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

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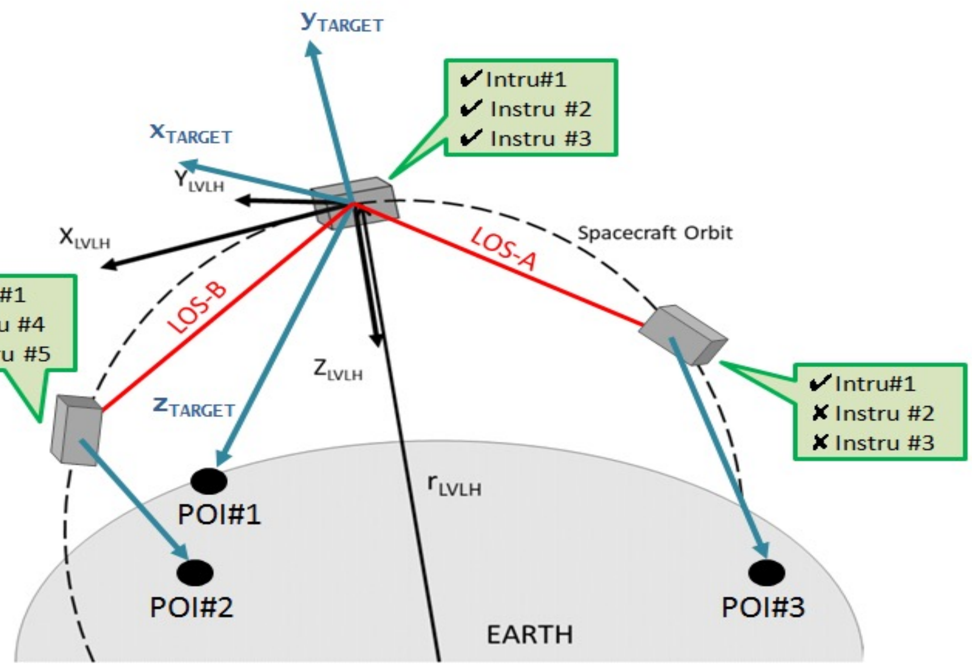
Background: Motivation

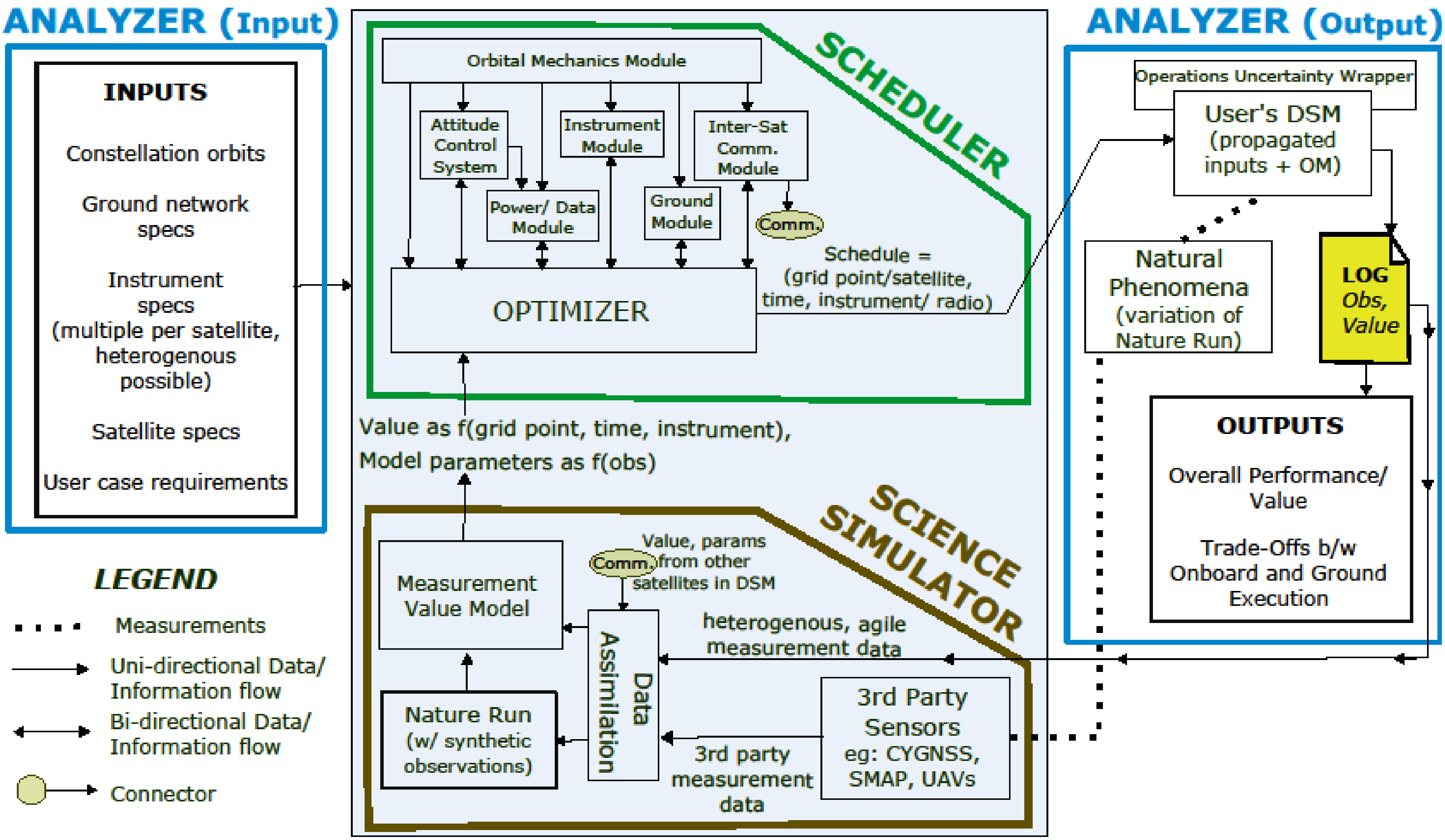
- Multi-payload, multi-spacecraft constellation scheduling for spatio-temporally varying science observations
- Small Sat constellation + Full-body reorientation agility + scheduling autonomy = More Coverage, for any given number of satellites in any given orbits
- Ground scheduling algorithm allows 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: 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 (<u>underscored</u> in conflict with all others)

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

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

Alternative Solution: 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

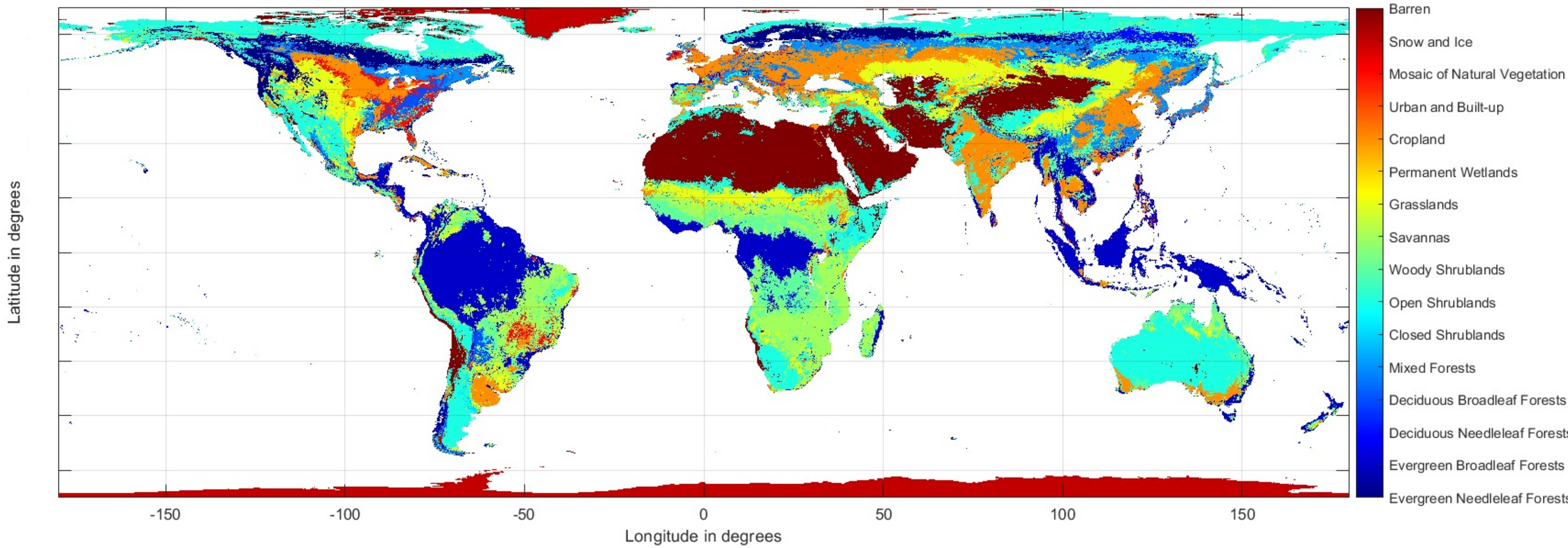
* ~7m AT and >250m CT resolution

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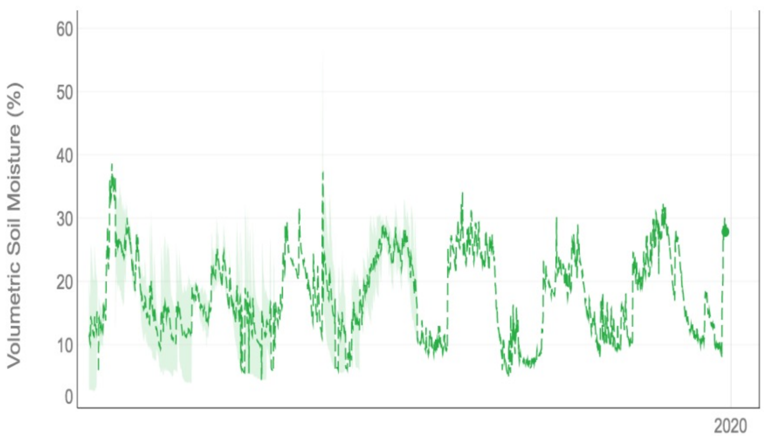
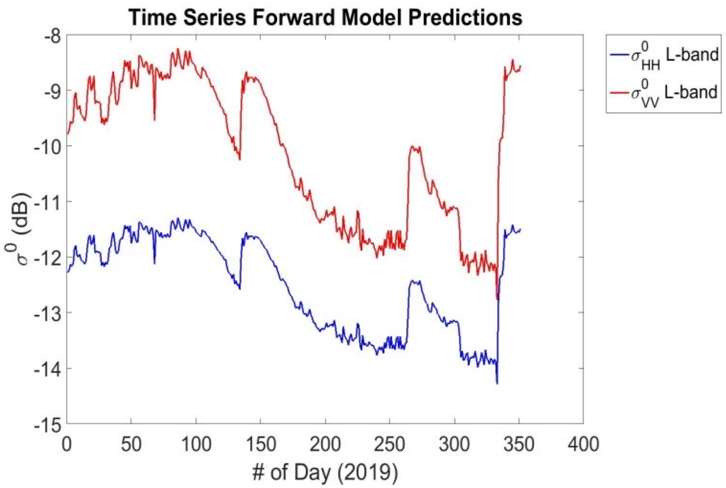
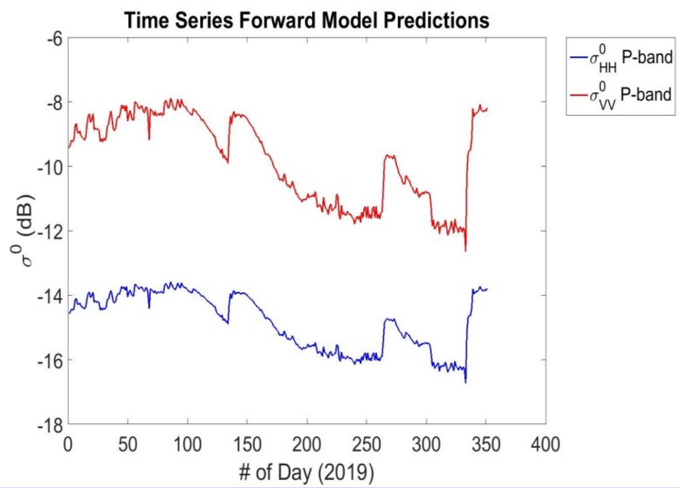
Will be accounted for in the speckle noise model of the science simulator

Time series at SoilSCAPE Node ID 1503 (**Point**)



*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*





ESTO Earth Science Technology Office

Goal: Measure to reduce Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

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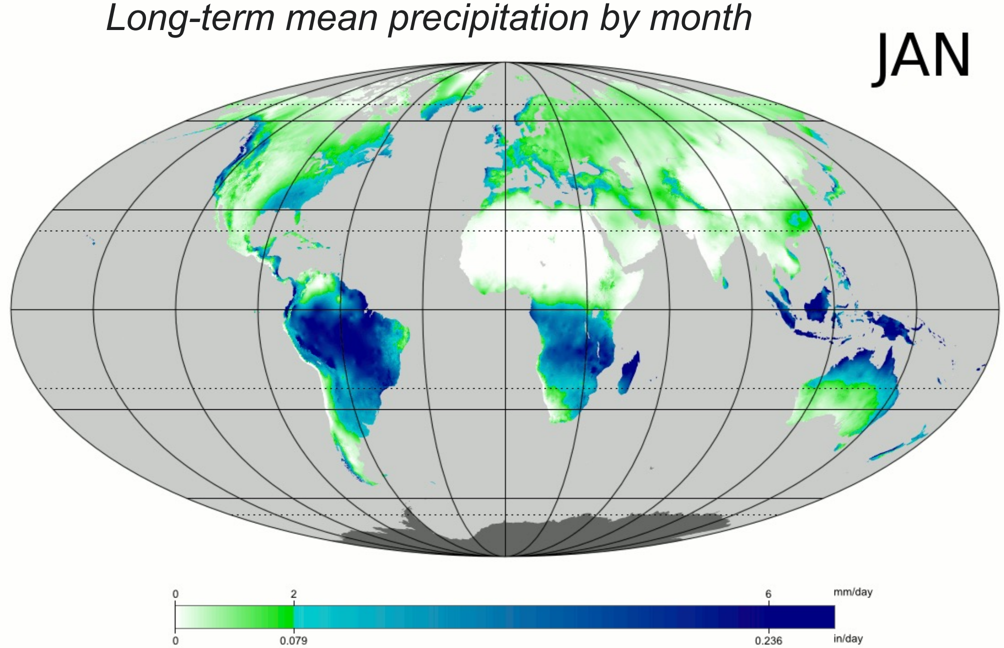
4. Saturation of Soil

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) …

Ideal measurements are after long periods of dryness followed by rain, no rain after a long period of rain, etc.

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/

Goal: Measure to reduce Soil Moisture Uncertainties

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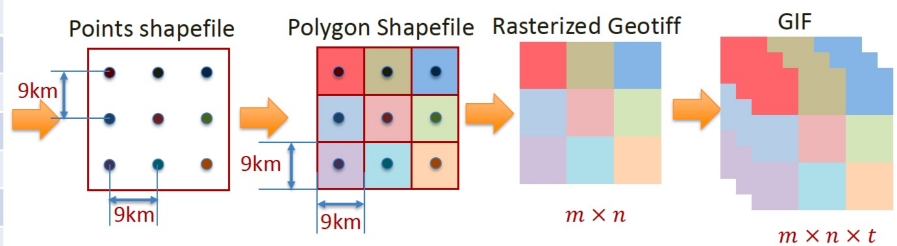
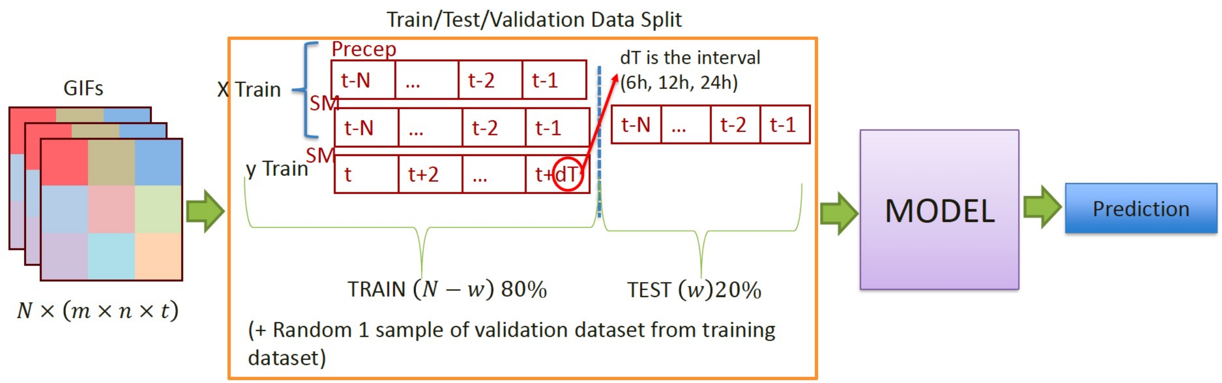
SMAP saturated pixel product globally available every 3 days. Interesting pixels are those that are not saturated and there has been rain recently…

Soil Moisture Predictor using SMAP L4 and LSTM (NN)

CSV from HDF5

Latitude	Longitude	SM
49.48766	-124.87	0.23311
49.48766	-124.777	0.355455
49.48766	-124.684	0.345821
49.48766	-124.59	0.355642
49.48766	-124.497	-9999
49.48766	-124.404	0.239824
49.48766	-124.31	0.216903
49.48766	-124.217	0.233664





Output = SM and Variance as a function of space and future time

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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

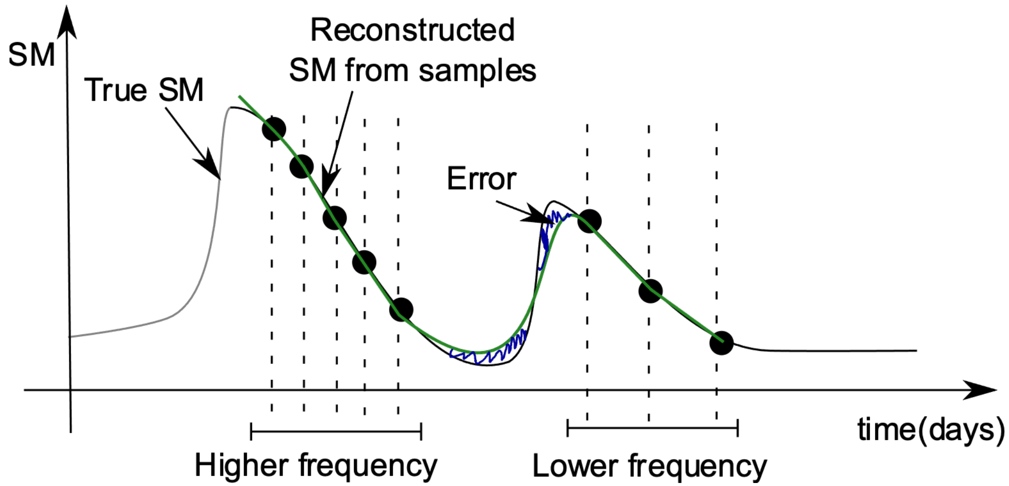
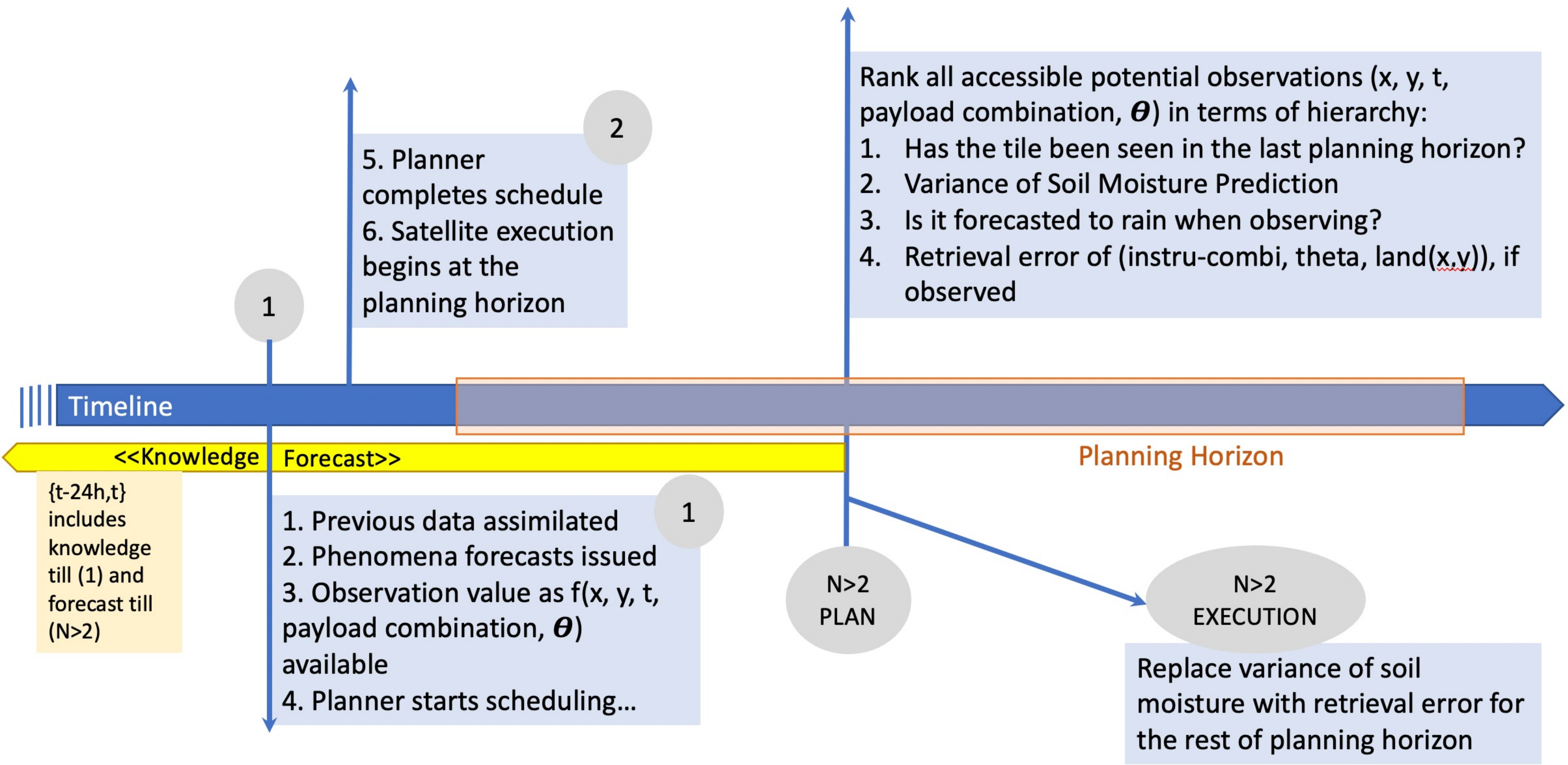


Table B Coding:		Shrubland, wet period				
Code	Meaning	Sat#1 Pay#1	Sat#1 Pay#2	Sat#2 Pay#1	Sat#2 Pay#2	M.E.E.SM
		0	0	0	0	
0	No operation	0	0	0	1	0.0039
1	35+/-5 deg inc, 1 obsvs	0	0	0	2	0.0048
2	45+/-5 deg inc, 1 obsvs	0	0	0	3	0.032
3	55+/-5 deg inc, 1 obsvs	0	0	0	4	0.0038
4	35+/-5 deg inc, 2 obsvs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

Concept of Operations

Planning Ops using dynamic knowledge and forecast of soil moisture and precipitation.
Season, vegetation, soil types are known constants

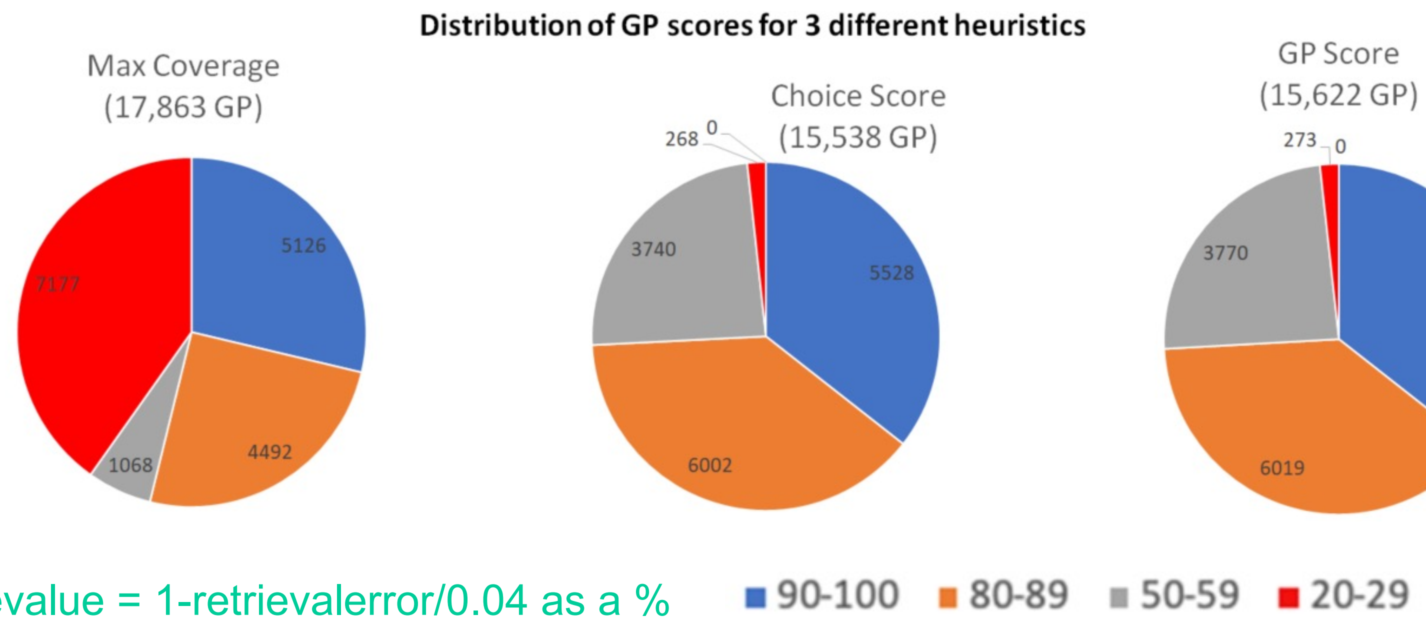


Planner: Optimizing the Observation Schedule

Search space size for a single satellite:

- 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



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

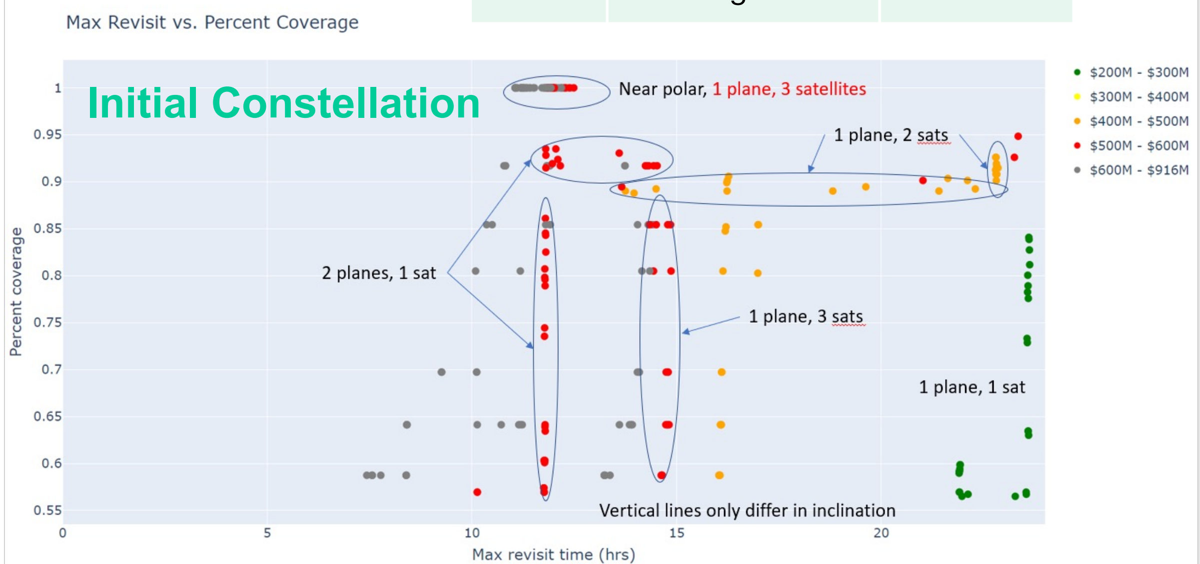
Extending the Constellation

Initial Constellation:
Single Plane, 3 sats, 2 radars on each
Extended Constellation:
Single Plane, 6 sats, heterogeneous distribution of instruments with shared antenna
Minimized Cost and Revisit time of every instrument using **VASSAR Tool**, w/ spacecraft sizing applied to custom instrument

Extended Constellation

	True Anomaly	Payload
Sat1	0 deg	All
Sat 2	60 deg	ID 3-6
Sat 3	120 deg	All
Sat 4	180 deg	ID 3-6
Sat 5	240 deg	All
Sat 6	300 deg	ID 3-6

ID	Instruments
1	L-band SAR
2	P-band SAR
3	Antenna (sized for P-band)
4	P-band Reflectometer
5	L-band Reflectometer
6	FMPL-2 (L-band radiometer)



Reference: B. Gorr, A. Aguilar, D. Selva, V. Ravindra, M. Moghaddam, S. Nag, *"Heterogeneous Constellation Design for a Smart Soil Moisture Radar Mission"*, IGARSS 2021

Extending the Planner

- To multiple satellites with follow-up observations within ΔT and beyond
- Time constraints to slew between observations
- Ensure image lock for strip-map image
- Constraints for energy consumption by the instruments and slewing ADCS module
- Constraints for energy budget for given battery size and eclipse times

Plan for sat 1:

Time	Command
[2-4]	P.48
[5-14]	Idle
[15-17]	L.48
[18-36]	Idle
[37-40]	Slew
[41-43]	L.44
[44-45]	Slew
[46-48]	P.45
[49-49]	Idle
[50-51]	Slew
[52-54]	P.46

Experiment Results: Preliminary experiment results are presented below for our example with 3 satellites with a 6-hour planning horizon. We define *maxError* = 0.04 = our maximum allowable model error. All GP are initialized with a default error = maxError = 0.04.

Heuristic	# images (makespan)	# of GP observed	Avg Err /GP	maxErr %
MinGpChoiceErr	6,445	14,401	.015	0.375
MinGpChoiceRank	6,459	19,866	.023	0.525
MaxGpCount	6,452	24,641	.025	0.625

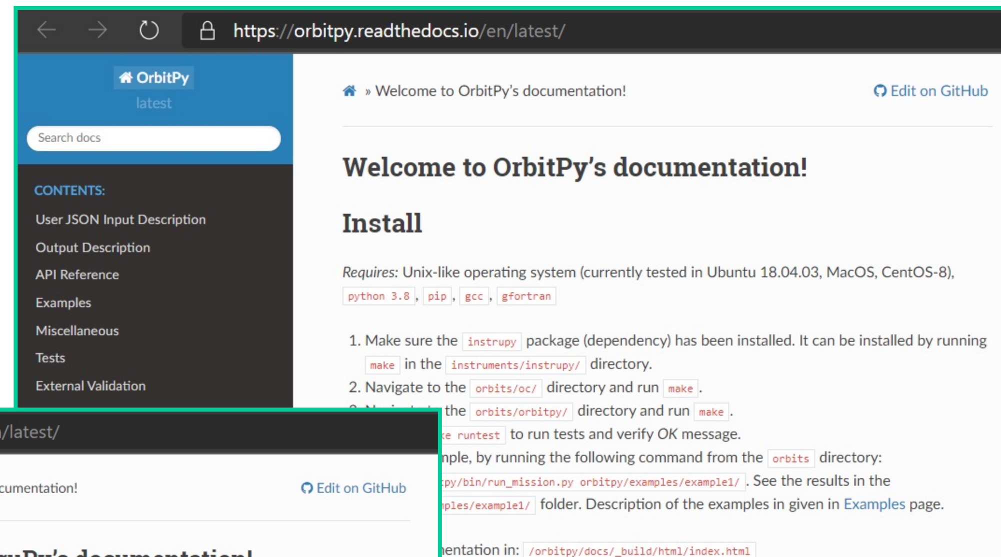
Figure 7: Preliminary experiment results comparing three local heuristics.

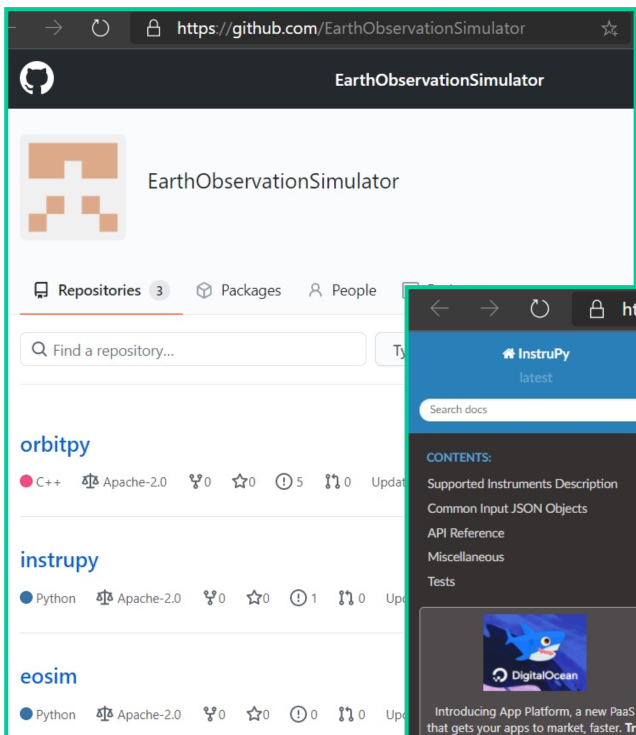
Reference: R. Levinson, S. Nag, V. Ravindran *"Agile Satellite Planning for Multi-Payload Observations to aid Earth Science"*, International Workshop on Planning and Scheduling for Space, 2021

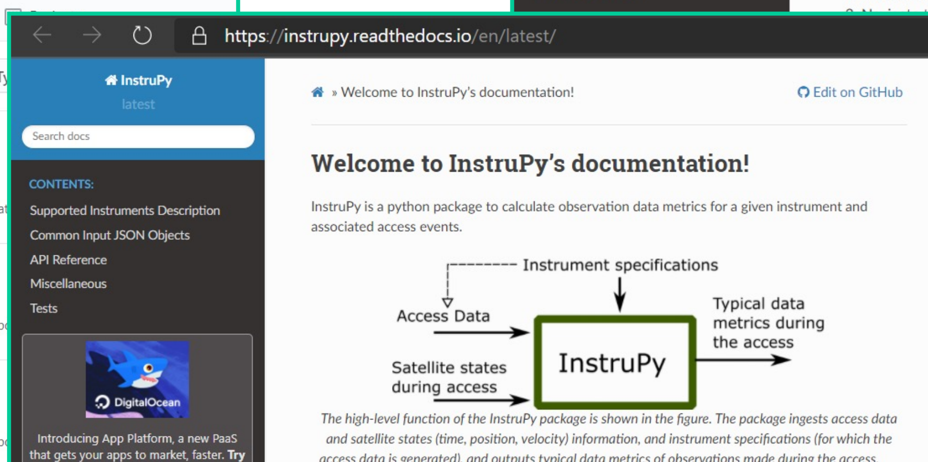
Other Modules that serve as Input to Planner

Reference for ADCS Module: E. Sin, S. Nag, V. Ravindra, A.S. Li, M. Arcak, *"Attitude Trajectory Optimization for Agile Satellites in Autonomous Remote Sensing Constellation*", AIAA Journal of Guidance, Control, and Dynamics, 2021
https://arxiv.org/abs/2102.07940

Publicly available Source Code on Orbit, Instrument, EO Simulator:







https://github.com/EarthObservationSimulator

https://orbitpy.readthedocs.io/
https://instrupy.readthedocs.io/

Thank you!

Questions?

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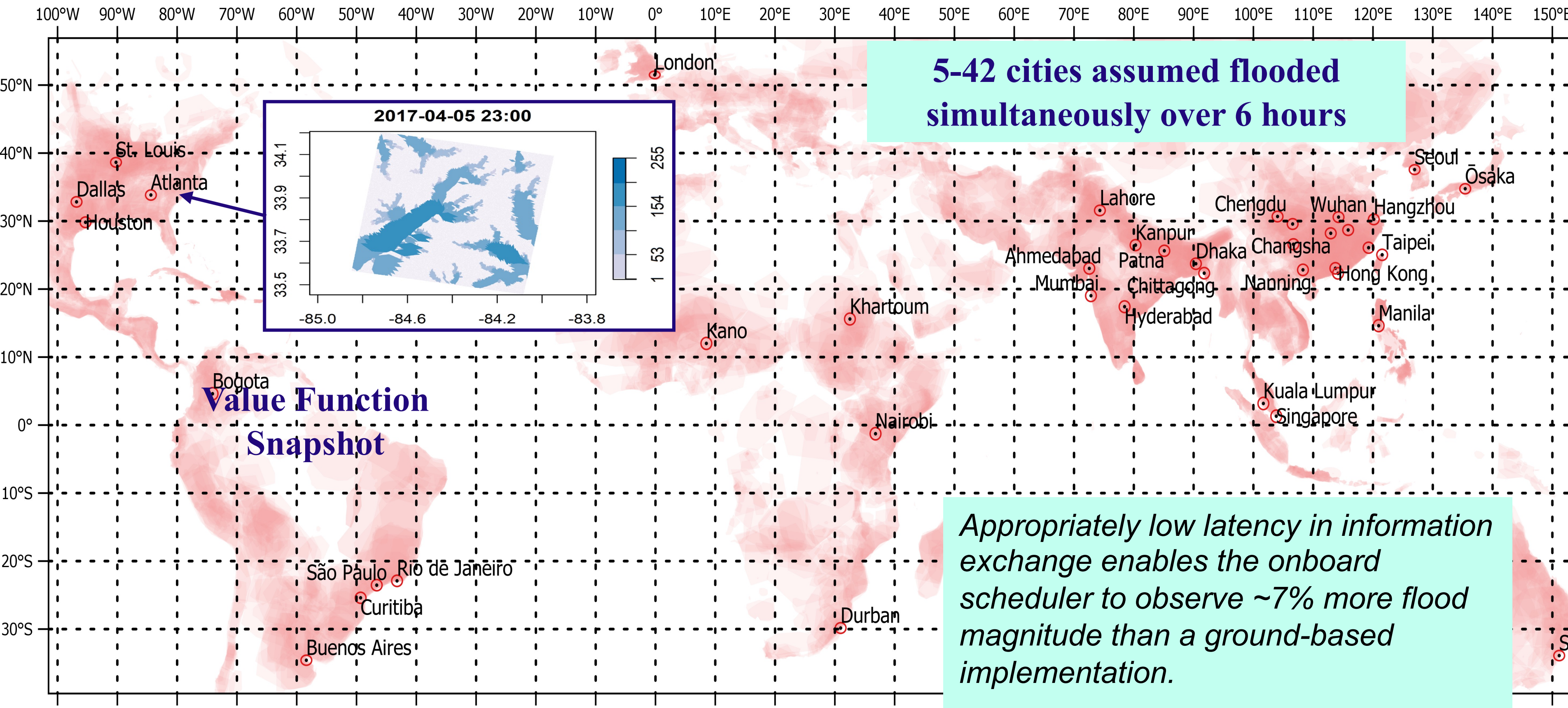
Backup Slides

Science Relevancy Scenario: Urban Floods



5-42 cities assumed flooded simultaneously over 6 hours

Value Function Snapshot

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.

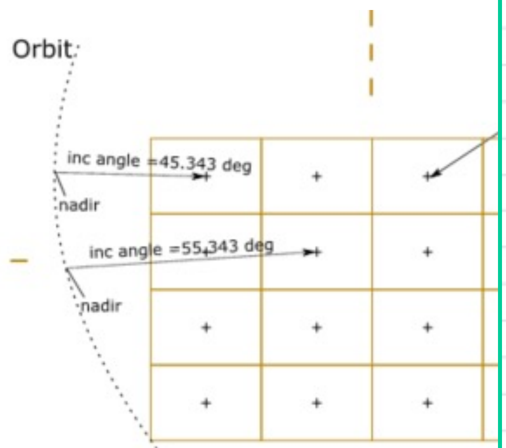
Data: Dartmouth Flood Observatory (Brakenridge 2012)

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

Addressing Spatial Resolution / Instrument Design

- *Instrument Design:* Create potential SARs in L,P band with comparable to SMAP's sigmaNEZ but diff operating modes
- *Considerations*: PRF, full or fixed swath, polarization
- *Modes:* StripMap, Scan SAR, spotlight SAR
- Used NSGA II for MOO
- *Variables:* Pulse width, Chirp bandwidth, Antenna beamwidth in Azimuth and elevation
- *Objectives:* Antenna area, swath, sigmaNEZ, looks per km2
- *Future instruments:* Radiometers and Reflectometers can be used from existing missions in the L and P band

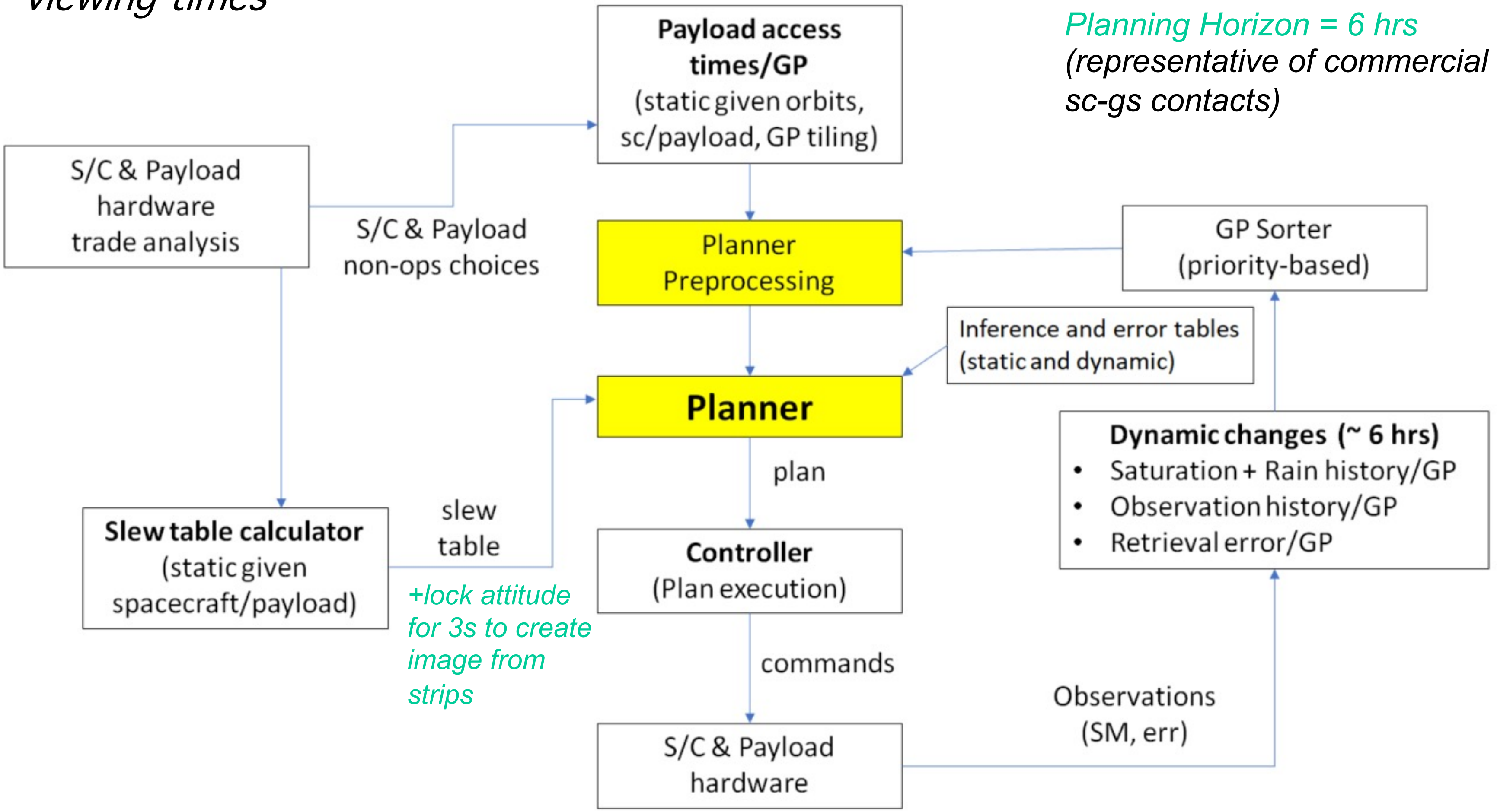


Opt. Design

Alt: 500km	Instrument metrics, specs: Instru #1 L-band Quad-Pol SAR	Instru #2 P-band Quad-Pol SAR
Metric@35deg inc	*Value*	
NESZ [dB]	-40.69	-41.45
AT res [m]	6.67	4.54
CT res [m]	364.66	52.28
N looks/ km2	411.136504	4213.16598
Swath [km]	25	50
PRF [Hz]	2666	2406
Metric@45deg inc		
NESZ [dB]	-37.29	-38.29
AT res [m]	6.67	4.54
CT res [m]	295.79	42.4
N looks/ km2	506.863104	5194.91314
Swath [km]	25	50
PRF [Hz]	2279	2113
Metric@55deg inc		
NESZ [dB]	-32.87	-35.38
AT res [m]	6.67	4.54
CT res [m]	255.33	36.6
N looks/ km2	587.181442	6018.15074
Swath [km]	25	50
PRF [Hz]	1578	2131
Instrument Specs		
Daz [m]	14.38	9.8
Delv [m]	1.48	9.04
Chirp BW [MHz[	0.86	6
Pulse Width [us]	14.16	22.14
Peak Tx Power [W]	1000	1000
Ant eff [%]	60	60
Sys Noise Figure [dB]	2	2
Radar Loss [dB]	2	2
Center Freq [MHz]	1.28E+03	4.35E+02

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

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)

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)