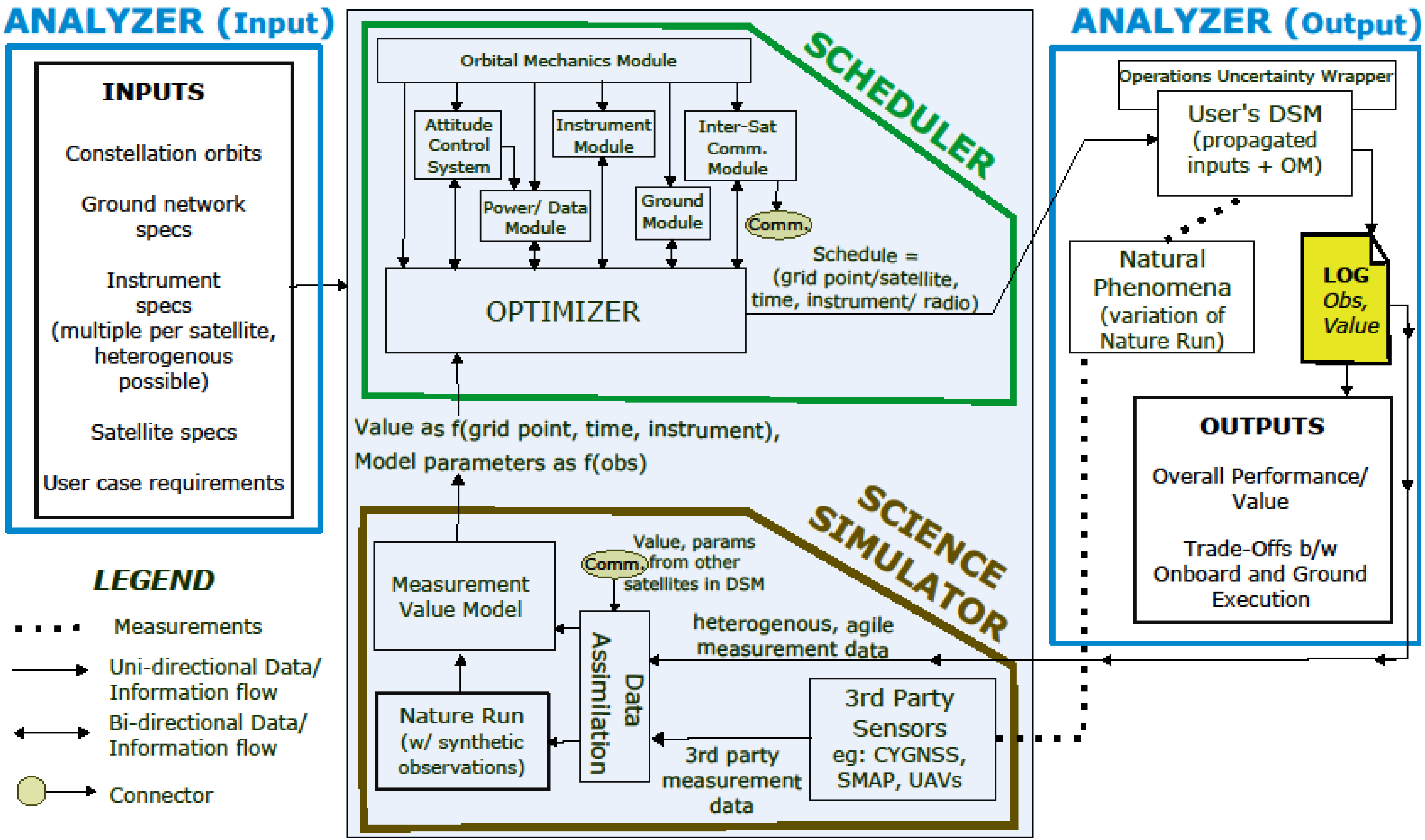
5 cities assumed flooded simultaneously over 6 hours

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.

Data: Dartmouth Flood Observatory (Brakenridge 2012)

D-SHIELD Solution:

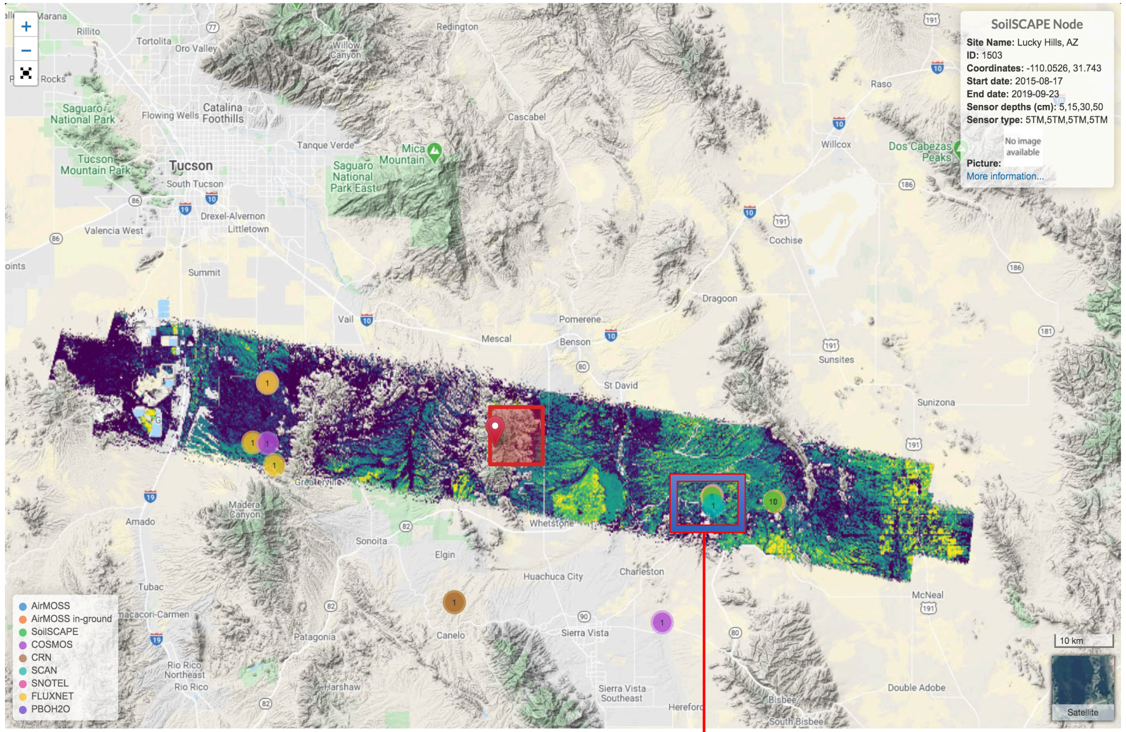


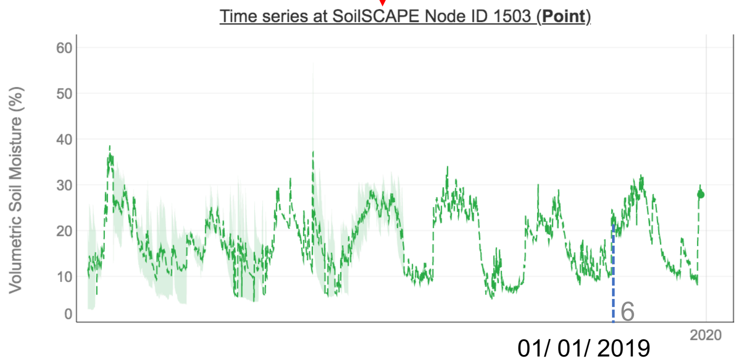
S. Nag, M. Moghaddam, D. Selva, J. Frank, et al, "D-SHIELD", IEEE International Geoscience and Remote Sensing Symposium, Hawaii, July 2020

Use Case: Soil Moisture Monitoring for Uncertainty Minimization

SoilSCAPE site in Walnut Gulch, AZ
www.ars.usda.gov

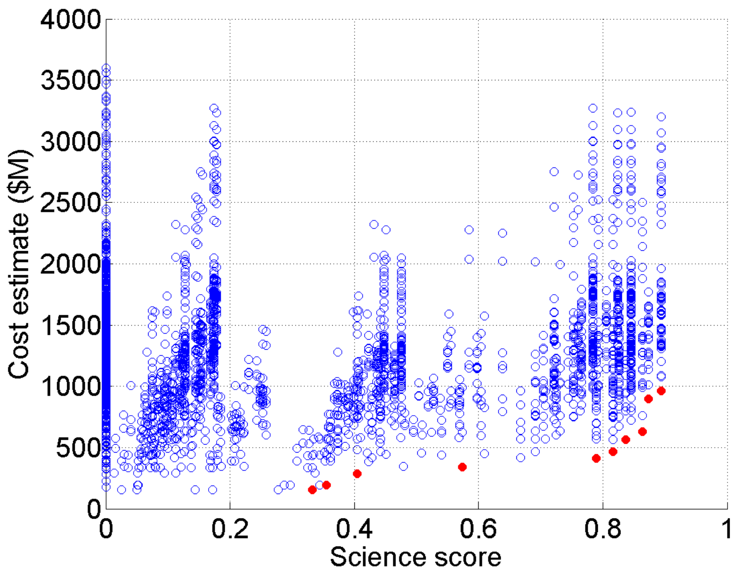
- Use soil moisture measurements from SoilSCAPE, add noise to it to find the minimum acceptable sigmaNEZ by small sat
- Size a representative constellation with 3 types of instruments
- Schedule the constellation to make multi-payload observations to reduce soil moisture uncertainty
- Science simulator: passive microwave, hydrologic land-surface model, data assimilator across third party sources – spaceborne (e.g. Sentinel-1, SMAP), airborne (e.g. P-band AirMOSS and L-band UAVSAR) or ground based sensors (e.g. SoilSCAPE) to compute value





Mission concept down-selection

- Consider mission concepts based heterogeneous constellations carrying combinations of L-band/P-band radars, radiometers, and reflectometers of different sizes in different orbits.
- Use VASSAR to evaluate mission concepts [2]
  - Estimate science/societal benefit by calculating capabilities and performance based on knowledge base and comparing against WMO requirements for soil moisture products.
  - Estimate lifecycle cost using spacecraft sizing algorithm and cost estimating relationships
- Use ESTO-funded TAT-C ML TSE algorithms to search over space of possible concepts [1]



Details of non-dominated architectures

Arch#	Payload	Instr allocation	h (km)	orbit type	#sats per plane
669 (*)	LRADIO XRADIO PSAR	[1, 1, 1]	800	SSO DD	2
586	LRADIO PSAR	[1, 1]	800	SSO DD	2
811	LRADIO PSAR	[1, 1]	800	SSO DD	1

Automatically generated explanations

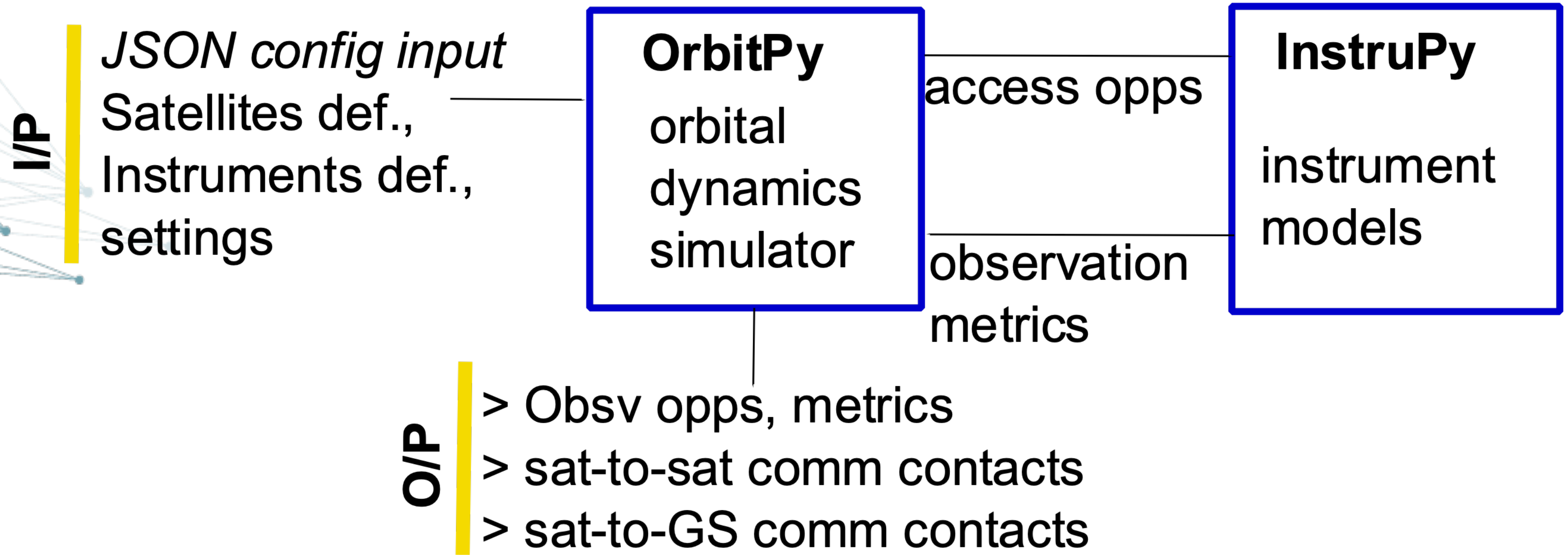
Architecture #3 achieves a score of 0.8730 because:
Subobj **CLI2-2** (meas **"3.4.1 Ocean surface wind speed"**) gets a score of 0.5 (loss of 0.010 value) because:
Atribute orbit-inclination gets a score of "Half" because of SSO orbit does not provide adequate tidal sampling (polar orbit required)
Subobj **ECO2-1** gets a score of 0 because no measurement of parameter **"2.3.3 Carbon net ecosystem exchange NEE"** is found (requires multispectral measurements)

[1] P. G. Buzzi and D. Selva, "Evolutionary formulations for design of heterogeneous Earth observing constellations," in *2020 IEEE Aerospace Conference*, 2020.

[2] D. Selva, B. G. Cameron, and E. F. Crawley, "Rule-Based System Architecting of Earth Observing Systems: Earth Science Decadal Survey," *J. Spacecr. Rockets*, vol. 51, no. 5, pp. 1505–1521, 2014.

Tech Details: Orbits and Instruments

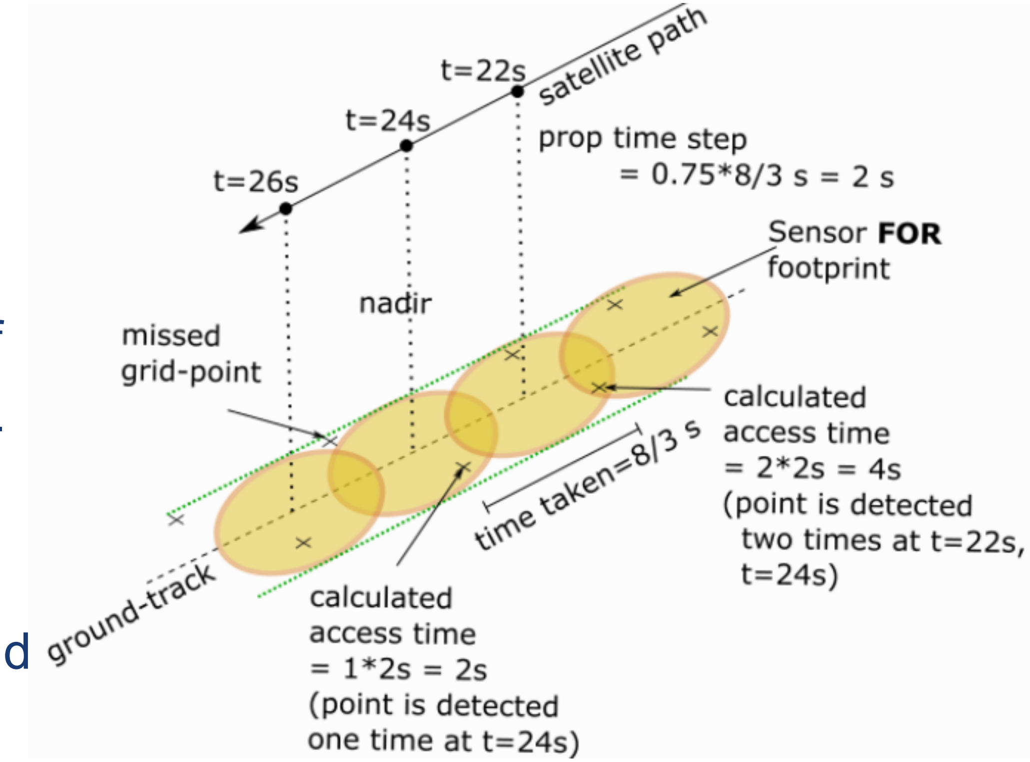
- Work in tandem to produce set of observation opportunities and communication contact opportunities.
- Avail as standalone python packages.



Tech Details: Orbits

OrbitPy Package --

- Simple analytical orbital dynamics model with consideration of only J2 perturbations.
- Coverage calcs
  - Point-Grid method: Discretize region by set of grid-points and calculate the times are which the satellite "can potentially observe" the grid-points (support conical FOR and rectangular FOR).
  - Pointing options method: Discretize maneuverability of an agile satellite by set of pointing-options (eg: roll: [-10, 0, 10] degs) and calculate locations "covered" over the entire mission period.
- Communication contact opps
  - Line-of-Sight (LOS) calculation between entities of interest (satellites, ground-stations). Availability of LOS (with elevation constraint for GSs) => comm opportunity

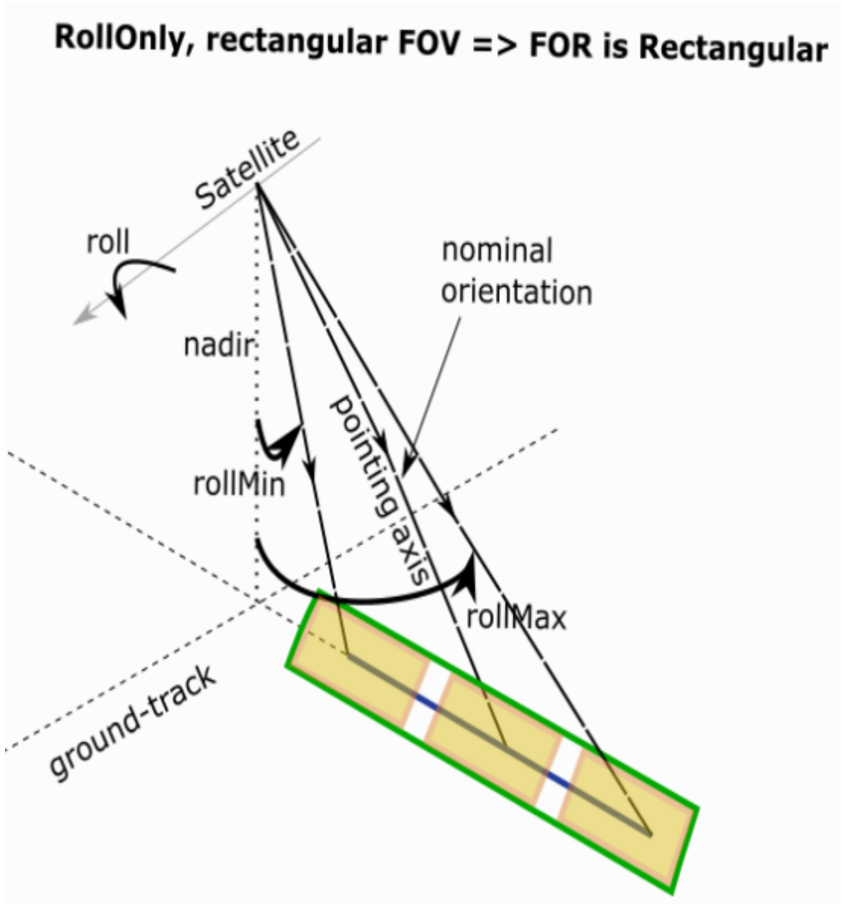


Coverage calculations using the point-grid method

Tech Details: Instruments

InstruPy Package --

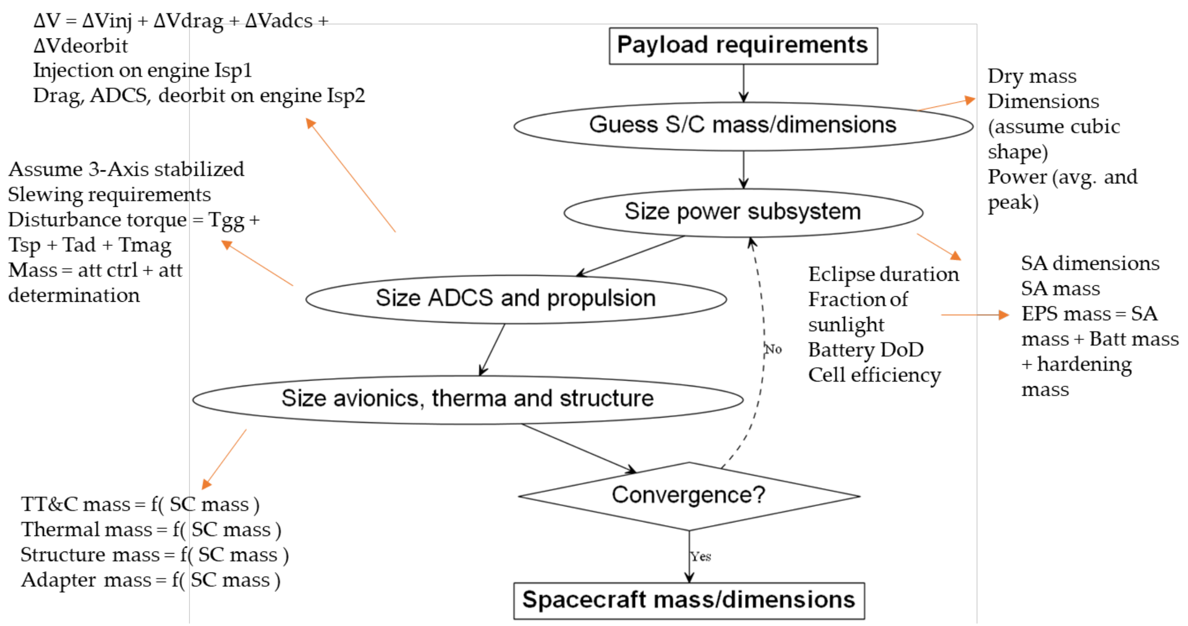
- Simple observation metric model considering observation geometry and instrument specs.
- Current suite of instruments with metrics:
  - Basic: Range, Incidence angle, Solar elevation angle
  - Passive-Optical: SNR, NEDT, Dynamic range, pixel resolutions
  - SAR: Sigma NEZ, Incidence angle, pixel resolutions
- Calculation of sensor FOR given the sensors/satellites maneuverability and the sensor FOV



Field-Of-Regard (FOR) calculation from a rectangular FOV and roll only maneuverability.

Tech Details: Spacecraft sizing

- Adapt existing spacecraft sizing algorithm [1] that estimates mass/power/size of each spacecraft based on payload+orbit characteristics.
- Combination of first principles calculations, empirical mass fractions, and expert-based complexity penalties.
- Informs instrument and satellite sizing trades
- Informs operational constraints for the planner (e.g., instrument power, duty cycle)



[1] D. Selva, B. G. Cameron, and E. F. Crawley, "Rule-Based System Architecting of Earth Observing Systems: Earth Science Decadal Survey," *J. Spacecr. Rockets*, vol. 51, no. 5, pp. 1505–1521, 2014.

Work in Progress

- D-SHIELD Optimizer is protoyped on greedy path selection using dynamic programming (DP). Currently developing a modular, fast optimization approach that can handle the newly added complex aspects of payload operations and guarantee solutions in real time for operational use in global missions, scalable to scores of assets
- Work ongoing to maturing the ACS, DTN module and building the ground, power, data modules
- D-SHIELD Science Simulator to be based on an OSSE developed for a soil moisture relevancy scenario
- After sizing is finalized, will build the spatio-temporal value model (OSSE+Instruments) and the D-SHIELD Analyzer

Questions?

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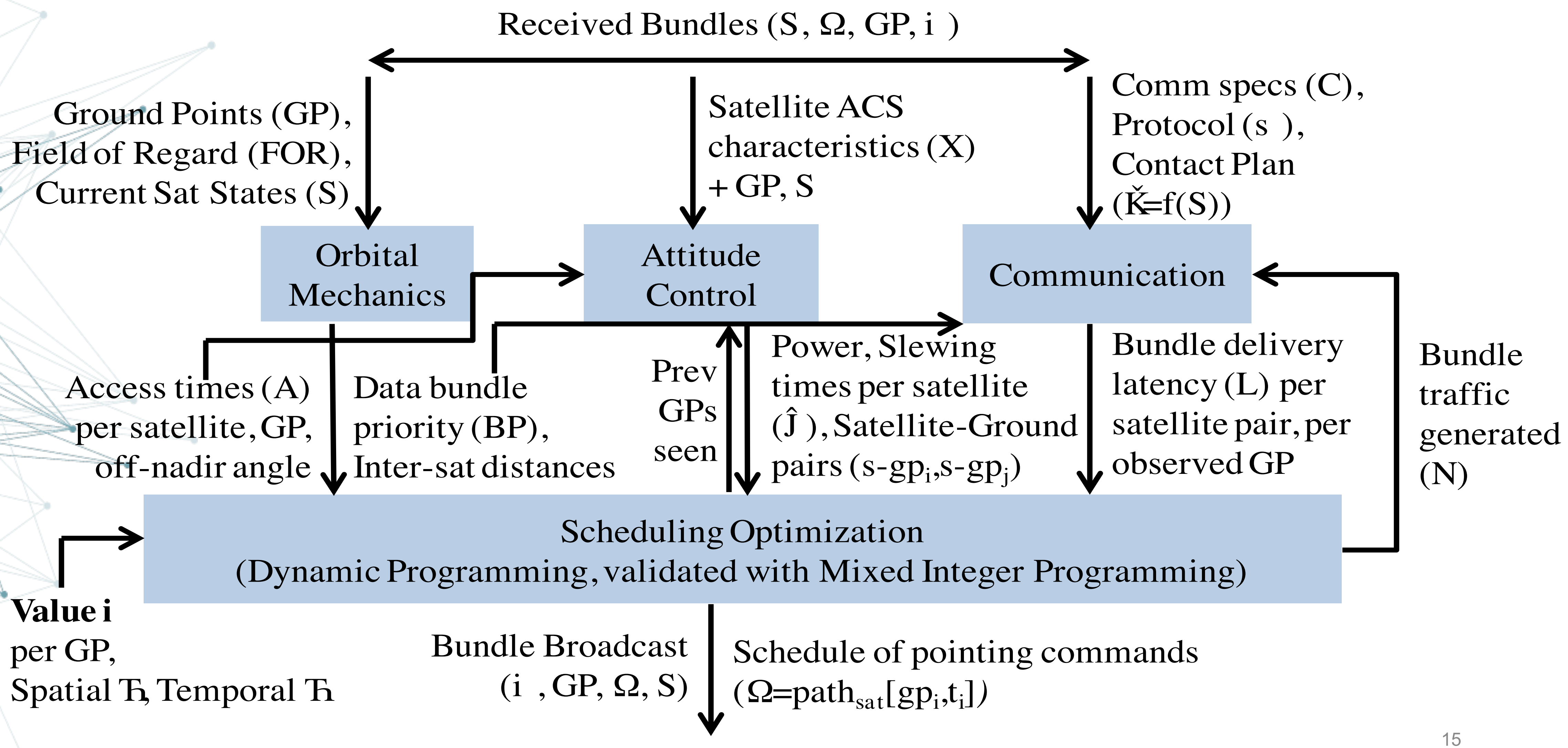
Back Up Slides

Onboard/Ground Scheduler

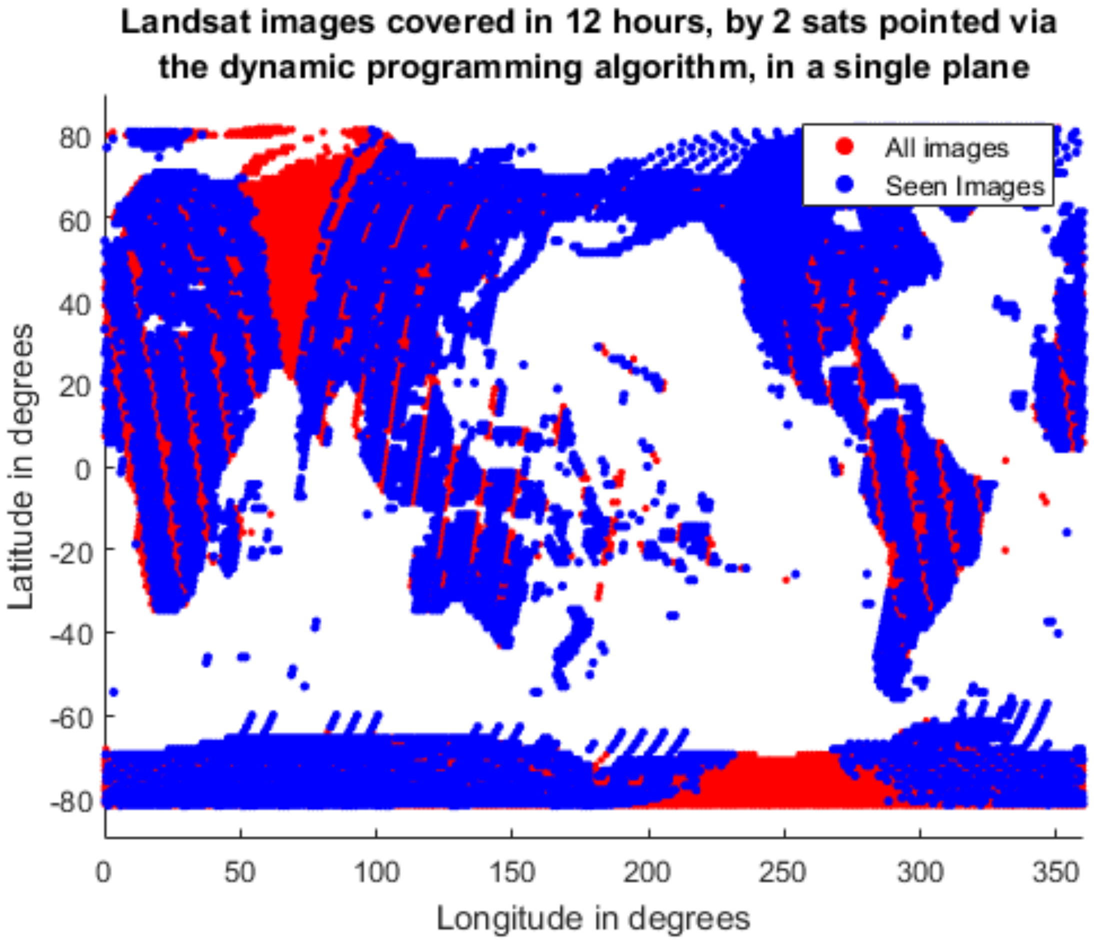
Information Flow between Scheduler Modules:



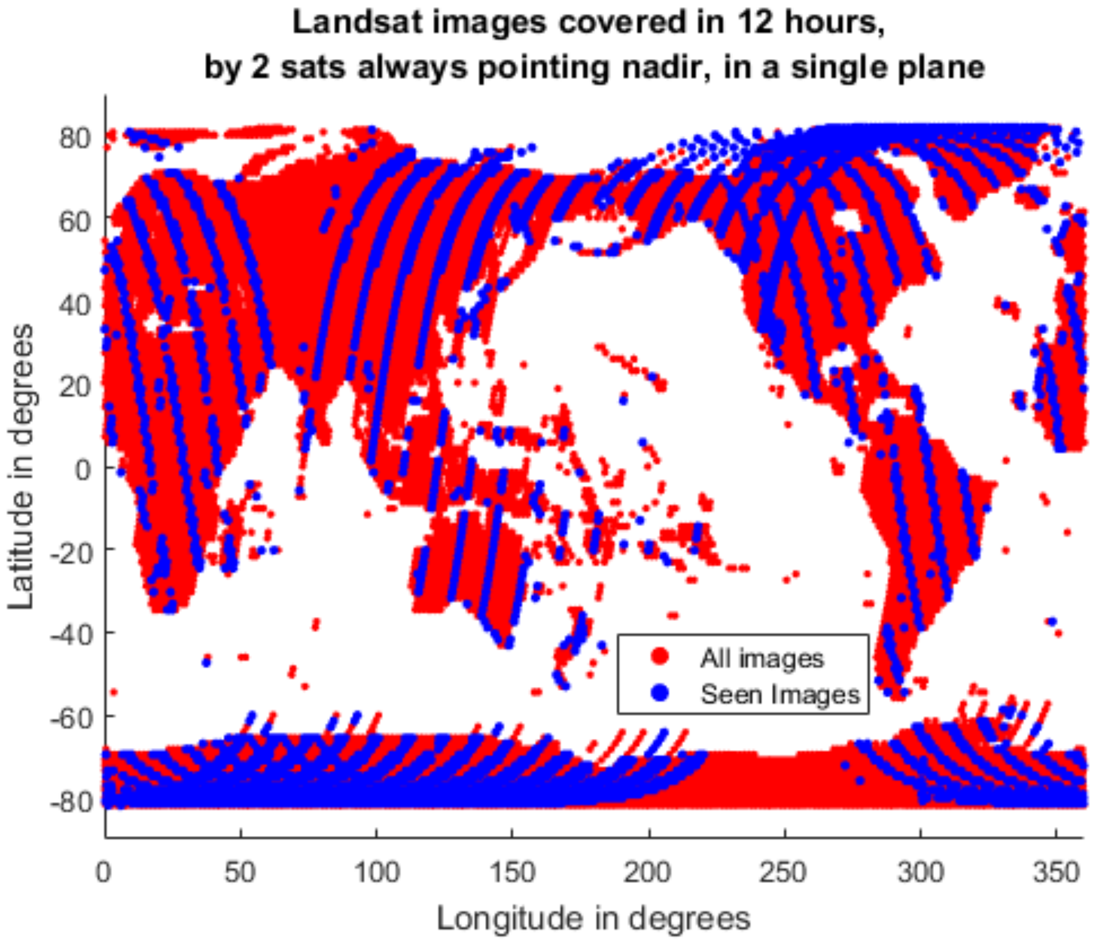
Tech: Agile Spacecraft Constellations Maximizing Coverage and Revisit

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?

MIP applied to Downlink Scheduling

- S1 collects high priority data from target p1 from tick 1 through tick 3.
- After tick 1, S1 begins downloading high priority data to R1 until it empties its bucket of high priority data at tick 4, then S1 downloads low priority data on ticks 5 & 6.
- S1 begins collecting high priority data on tick 6, so resumes high priority download at tick 7 until the end of S1's download window to R1 at tick 7.
- Receiver R2 is being used by Sat S2 for ticks 6-9, so S1 must *slew* to R3 during tick 8 and then download it's remaining 2 units of high priority data to R3 on ticks 9 and 10, then resumes downloading low priority data. R3 then *slews* to S2 on tick 14 and S2 begins downloading high priority data to R3 on tick 15.

Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Inputs																
Satellite S1																
Obs windows																
High	**p1**	**p1**	**p1**			**p3**	**p3**	**p3**		**p4**	**p4**					
Low	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2	p2
slew								*slew*								
DL windows																
R1		1	1	1	1	1	1									
R2				2	2											
R3								3	3	3	3	3	3			
Satellite S2																
Obs windows																
High		**p4**	**p4**		**p6**	**p6**	**p6**			**p7**	**p7**	**p7**				
Low	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8	p8
DL windows																
R1			1	1	1	1	1	1								
R2					2	2	2	2	2							
R3								3	3	3	3	3	3	3	3	3

Output (plan)																
Receiver																
R1		*1H*	*1H*	*1H*	1L	1L	*1H*									
R2						*2H*	*2H*	*2H*	*2H*	*2H*						
R3									*1H*	*1H*	1L	*1H*	*1H*	*slew*	*2H*	*2H*

pN = observation position N. RM = receiver M.
Italics = High priority: NH = high priority download from sat N. NL = low priority download from sat N.