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

Sreeja Nag (PI, NASA Ames Research Center/BAER Institute)

Mahta Moghaddam (co-I, University of Southern California)

Daniel Selva (Co-I, Texas A&M University)

Jeremy Frank (co-I, NASA Ames Research Center)

Team Members: Vinay Ravindra (ARC), Richard Levinson (ARC), *Emmanuel Sin (UCB), Amir Azemati (USC), Ben Gorr (TAMU), Ryan Ketzner (KSC), Alan Aguilar (TAMU),* Ruzbeh Akbar (MIT), Alan Li (ARC)

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

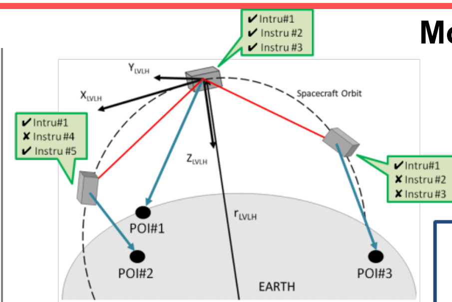
PI: Sreeja Nag, ARC and Bay Area Environmental Research Institute

Objective

Develop an operations design tool that will, for a given distributed space mission (DSM) architecture:

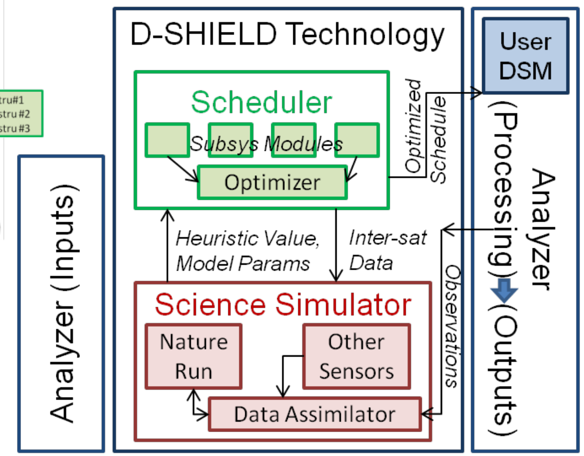
- plan re-orienting and operations of heterogeneous payloads
- account for power/payload constraints
- maximize science value using an iterative science observable simulator based on Observing System Simulation Experiments (OSSEs) adapted for real time planning and rapid mission design

This project contributes to the New Observing Strategy (NOS) thrust area by developing an AI-based planning and scheduling-based DSM operations tool



(above) Cartoon of 3-satellite constellation with multiple instruments and D-SHIELD coordinated decisions

Modular Technology and Assessment:



(right) D-SHIELD system diagram including data flows.

Approach:

- Build an intelligent scheduler that can run on the ground in a centralized way or onboard multiple spacecraft in a distributed manner
- Build an observable science simulator enabling scheduler decisions and science performance comparisons.
  - Baseline simulator will model soil moisture scenarios
  - Project developments will enable applications to other responsive remote sensing (e.g. fires, cyclones).
- Build an operations tradespace analyzer to evaluate system performance and inform trade-offs such as running onboard vs. offline
- Integrate system; apply to soil moisture science and flood monitoring applications

Key Milestones

• Optimization Algorithms study completed	07/20
• Payload Module developed	10/20
• ~~Passive~~Active MW Simulator developed	10/20
• Operations tests developed	10/20
• Power Module dev, integrate w/ current modules	01/21
• Hydrologic land-surface model developed	03/21
• Scheduler Optimizer developed	07/21
• Scheduler and Science Sim. Modules integrated	10/21
• Full system integrated with Analyzer	01/22

$TRL_{in} = 2$

Co-Is/Partners: J. Frank, ARC; M. Moghaddam, USC; D. Selva, Texas A&M University

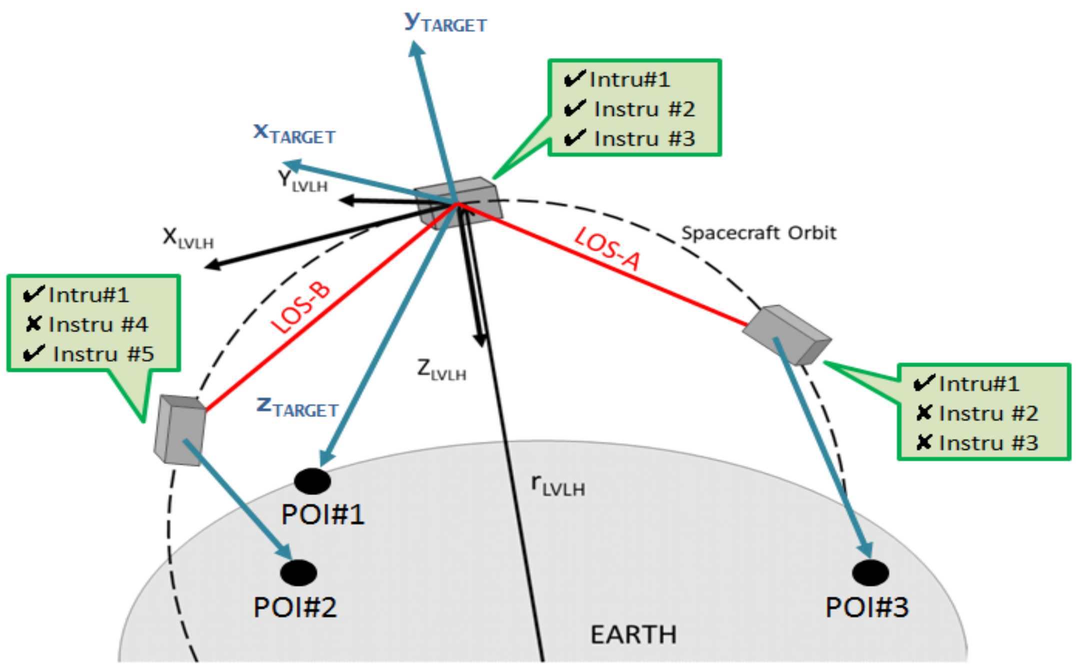
Presentation Contents

- Background and Objectives
- Technical and Science Advancements
- Summary of Accomplishments and Future Plans
- Publications - List of Acronyms

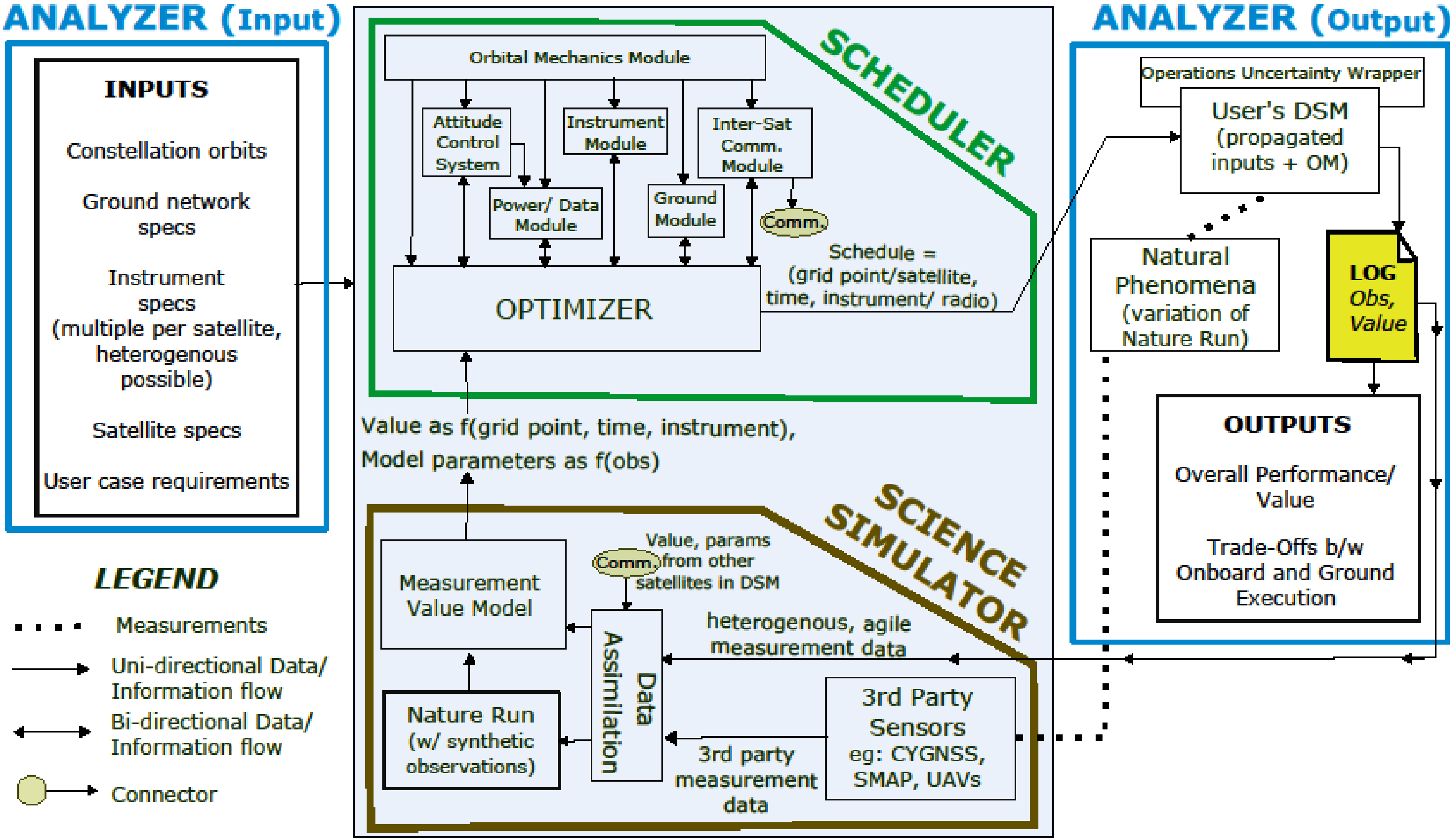
Background: Motivation

- Multi-payload, multi-spacecraft constellation scheduling for spatio-temporally varying science observations
- Small Sat constellation + Full-body reorientation agility + Ground 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

AIST Use Case: Soil Moisture Monitoring for Uncertainty Minimization (Water and Energy R&A)



D-SHIELD Proposal



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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

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

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

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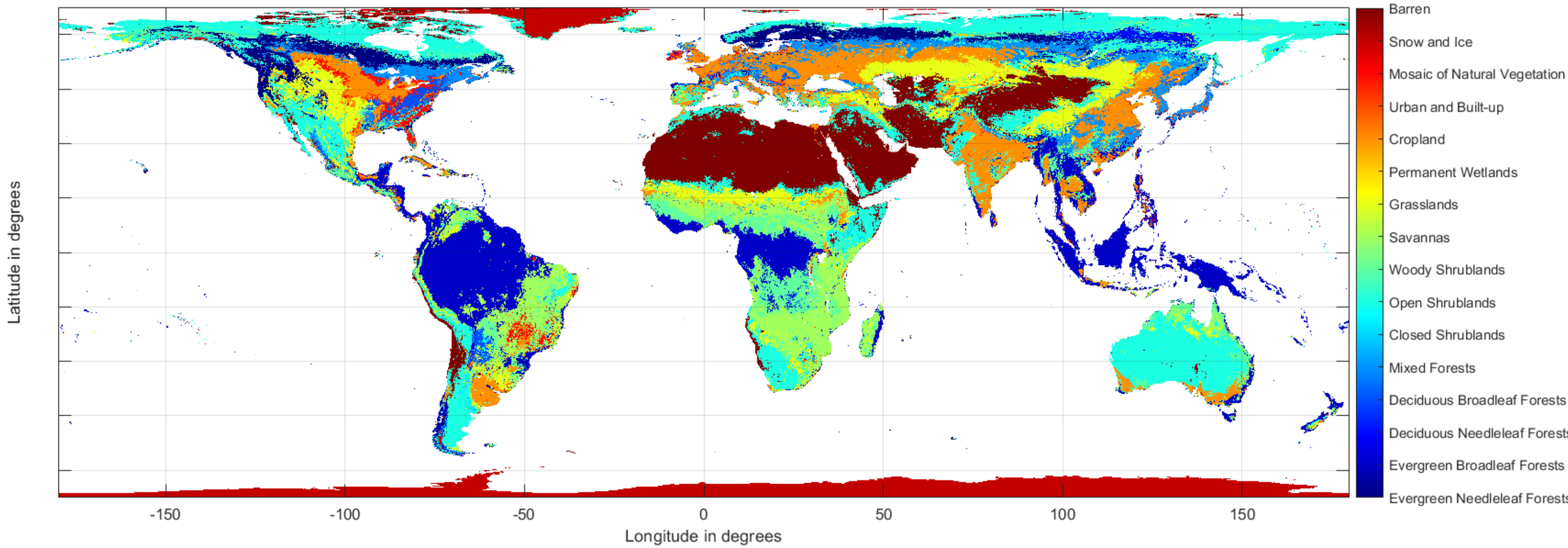
Soil Moisture Uncertainties

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

Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

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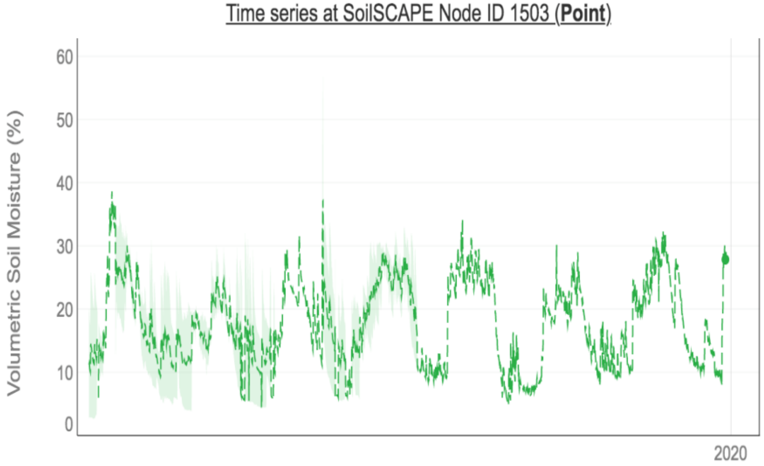
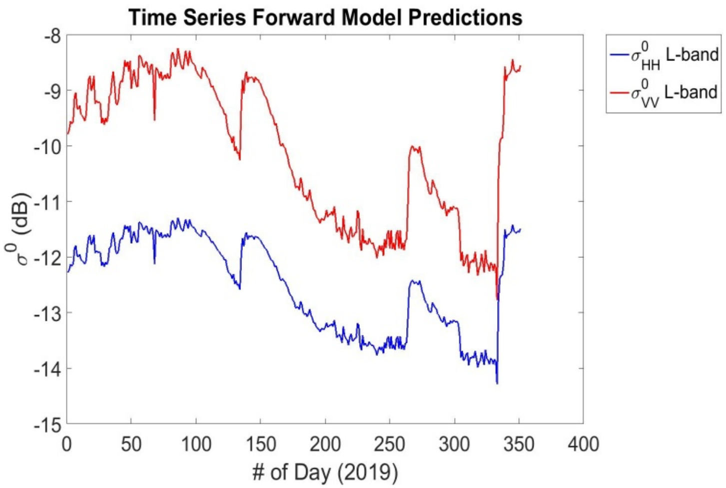
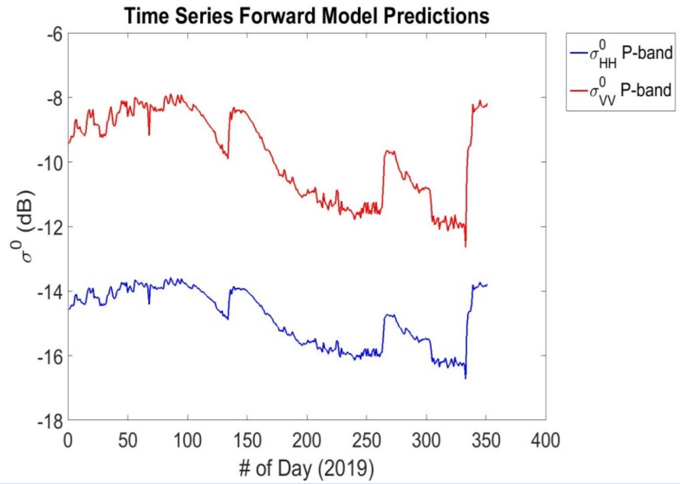
4. Saturation of Soil

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*





Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

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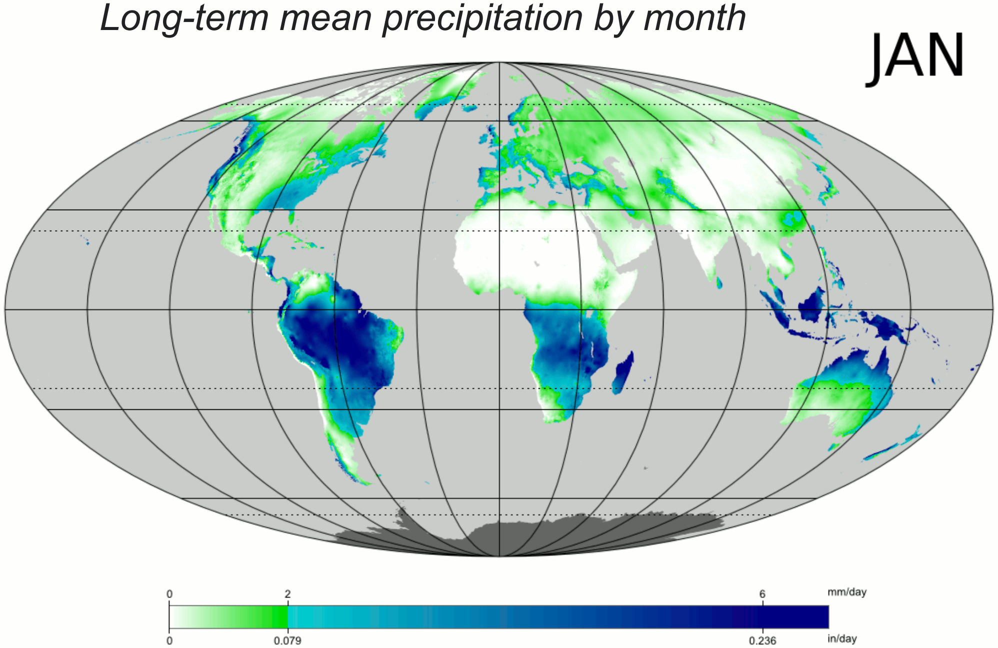
Hourly precipitation forecast from GEOS FP in Cubed-sphere grid C720 resolution (12 km) and ~30km lat-lon. Using PRECTOT - Total precipitation (kg m-2 s-1) …

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

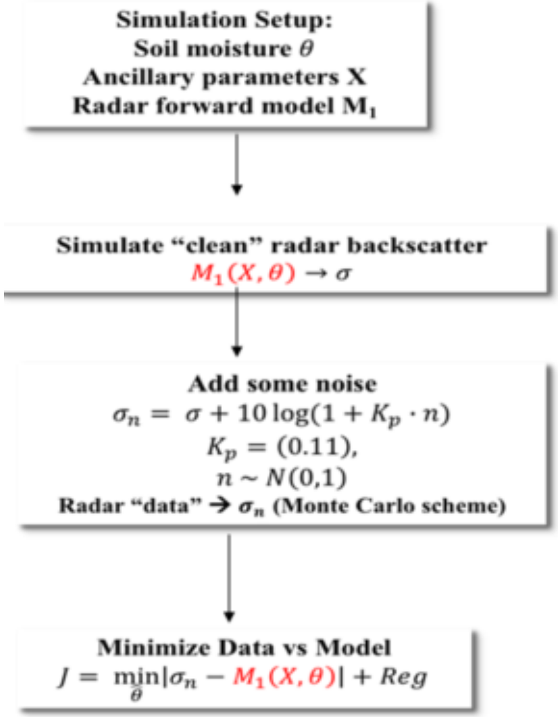
Long-term mean precipitation by month



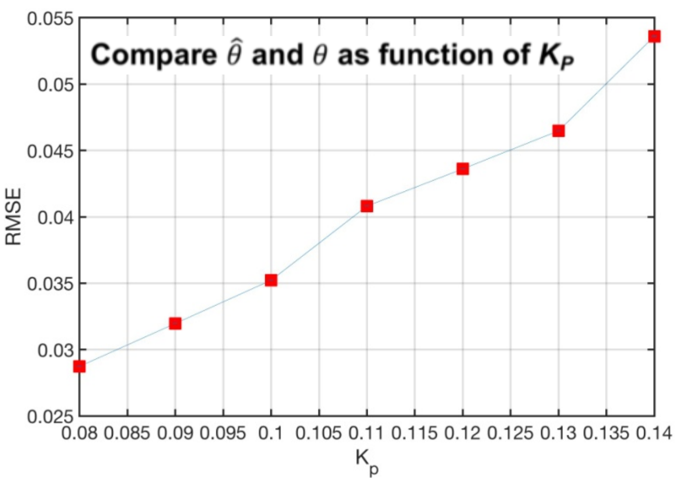
Website: https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php
Forecast data: https://fluid.nccs.nasa.gov/weather/

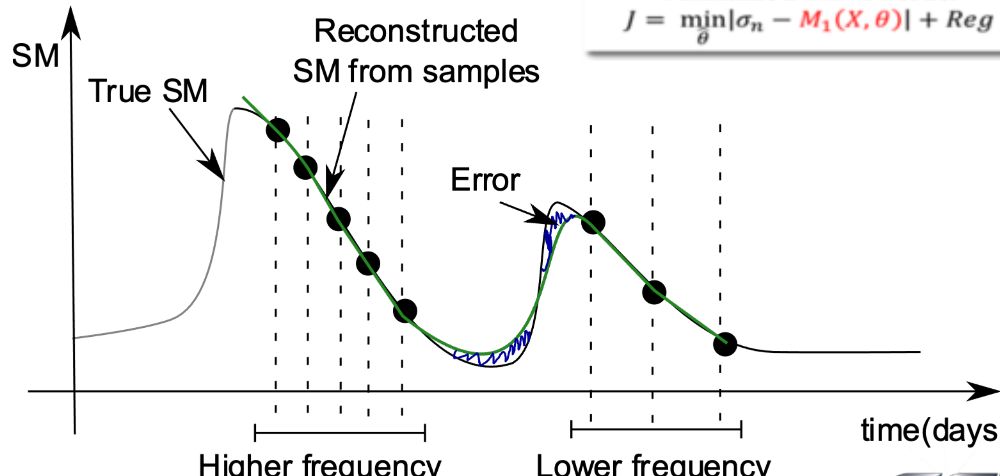
Addressing Temporal Resolution / Science Needs

- Temporally close measurements (just as neighboring pixels) can be combined to reduce speckle noise. What is the maximum ΔT up to which SM dynamism does not prevent meaningful integration?
- Ran forward model on SM from SoilScape in-situ sensors (θ) and surface roughness/vegetation params (X) to get radar backscatter; added varying speckle noise (Kp) and generated new RCS; retrieved SM using a hybrid global/local optimizer; calc RMSE



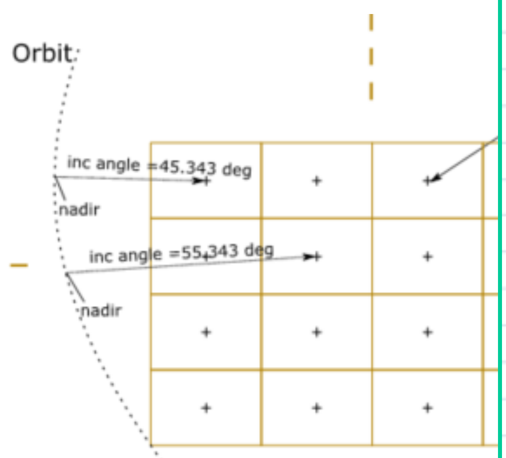
ΔT=2hours





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

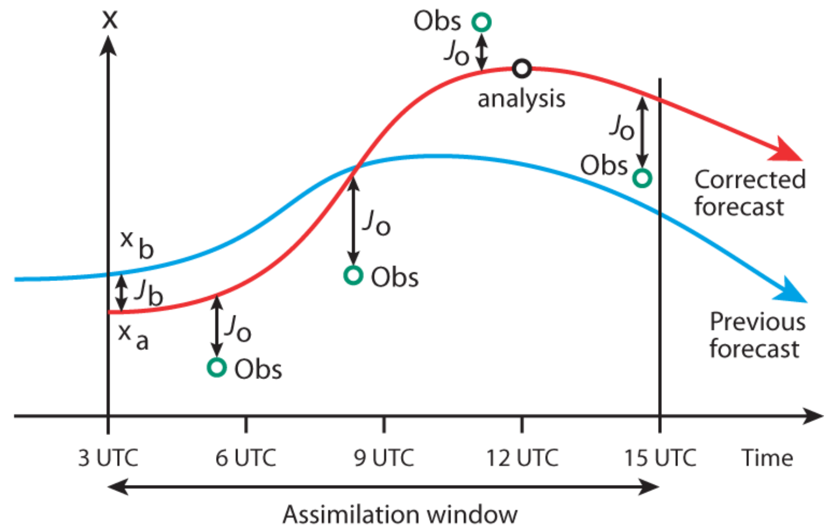
Alt: 500km	Instrument metrics, specs *Instru #1* *L-band Quad-Pol SAR*	*Instru #2* *P-band Quad-Pol SAR*
Metric@35deg inc	*Value*	
NESZ [dB]	-40.69	-41.45
AT res [m]	6.67	4.54
CT res [m]	364.66	52.28
N looks/ km2	411.136504	4213.16598
Swath [km]	25	50
PRF [Hz]	2666	2406
Metric@45deg inc		
NESZ [dB]	-37.29	-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

Adding Spatio-Temporal for “Single” Retrievals

Example cartoon to the right: 4 obs in ΔT=12hrs

#obs is a function of sat access (#sats, #payloads, FOV, altitude) ~ each already includes 400-600 looks per km2 in L and 4k-6k in P ~ more is better for speckle!

Retrieval error is then a function of #obs, incidence angle, payloads used.



Simulated Error for all combinations in which 2 sats with L+P each can make upto 2 obs (ΔT=2hrs) ~ for 1 biome, 1 season

Table B Coding:

Code	Meaning
0	No operation
1	35+/-5 deg inc, 1 obsvs
2	45+/-5 deg inc, 1 obsvs
3	55+/-5 deg inc, 1 obsvs
4	35+/-5 deg inc, 2 obsvs
5	45+/-5 deg inc, 2 obsvs
6	55+/-5 deg inc, 2 obsvs

Shrubland, wet period

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	0	0	1	0.0039
0	0	0	2	0.0048
0	0	0	3	0.032
0	0	0	4	0.0038
0	0	0	5	0.0048
0	0	0	6	0.0319
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

Preliminary rules as a strawman for the science simulator:

Rank all accessible potential observations (x, y, t, payload combination, θ) in terms of hierarchy:
[i] 5cm of rain has occurred within {t-24h,t} if (x,y) is forest or savannah or 2.5cm if (x,y) is bare, shrubland, cropland?
[ii] Is the tile saturated?
[iii] Has the tile been seen in the last 24h?
[iv] Retrieval error of (instru-combi, theta, land(x,y))

2

5. Planner completes schedule
6. Satellite execution begins at the planning horizon

1

Timeline

<Knowledge

Forecast>

Planning Horizon

{t-24h,t} includes knowledge till (1) and forecast till (N>2)

1

1. Previous data assimilated
2. Phenomena forecasts issued
3. Observation value as f(x, y, t, payload combination, θ) available
4. Planner starts scheduling…

N>2

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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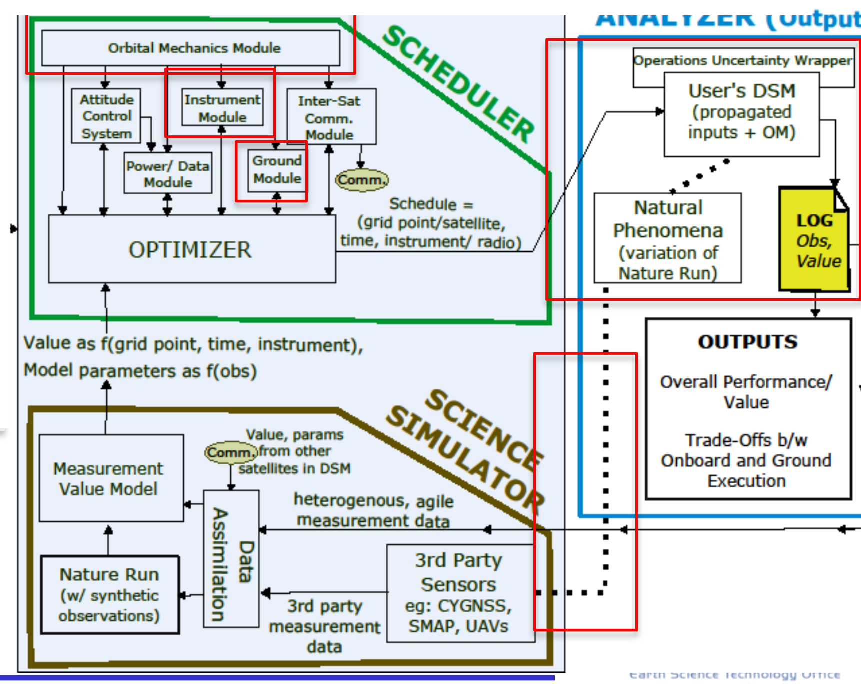
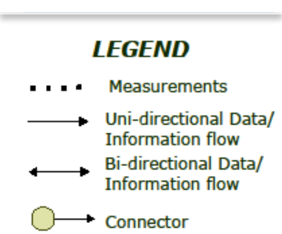
Observing System Model and Simulation

- Suite of Python packages: EOSim, OrbitPy and InstruPy
- Beta version avail in a public Github repo* under a permissive open-source license (Apache 2.0) in Jan 2021
- Features:
  - Desktop app w/ GUI and visualization options; modular w/ Python
  - Simulation of constellation missions (orbit and coverage) with multiple satellites, multiple and heterogenous distribution of instruments per satellite and across the constellation.
  - Simulation of inter-satellite and ground-station comm links.
  - Synthetization of artificial satellite imagery from DBs

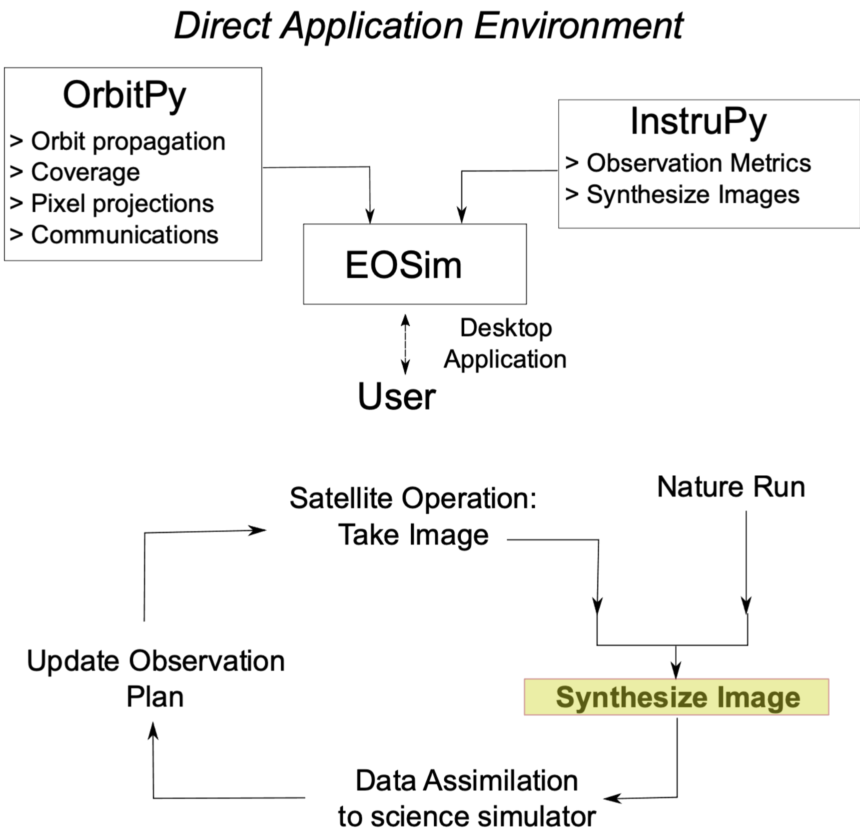
*https://github.com/EarthObservationSimulator



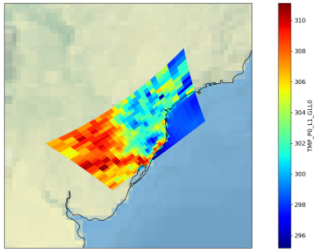


Observing System Feedback to Science Value

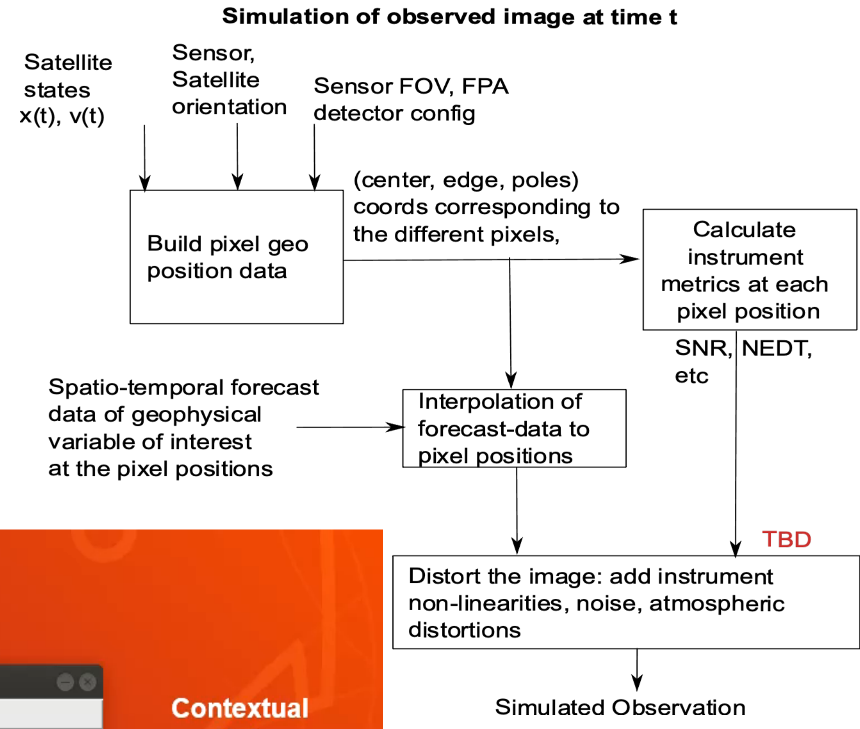
- OrbitPy module* is a significant improvement to our AIST 2014 work for TAT-C (GMAT open source)
- InstruPy* module is a significant add-on to our AIST 2016 work
- EOsim module with ability to couple the two with nature run sub-sampling for science value
- Built with Python, C++, JS with the support of third-party permissive open-source software such as: Tkinter: GUI framework, CartoPy: Map projections, MetPy: Calculations on weather data, CesiumJS: 3D Geodata visualization, and many more….

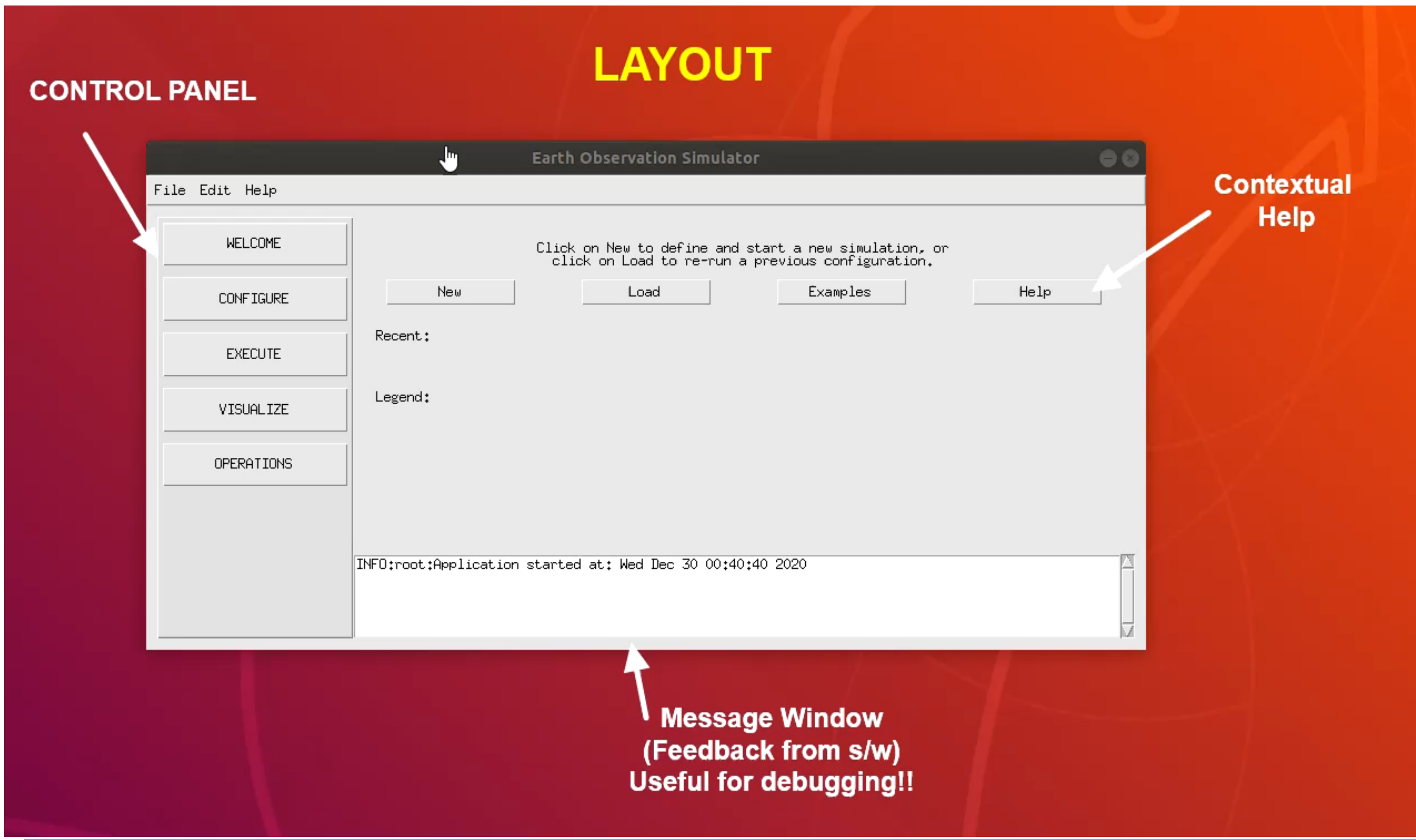


* https://orbitpy.readthedocs.io/
https://instrupy.readthedocs.io/



Observing System Feedback to Science Value (Demo)

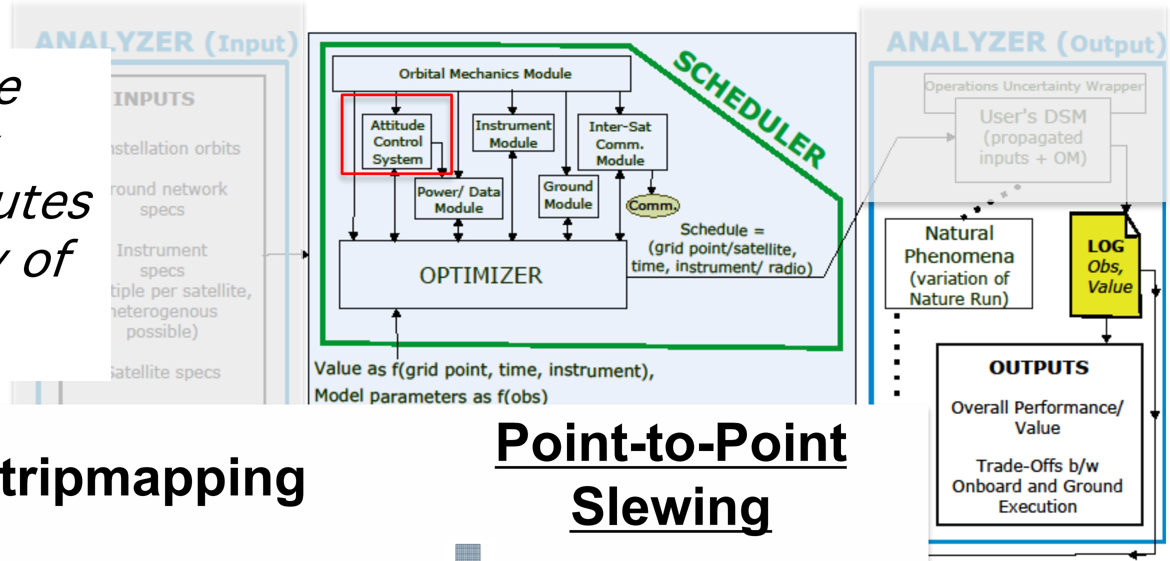


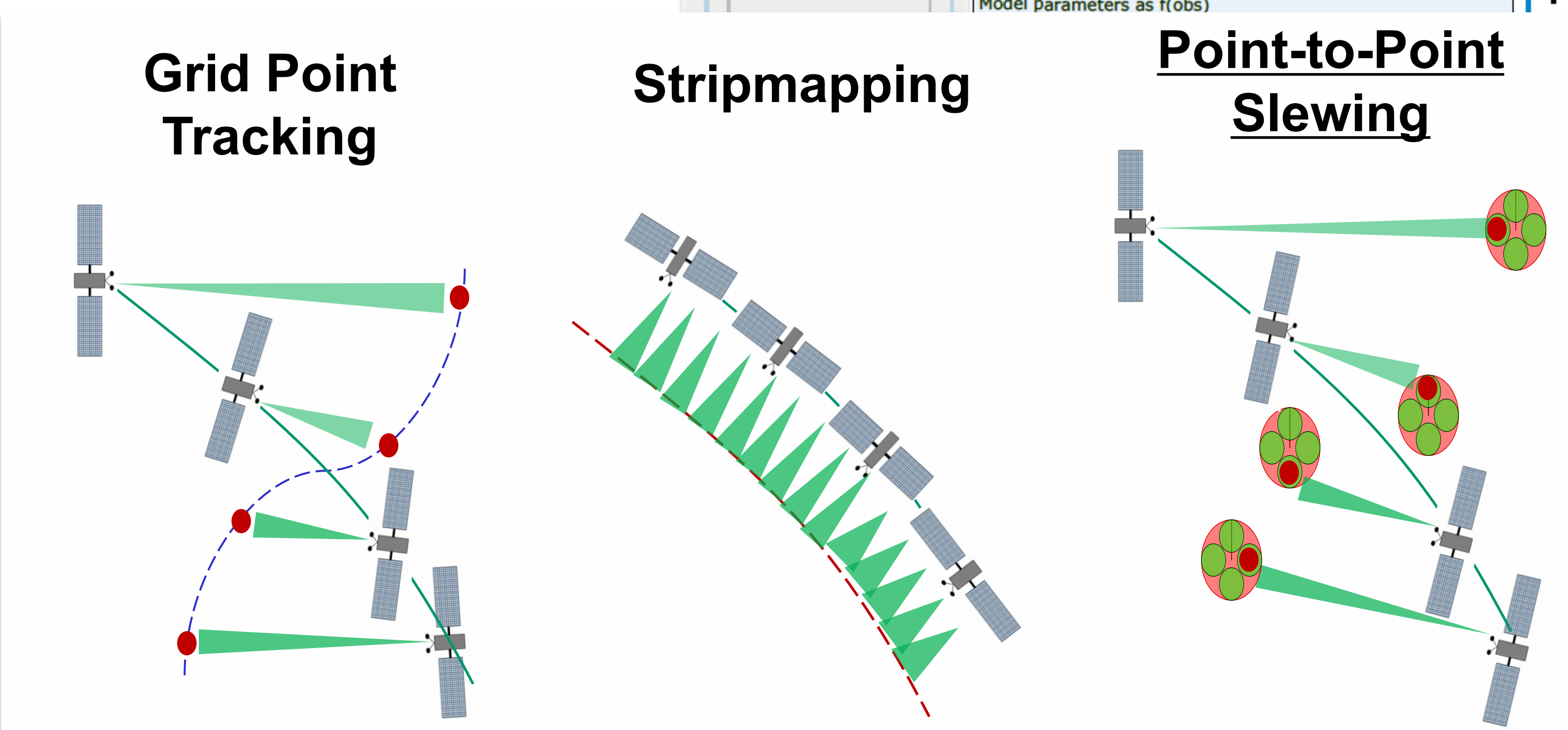


Video: https://drive.google.com/file/d/1K9VDWxO07MI3DiDMkjgBTjau8KzZ5WxT/view?usp=sharing

Attitude Control Systems for Agile Slewing

*ACS module informs the planner of time/energy constraints *and* executes commanded plan in any of 3 modes:*





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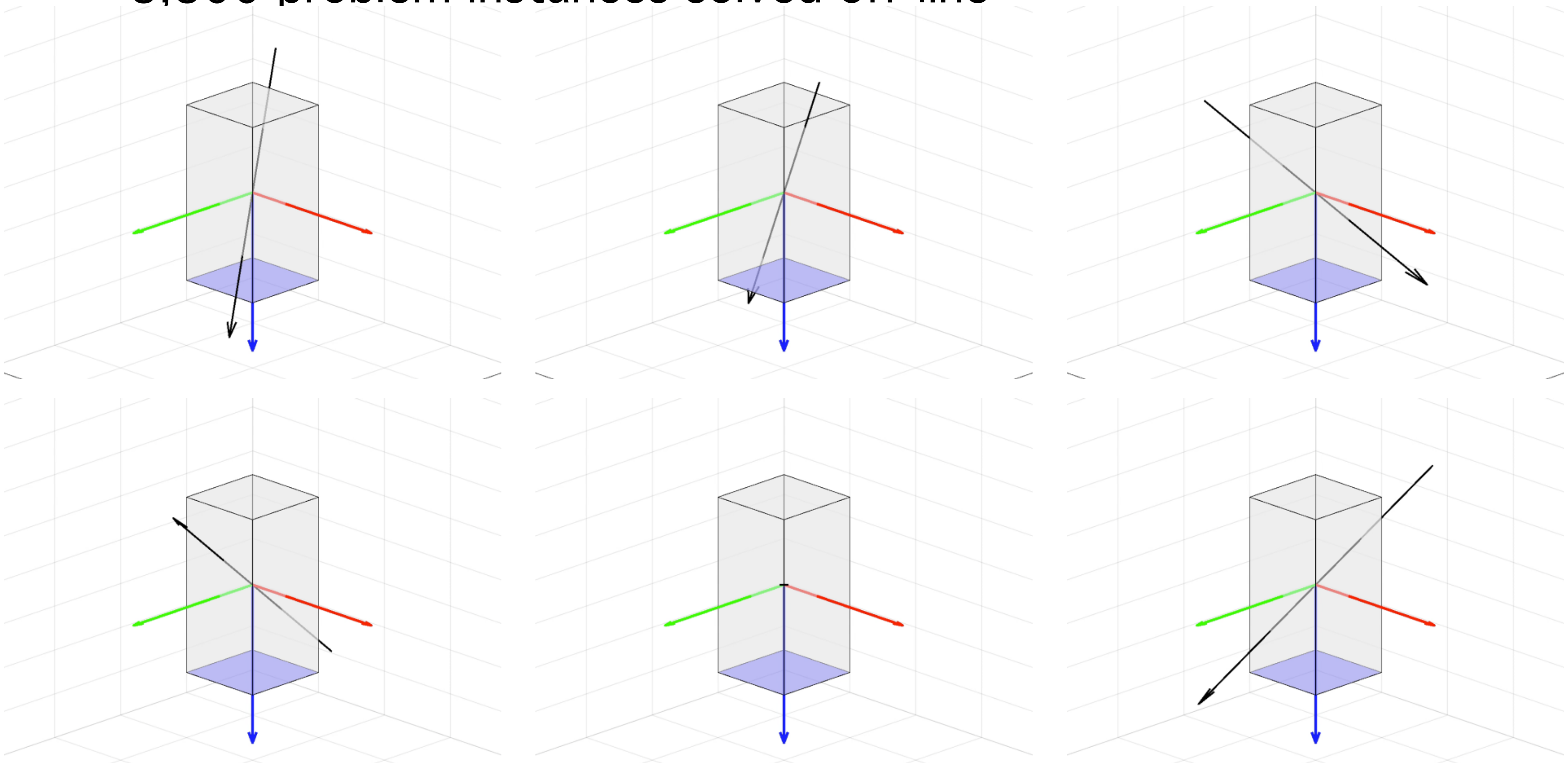
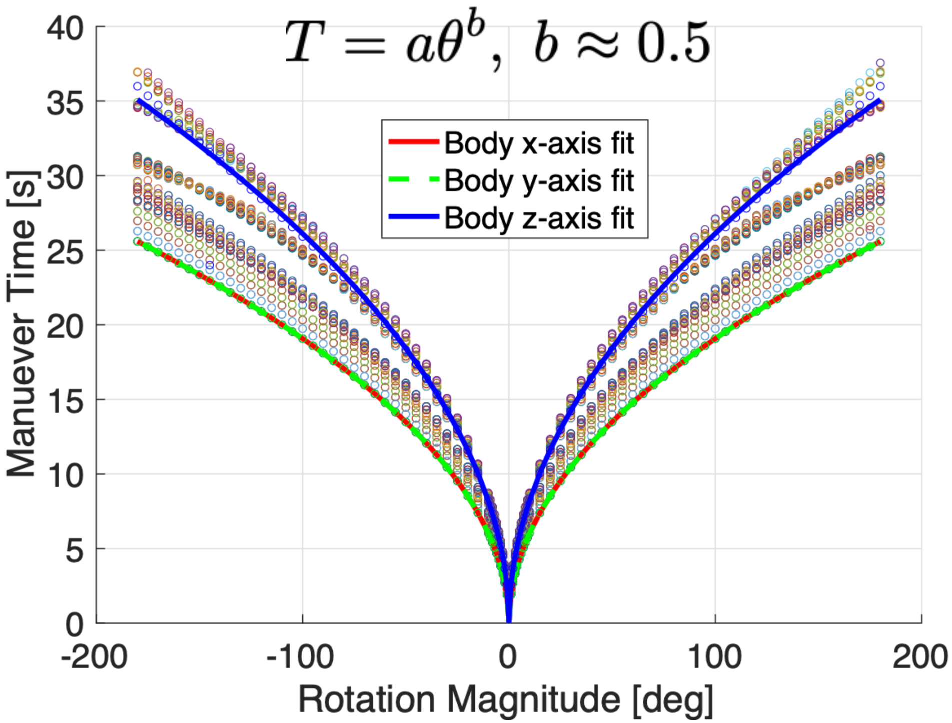
Attitude Control Systems for Agile Slewing

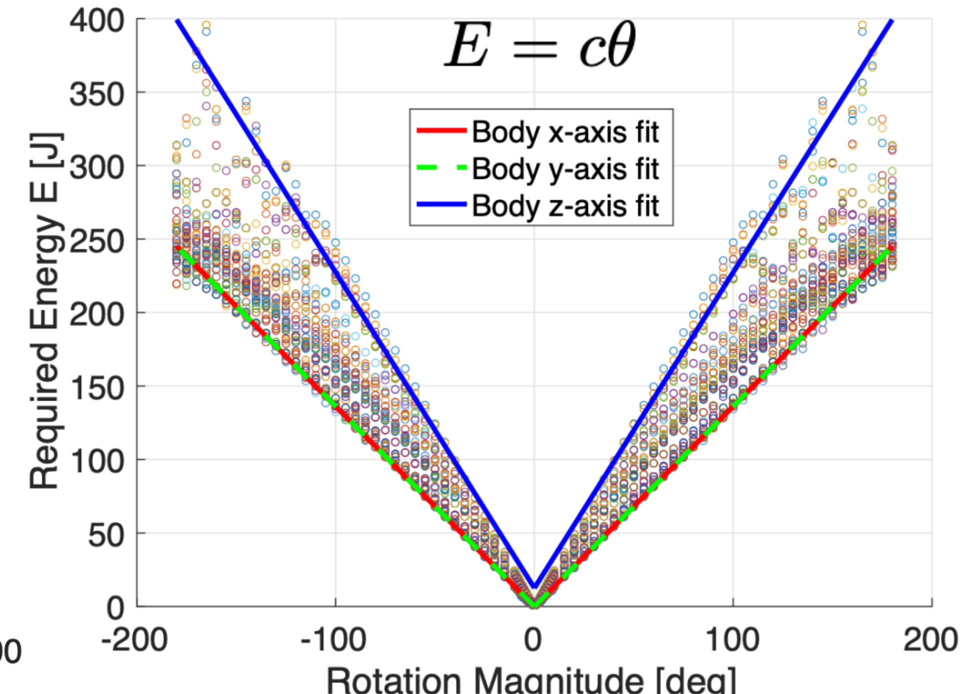
- Module validated on reference Planet Skysat of 110kg mass
- 100 rotation axes, 88 rotation magnitudes {-180,-175, ..., +175,+180}
- 8,800 problem instances solved off-line



Attitude Control Systems for Agile Slewing

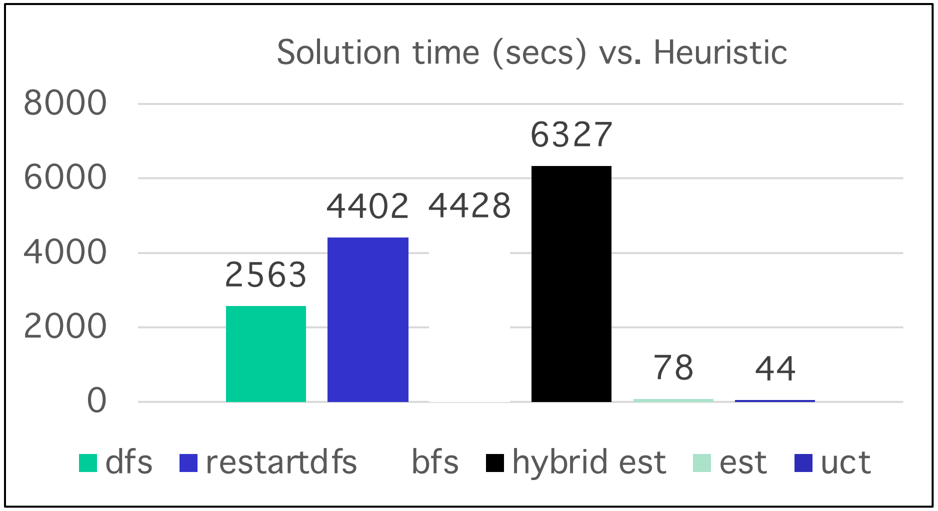
- Minimum time / error / energy optimizations of slew solved using sequential convex programming
- “Bang-bang” eigenaxis slew is not necessarily time-optimal.
- Optimal time approximately proportional to square-root of slew angle
- Required energy directly proportional to slew angle

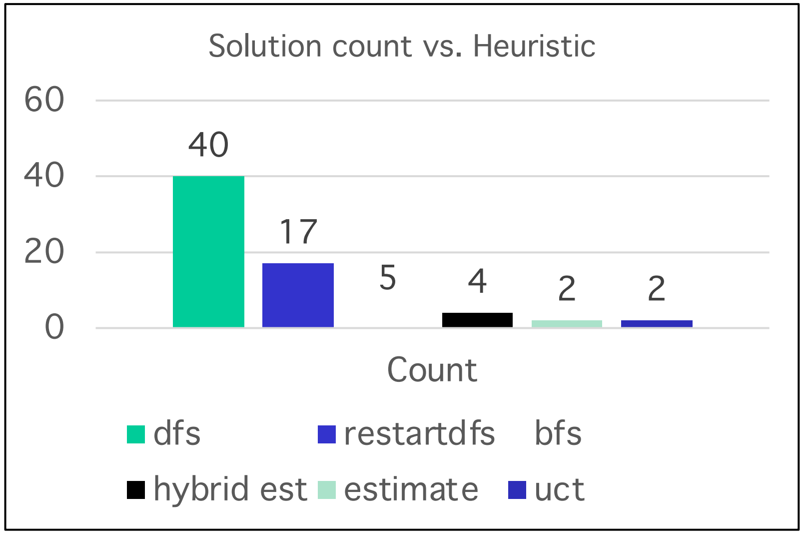


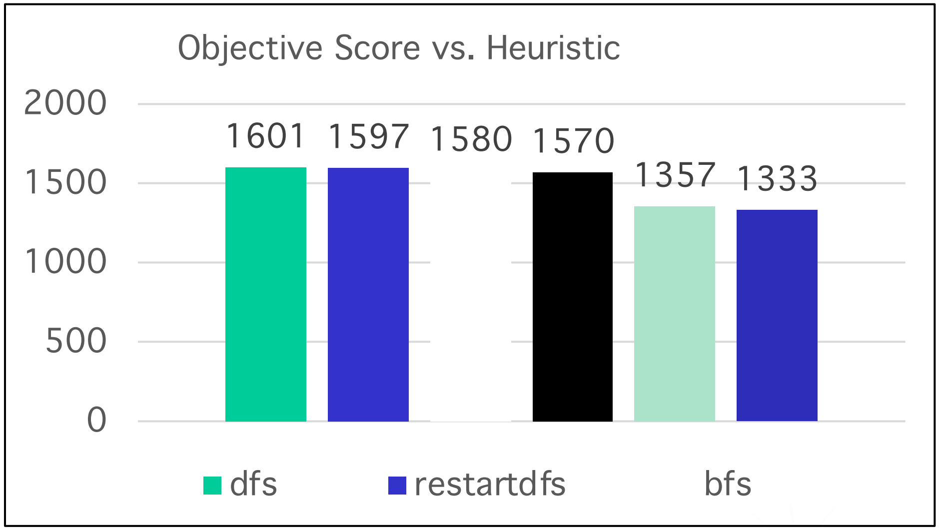


Planner Algorithm Exploration: Downlink

Generate an optimized coordinated schedule for a swarm of satellites to download data. Each satellite has multiple payloads with multiple priorities and multiple downlink receiver choices. Assumption-All data collection is mandatory and only downlink is scheduled. *Actual problem is the opposite, but framed as such to compare algorithms*

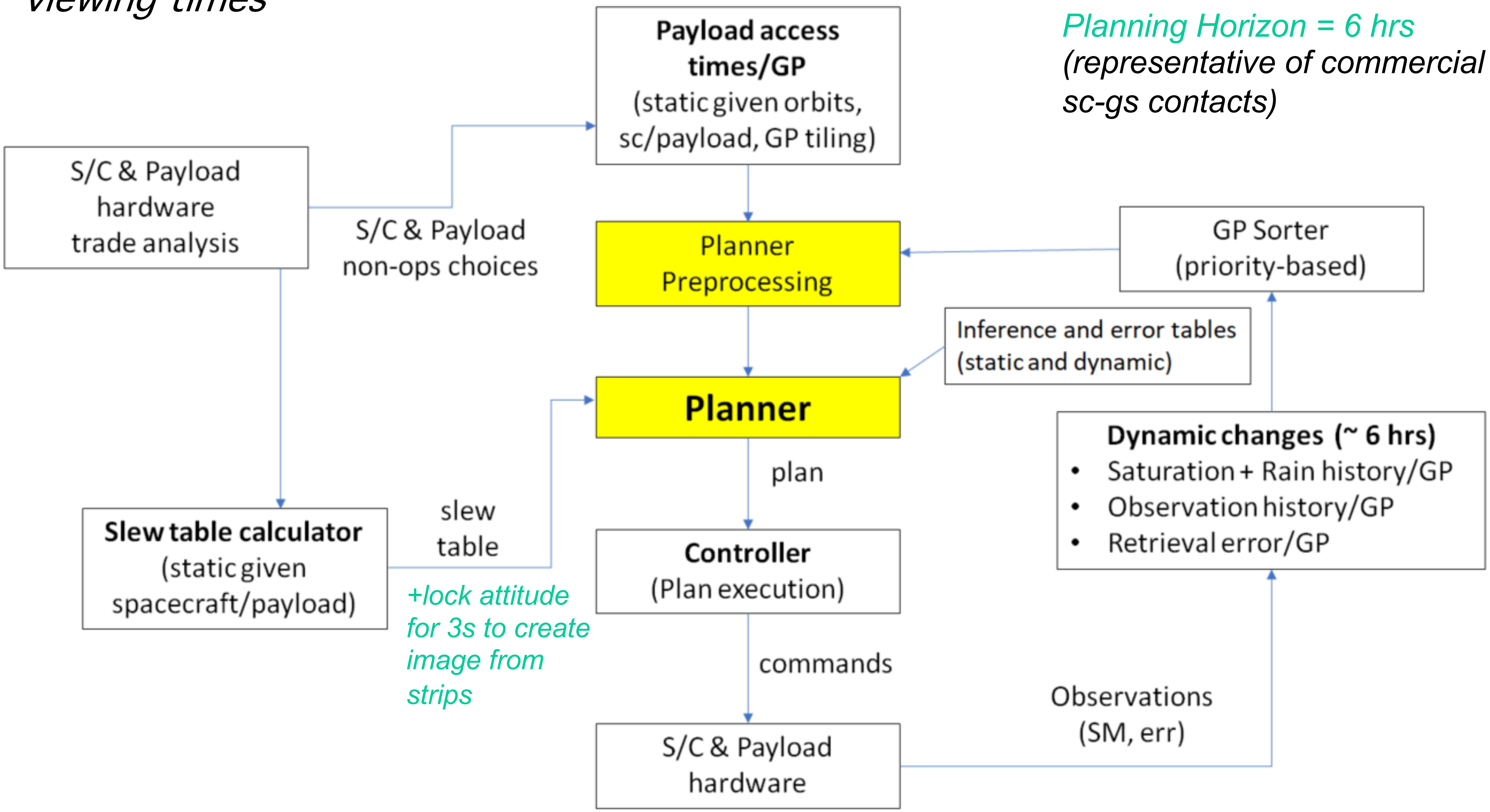






Observation Planner: Optimizing the Schedule

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

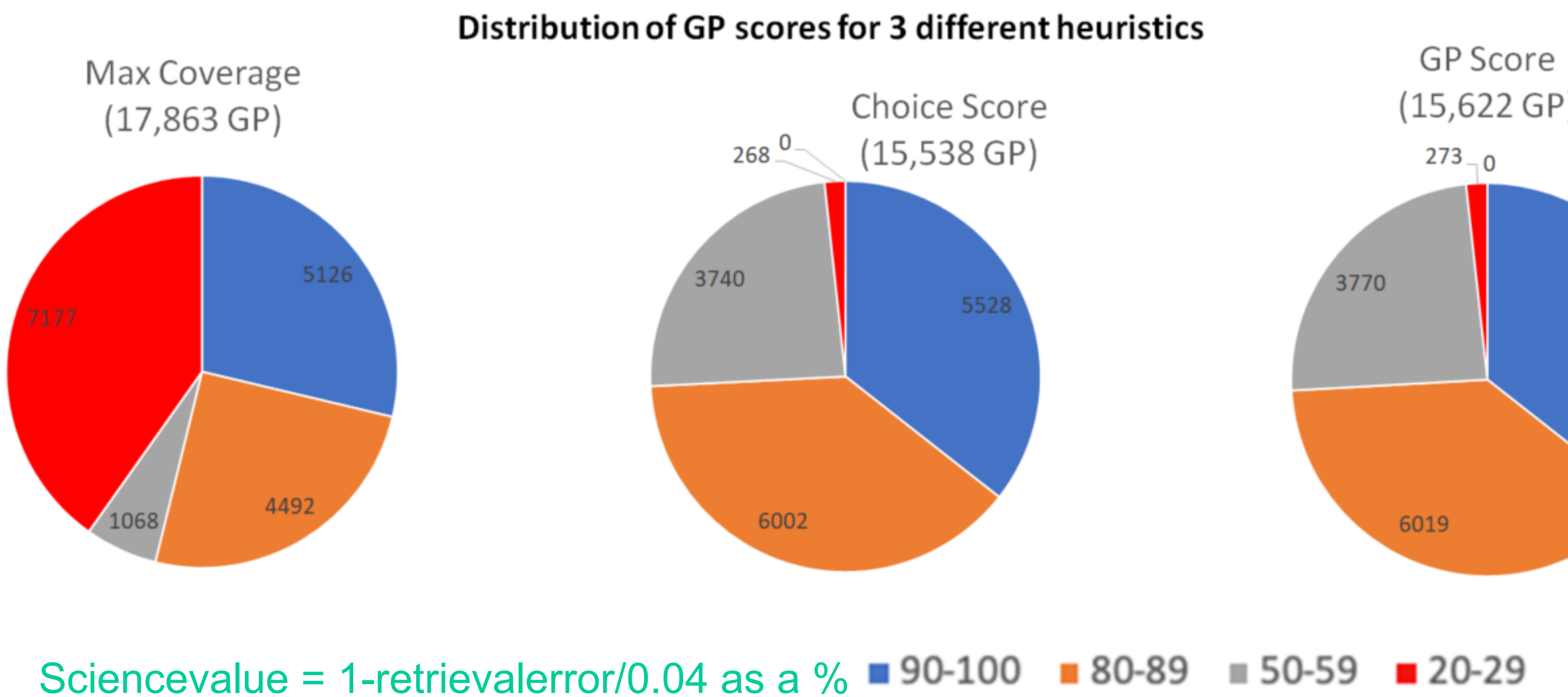
sciencevalue= 1-retrievalerror/0.04 (after ranking for seen, rain, saturation)

Planner: Optimizing the Observation Schedule

Local and Global Heuristics are ongoing topics of research:

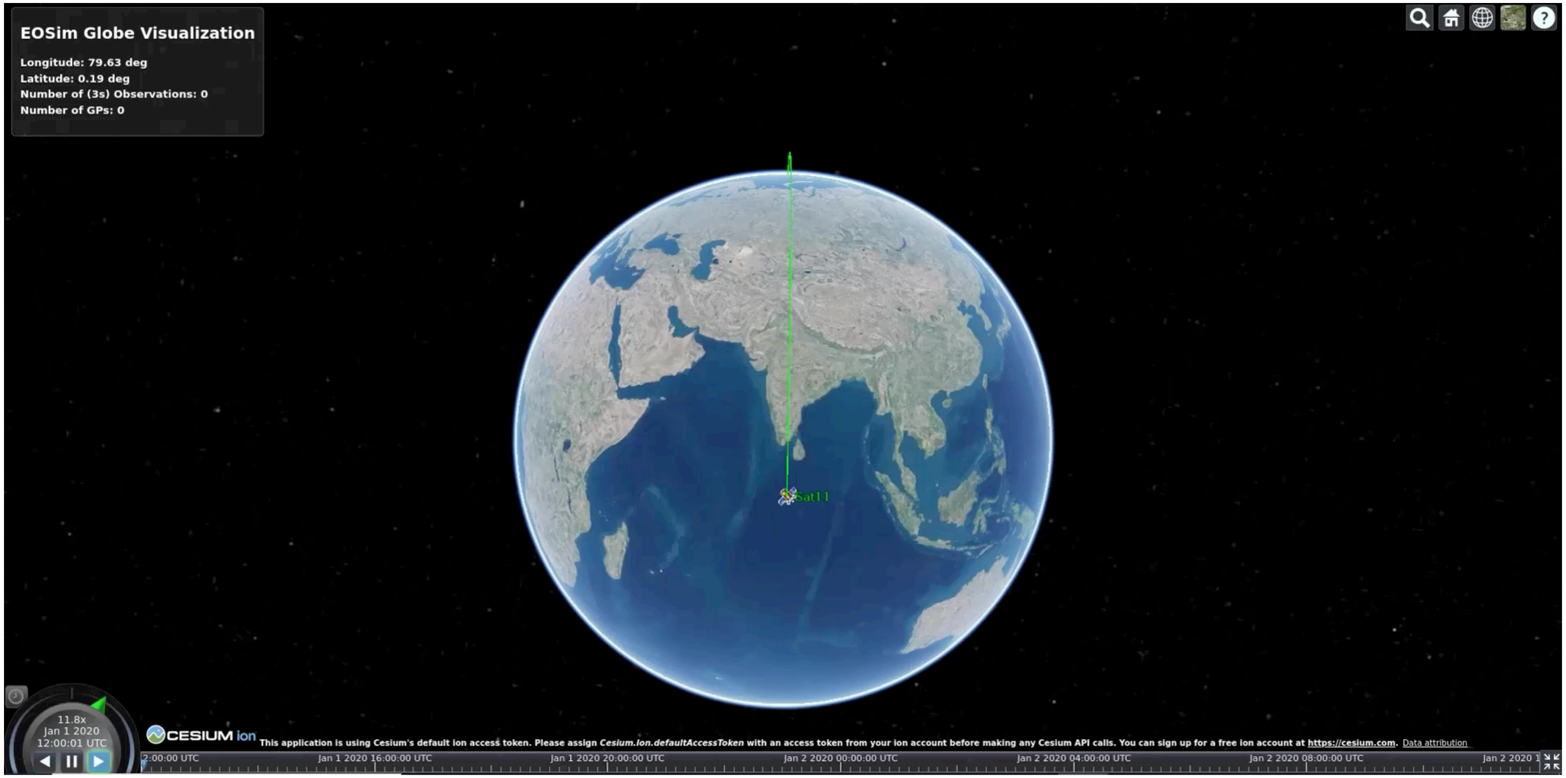
1. Max Coverage maximizes number of GPs seen but does not use science value
2. Choice Score maximizes science value without accounting for GPs seen
3. GPscore maximizes product of GPs and science value (*current POR*)
4. Other options: max GP choice rank, max RareGP (TBD with improved science simulator)

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

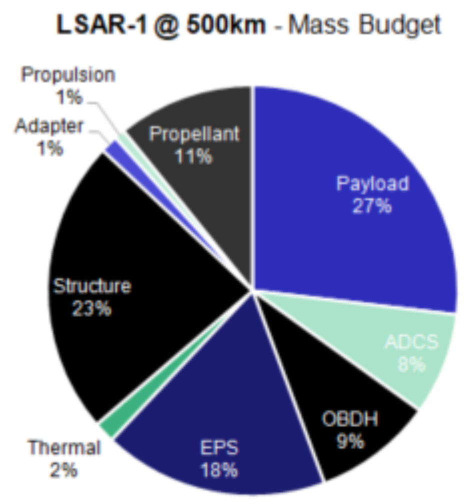
Very prelim Planner: Single Sat has 15% SMAP temporal coverage at 60x AT spatial resolution

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

Addressing Temporal Resolution / Constellation

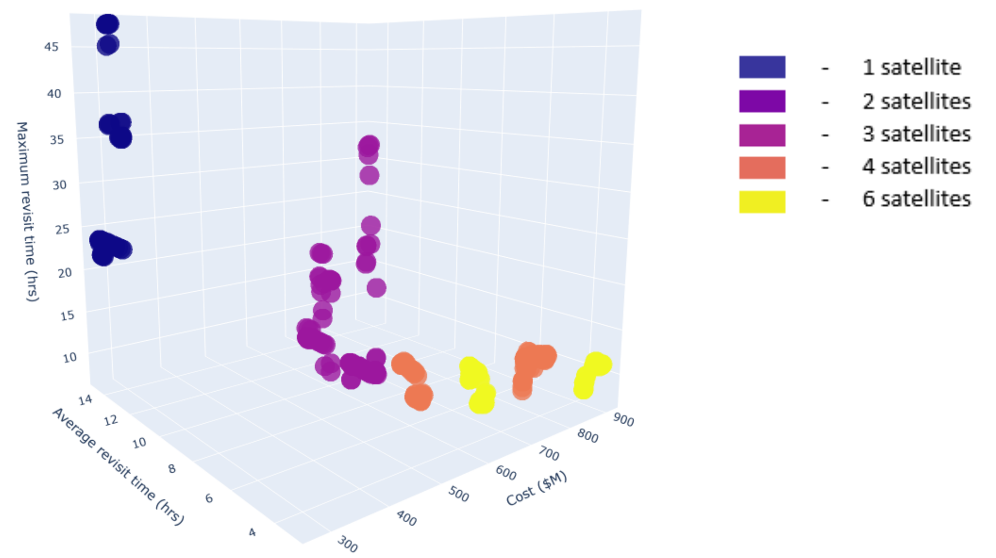
- Payload input => spacecraft sizing => Constellation sizing
- Options: Prior knowledge e.g. IceEye, Capella, Tradespace tool e.g. TAT-C, self-evaluation to account for P/L band radars + multi-instrument spacecraft + heterogeneous constellation + loose coupling with spatio-temporal resolution of agility on soil moisture science

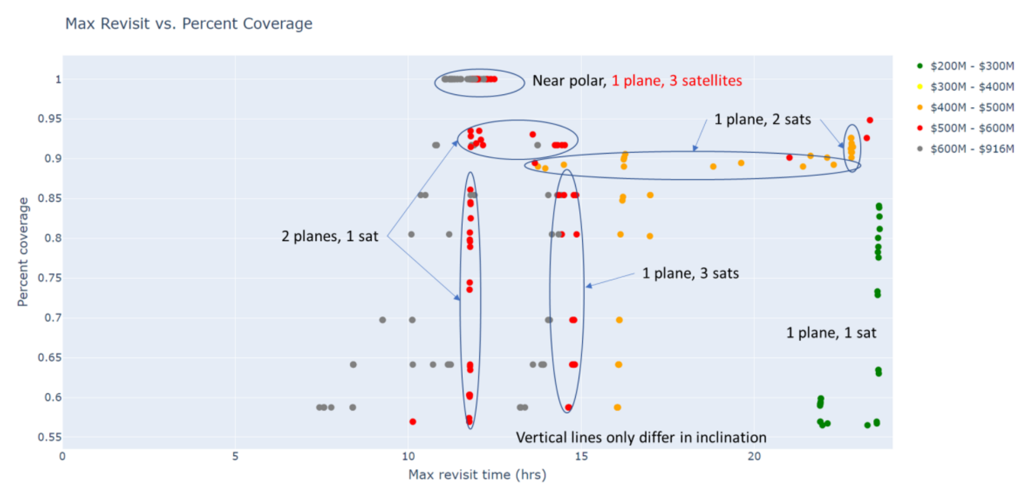
- Used JESS-based tool to size the s/c at 10% duty cycle, 500 km orbit, pending better estimates of electronics mass (old tech) for radars<100kg and extension to radiometers and reflectometers
- Used VASSAR to find baseline constellations that minimizes lifecycle cost and maximizes ability to point to SM-relevant regions as frequently as possible



Baseline Constellation

- Model parameters
  - 10deg coverage grid over -70/+70 deg lat
  - 24h simulation time
- Design space
  - 1-4 pl., 1-4 sat/pl., but max 6 sats total
  - 1-10 day repeat cycle (~500km)
  - 0 to 90 deg inclination
  - L-band + P-band radars only
- Results
  - 1plane, 3-sats polar constellation emerges as good design (<15 hr max revisit, ~5 hr avg revisit, 100% coverage, <$539M)





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- Summary of Accomplishments and Future Plans
- Publications - List of Acronyms

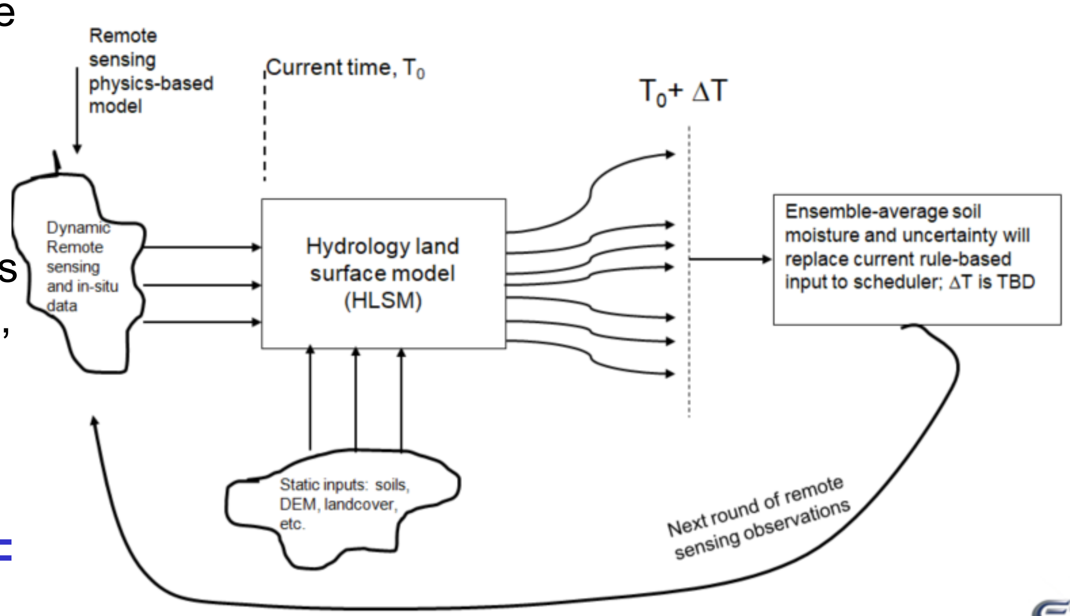
Summary of Accomplishments and Future Plans

- EOsim, Orbitpy, Instrupy beta version available online. ADCpy is complete to release 2021
- Preliminary rules and objectives for Soil Moisture uncertainty quantified
- Active radar model and error nearly complete
- Planner algos compared; Planner prototyped with prelim heuristics and algos
- Simple instrument, spacecraft, constellation sizer prototyped to change baseline based on appropriate feedback from planner

DONE

TO DO

- Software quality control and validation of all modules
- Addition of radiometer to InstruPy and spacecraft power/data to OrbitPy
- Improve Earth coverage algorithms and synthesizing nature runs into science value
- Planner: Couple heuristics to science sim, better algos, add downlink/power/constraints
- Science Simulator: Add multiple noise sources to active radar and add passive radiometer, Hydrology land surface model (HLSM), couple static/dynamic params into sim
- Explore non soil moisture applications of D-SHIELD (urban floods, cyclones, clouds)
- Implement Hybrid planner coupling onboard and ground based planning



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Publications

Journal Papers

1. V. Ravindra, S. Nag, A.S. Li, "Ensemble Guided Tropical Cyclone Track Forecasting for Optimal Satellite Remote Sensing", IEEE Transactions on Geoscience and Remote Sensing (TGRS), July 2020, DOI: 10.1109/TGRS.2020.3010821

Conference Papers

1. S. Nag, M. Moghaddam, D. Selva, J. Frank, V. Ravindra, R. Levinson, A. Azemati, A. Aguilar, A. Li, R. Akbar, *"D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions"*, IEEE International Geoscience and Remote Sensing Symposium, Hawaii USA, July 2020
2. V. Ravindra, S. Nag, *"Instrument Data Metrics Evaluator for Tradespace Analysis of Earth Observing Constellations"*, IEEE Aerospace Conference, Big Sky, Montana, March 2020
3. A. Aguilar Jaramillo, D. Selva, "Decentralized Task Allocation in Distributed and Federated Earth Observation Satellite Systems Using a Consensus-Based Algorithm", AIAA ASCEND Conference 2020
4. E. Sin, M. Arcak, A. S. Li, V. Ravindra, S. Nag, *"Autonomous Attitude Control for Responsive Remote Sensing by Satellite Constellations"*, AIAA Science and Technology Forum and Exposition (SciTech Forum), Nashville, January 2021
5. S. Nag, M. Sanchez Net, A. S. Li, V. Ravindra, *"Designing a Disruption Tolerant Network for Reactive Spacecraft Constellations"*, AIAA ASCEND Conference, Las Vegas, November 2020

Conference Talks

1. S. Nag, "D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions", Analysis-Ready Data Workshop at Planet Labs SF, November 2020
2. S. Nag, "Combinatorial Optimization for Distributed Vehicles", Quantum Technologies and Geospatial Intelligence Webinar, September 2020
3. S. Nag, A. Aguilar, R. Akbar, A. Azemati, J. Frank, R. Levinson, A. Li, M. Moghaddam, V. Ravindra, D. Selva, "D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions", NASA ESTF, June 2020
4. S. Nag, M. Moghaddam, D. Selva, J. Frank, V. Ravindra, R. Levinson, A. Azemati, A. Aguilar, A. Li, R. Akbar, *"Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions (D-SHIELD) for Soil Moisture Monitoring"*, American Geophysical Union Fall Meeting, San Francisco CA, December 2020
5. S. Nag, M. Sanchez Net, A. S. Li, V. Ravindra, *"Designing a Disruption Tolerant Network for Reactive Spacecraft Constellations"*, American Geophysical Union Fall Meeting, San Francisco CA, December 2020

ESTO Earth Science Technology Office

Thank you!

Questions?

Sreeja.Nag@nasa.gov

Publicly available Source Code and Docs: