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

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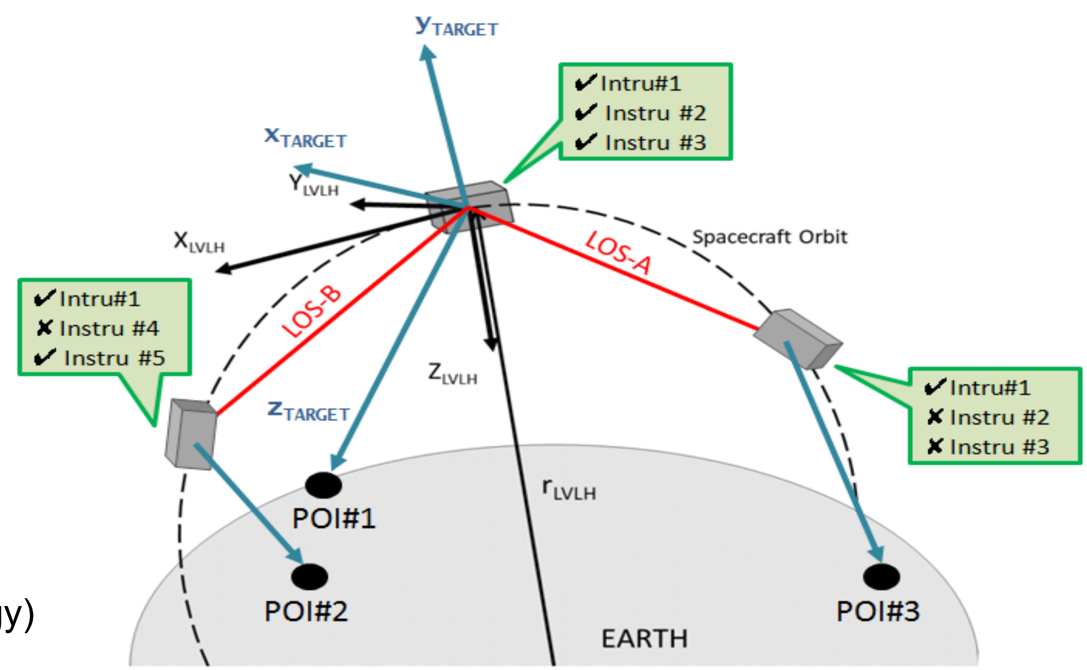
Background: Motivation

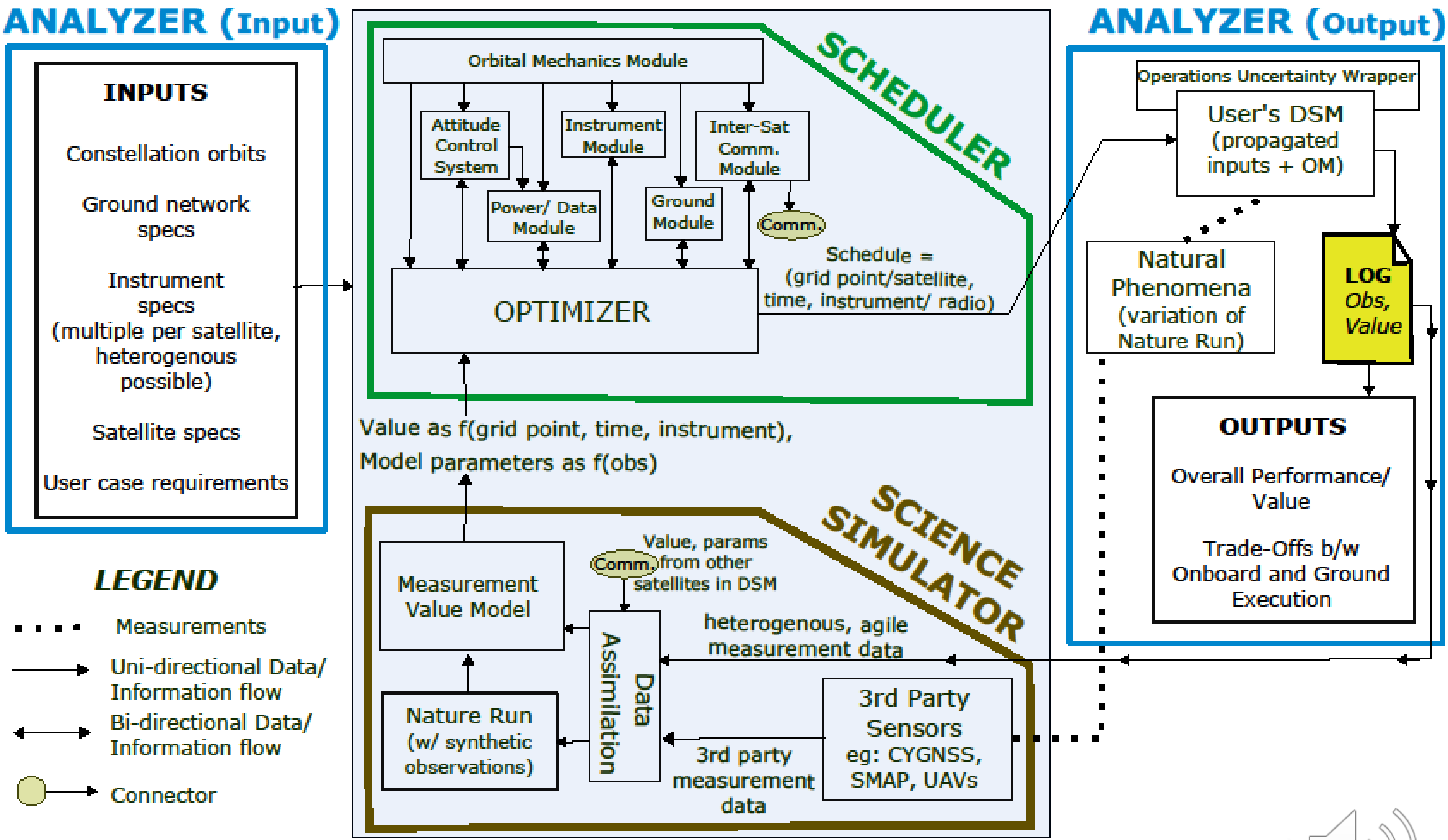
- Multi-payload, multi-spacecraft constellation scheduling for spatio-temporally varying science observations
- Small Sat constellation + Full-body reorientation agility + scheduling autonomy = More Coverage, for any given number of satellites in any given orbits
- Ground scheduling algorithm allows 2-sat, 1-imager constellation over 12 hours to observe 2.5x compared to the fixed pointing approach. 1.5x with a 4-sat constellation
- Onboard scheduling algorithm allows 24-sat, 1-rainradar constellation to observe ~7% more flood magnitude than ground scheduling

Published Use Cases:

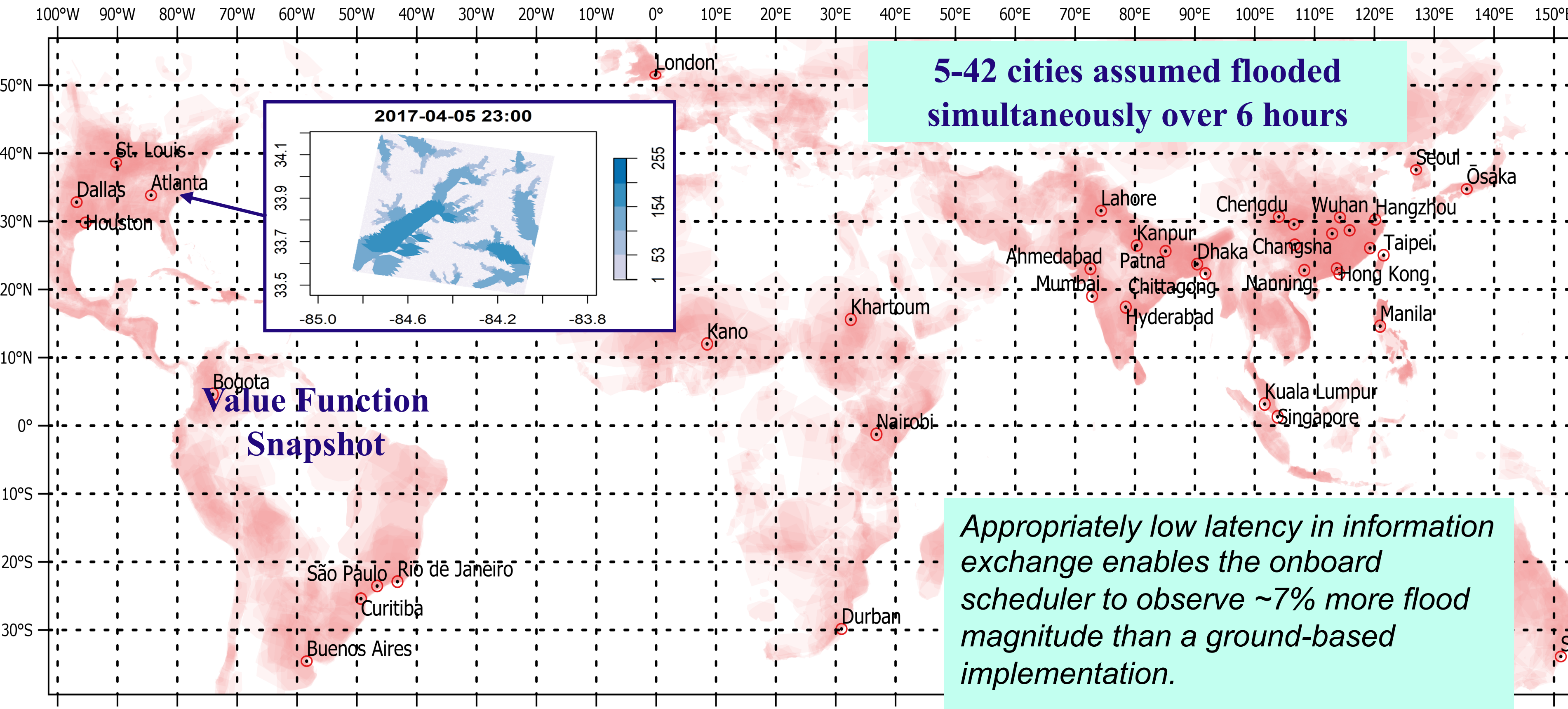
1. Land coverage and coral tracking (COSPAR ASR)
2. Cyclone tracking (IEEE TGRS)
3. Urban Floods (J.Hydrology)



D-SHIELD Proposal



Science Relevancy Scenario: Urban Floods



5-42 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)

Results: S. Nag, et al, "*Autonomous Scheduling of Agile Spacecraft Constellations with Delay Tolerant Networking for Reactive Imaging*", ICAPS SPARK Workshop, Berkeley CA, July 2019

Results: S. Nag, et al, "*Designing a Disruption Tolerant Network for Reactive Spacecraft Constellations*", AIAA ASCEND, Nov 2020

Science Relevancy Scenario: Soil Moisture

Goal: Use a combination of spaceborne radar, radiometers, reflectometers to make spatio-temporal measurements that will reduce soil moisture uncertainty

Traditional Solution: Design a single or constellation of instruments (size, altitude) to address spatio-temporal trade-offs (underscored in conflict with all others)

Radiometric: Noise sigma Speckle Kp	*Spatial Metrics:* Resolution => Static Uncertainty Coverage => Global Understanding	*Temporal Metrics:* Revisit => Dynamic Uncertainty Revisit => Global Understanding

Baseline = SMAP Conical Scanning:
-30dB sigNEZ ; 450m along track (AT) resolution ; 3 day global coverage+revisit

Alternative = Science-based Intelligent Planning of Stripmap SAR:
-30dB sigNEZ ; optimized* spatial resolution at the cost of speckle, coverage, revisit ~ to be addressed by more looks + measurements using constellation + intelligent agility

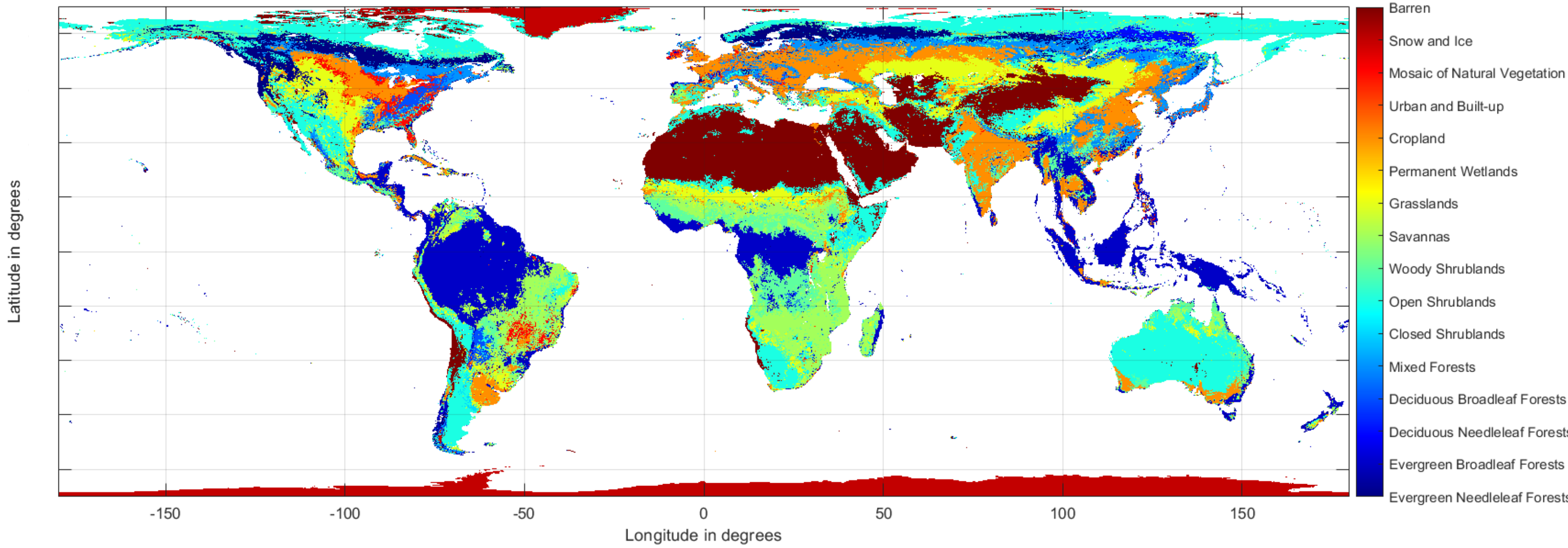
* ~7m AT and >250m CT resolution

Goal: Measure to reduce Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

International Geosphere–Biosphere Programme (IGBP) 16 classes distilled into 5 relevant for Soil Moisture: Forest, Shrubland, Cropland, Grassland, Bare



Ignoring water, wetland, urban, frozen

Goal: Measure to reduce Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

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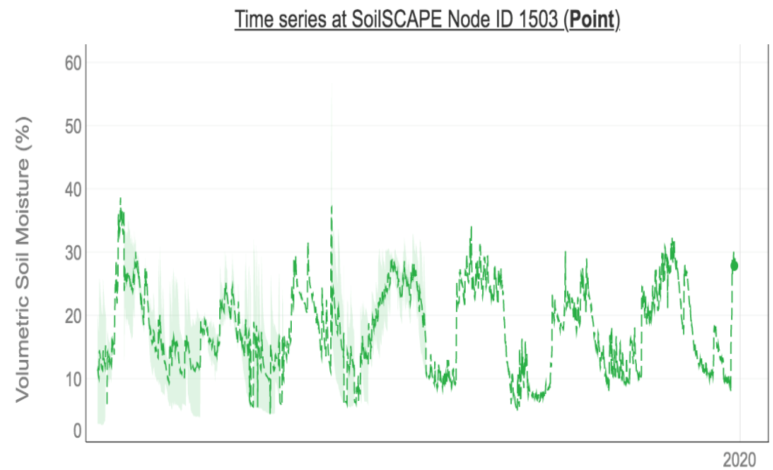
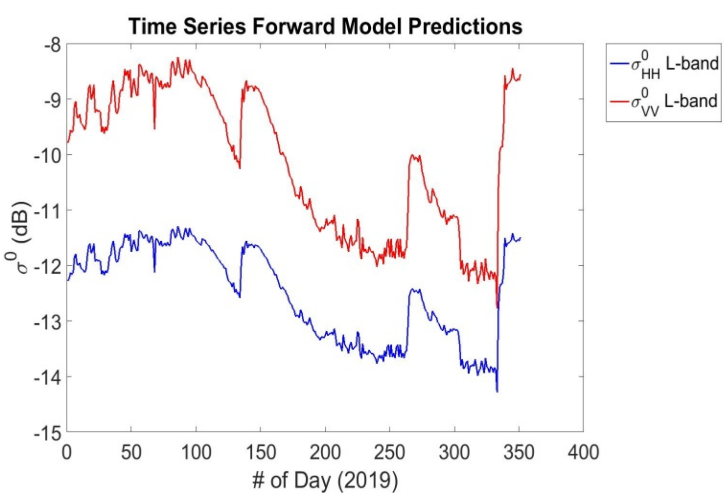
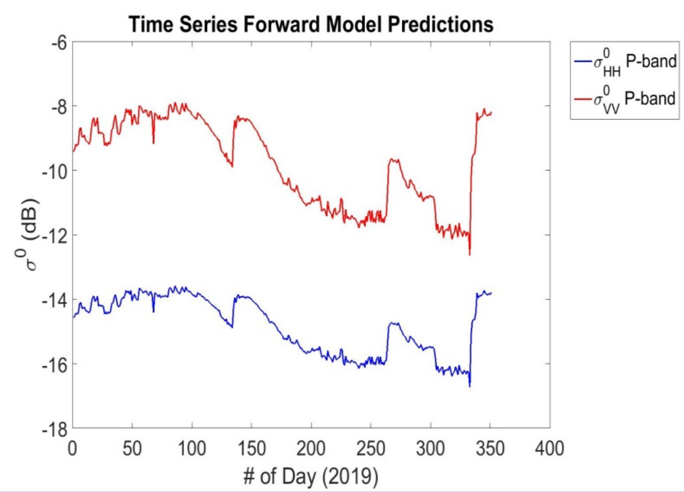
Will be accounted for in the speckle noise model of the science simulator



*Time Series radar cross section (RCS) prediction for Walnut Gulch at **L:**1.57GHz, **P:**430MHz, VWC = 0.29kg/m2, 40deg incidence, 0.02m roughness*





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Goal: Measure to reduce Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

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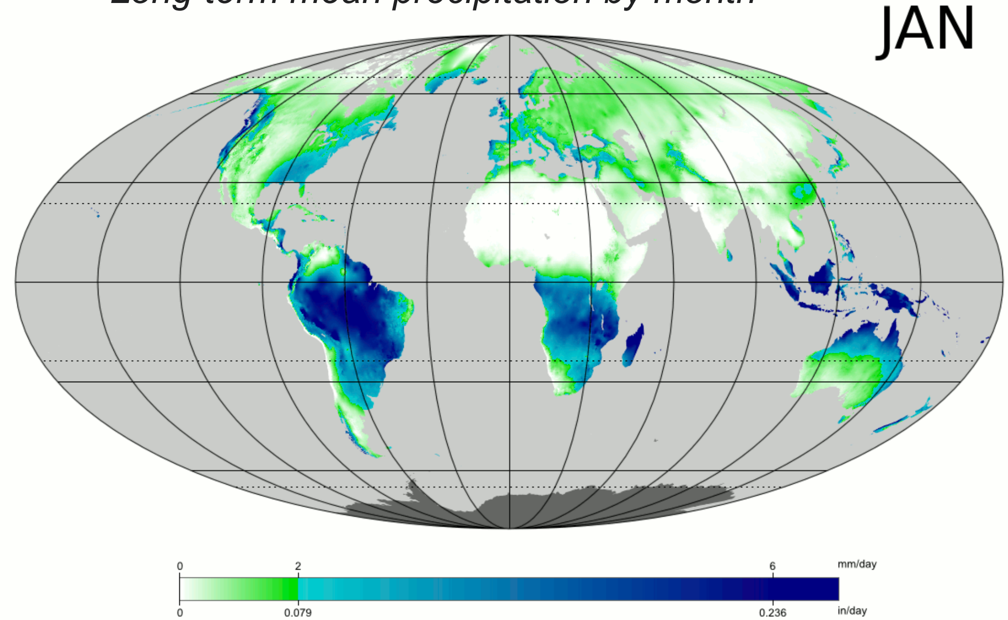
Hourly precipitation forecast from GEOS FP in Cubed-sphere grid C720 resolution (12 km) and ~30km lat-lon. Using PRECTOT - Total precipitation (kg m-2 s-1) …

SMAP saturated pixel product globally available every 3 days. Interesting pixels are those that are not saturated and there has been rain recently…

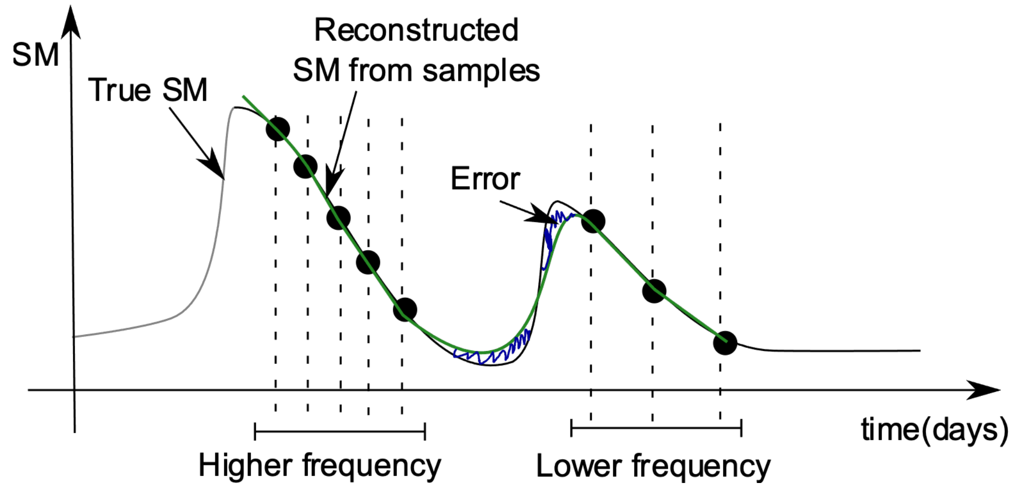
Long-term mean precipitation by month



Website: https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php
Forecast data: https://fluid.nccs.nasa.gov/weather/

Addressing Temporal Resolution / Science Needs

Temporally close measurements (just as neighboring pixels) can be combined to reduce speckle noise. Use inverse modeling to find maximum ΔT up to which SM dynamism does not prevent meaningful integration => ΔT=2hours



		Shrubland, wet period				
Table B Coding:		Sat#1 Pay#1	Sat#1 Pay#2	Sat#2 Pay#1	Sat#2 Pay#2	M.E.E.SM
Code	Meaning	0	0	0	0	
0	No operation	0	0	0	1	0.0039
1	35+/-5 deg inc, 1 obsvs	0	0	0	2	0.0048
2	45+/-5 deg inc, 1 obsvs	0	0	0	3	0.032
3	55+/-5 deg inc, 1 obsvs	0	0	0	4	0.0038
4	35+/-5 deg inc, 2 obsvs	0	0	0	5	0.0048
5	45+/-5 deg inc, 2 obsvs	0	0	0	6	0.0319
6	55+/-5 deg inc, 2 obsvs	0	0	1	1	0.0038
		0	0	1	2	0.0041
		0	0	1	3	0.0161
		0	0	1	4	0.0038

1000+ rows of combinatorics for 2 sats

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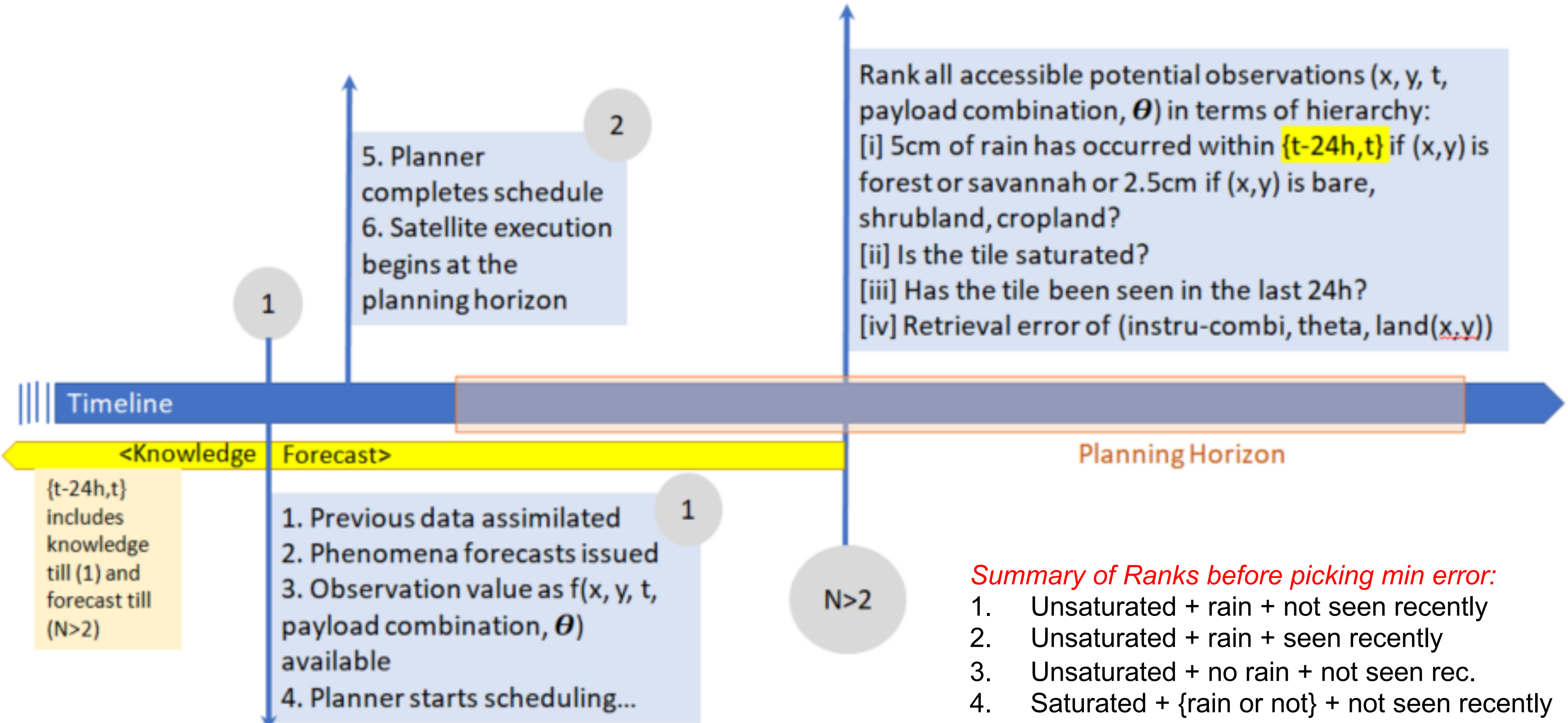
Concept of Operations

Preliminary rules as a strawman for the science simulator:



Summary of Ranks before picking min error:

1. Unsaturated + rain + not seen recently
2. Unsaturated + rain + seen recently
3. Unsaturated + no rain + not seen rec.
4. Saturated + {rain or not} + not seen recently
5. Unsaturated + no rain + seen recently
6. Saturated + {rain or not} + seen recently

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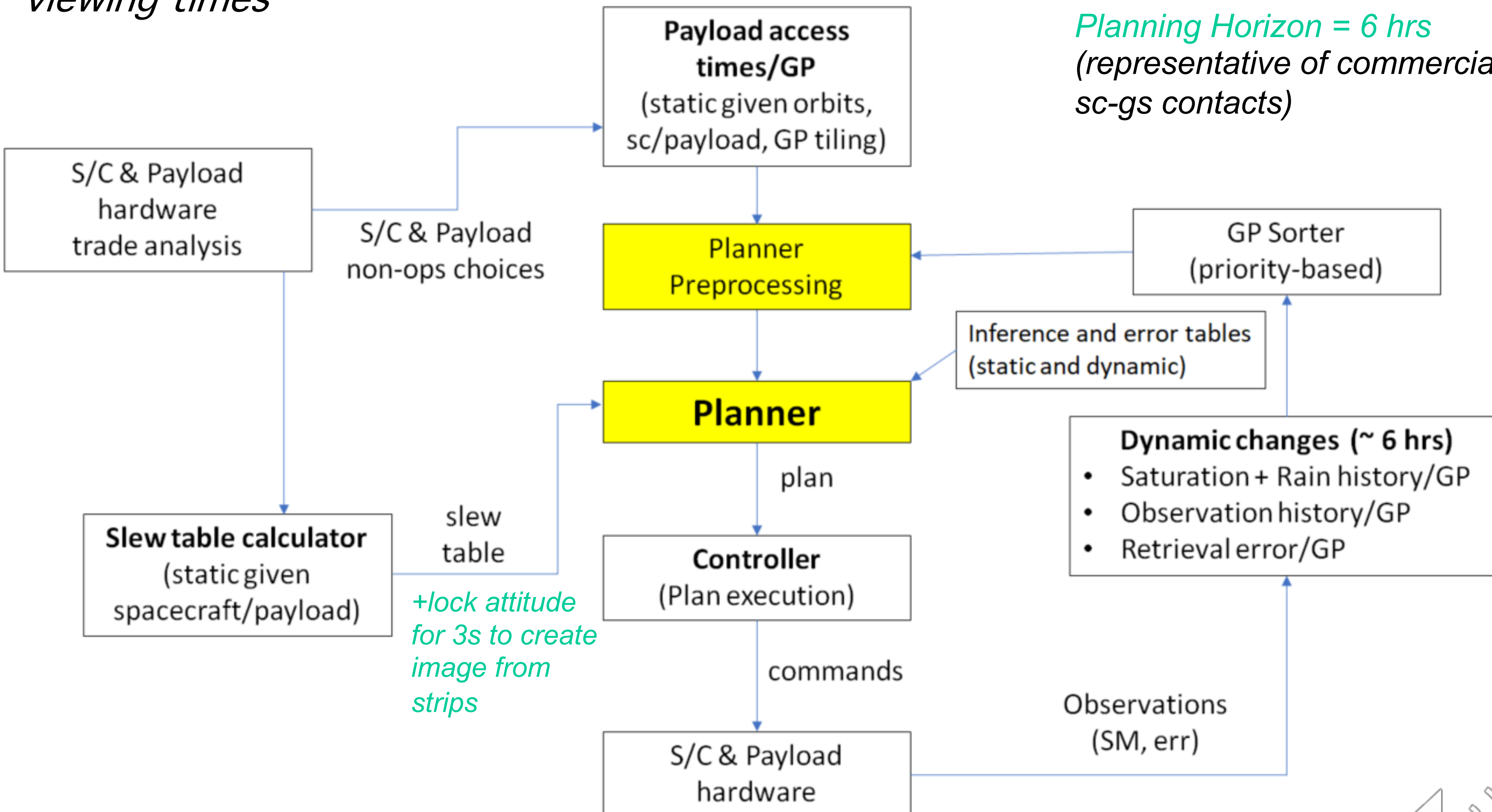
Observation Planner: Optimizing the Schedule

Planner-centric View to ***decide*** what to look at, ***when*** to look at it and ***how*** to look at it i.e. Choose command <instrument, viewing angle> *for all available viewing times*



Planner: Optimizing the Observation Schedule

Search space size:

- 24 hours (4 x 6-hour plans), 1-s increments (86.4k s)
- 2 instruments (L-band, P-band)
- 62 viewing angles/instrument
- 41,500 Access Time Points (TP)
- 1,662,486 Ground Positions (GP)

Pre-processing for choice flattening (reduces space by 65%)
Uses Constraint Satisfaction Problem (CSP) Algorithm to find solution

Timepoint (TP) choices:

Time	Inst/angle	GP	science value
1311:	L.32:	[3165]	score: 0.925
	L.34:	[3445, 3446]	score: 0.925
	P.32:	[3165]	score: 0.9
	P.33:	[3165]	score: 0.9
	P.34:	[3445, 3446]	score: 0.9
	P.35:	[3445, 3446]	score: 0.9

Gridpoint (GP) choices:

GP	Time	Inst/angle(s)	# obs	science value
3165:	1311:	[L.32]	1 obs,	score: 0.925
	1311:	[P.32]	1 obs,	score: 0.9
	1311:	[L.32, P.32]	2 obs,	score: 0.9
	12597:	[L.33]	1 obs,	score: 0.575
	12597:	[P.33]	1 obs,	score: 0.2
	12597:	[L.33, P.33]	2 obs,	score: 0.2

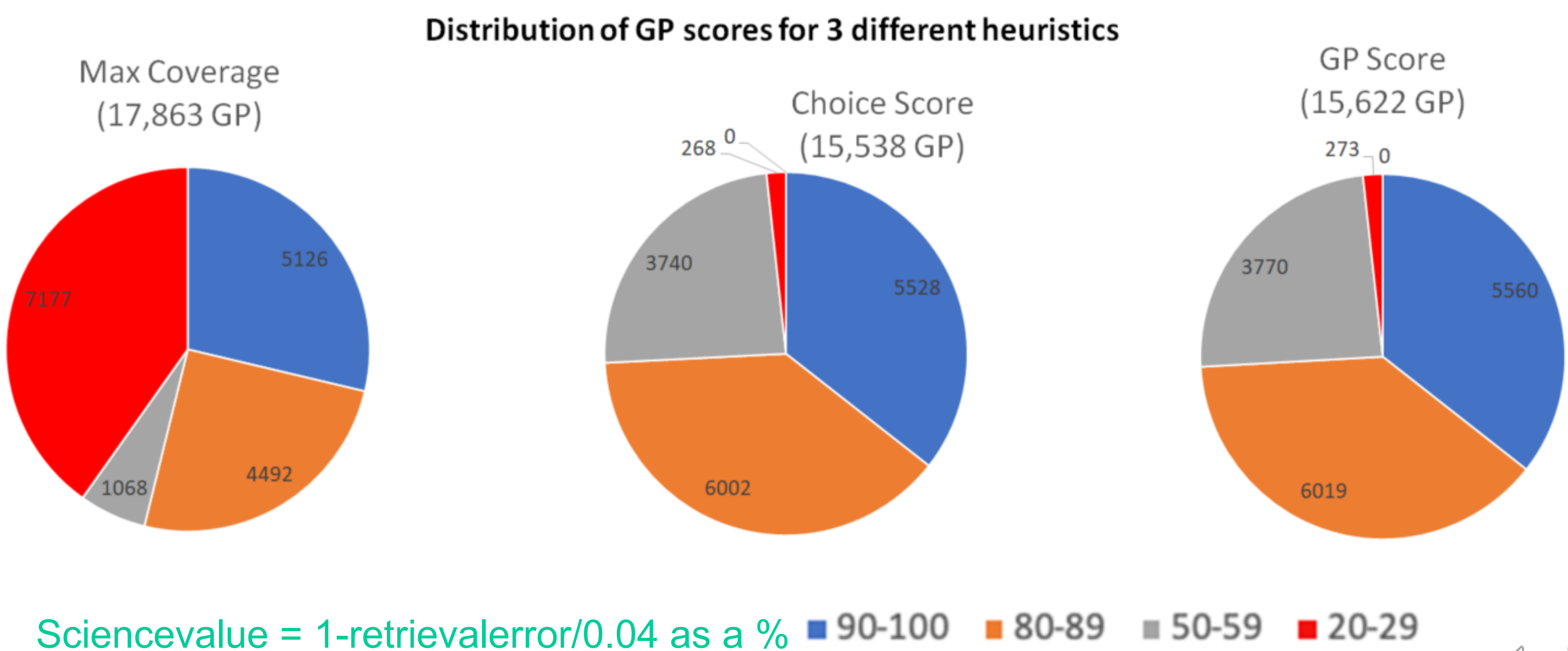
sciencevalue= 1-retrievalerror/0.04 (after ranking for seen, rain, saturation)

Planner: Optimizing the Observation Schedule

Local and Global Heuristics are ongoing topics of research:

1. Max Coverage maximizes number of GPs seen but does not use science value
2. Choice Score maximizes science value without accounting for GPs seen
3. GPscore maximizes product of GPs and science value (*current POR*)
4. Other options: max GP choice rank, max RareGP (TBD with improved science simulator)

For the first horizon of 6 hours by a single satellite



Sciencevalue = 1-retrievalerror/0.04 as a %

Planner: Optimizing the Observation Schedule

Over 24 hours by single sat:
Interesting land cover GPs = 1.662m
Rainy, unsat. GPs = 307.9k-309.8k
Total observed GPs = 53.4k (3.2%)
Rainy, unsat. observed GPs = 15.6k (~5%)

For 1 horizon of 6h:
Interesting land cover GPs = 637k
9.8k variables, 3.8mins to solve
Adding all constraints and heuristics
~16k GP, 3.2k variables, 43s to solve

Very prelim Planner: Single Sat has 15% SMAP temporal coverage at 60x AT spatial resolution

Video: https://sreejanag.github.io/Videos/eosim_demo_5x.mp4

Thank you!

Questions?

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Publicly available Source Code and Docs: