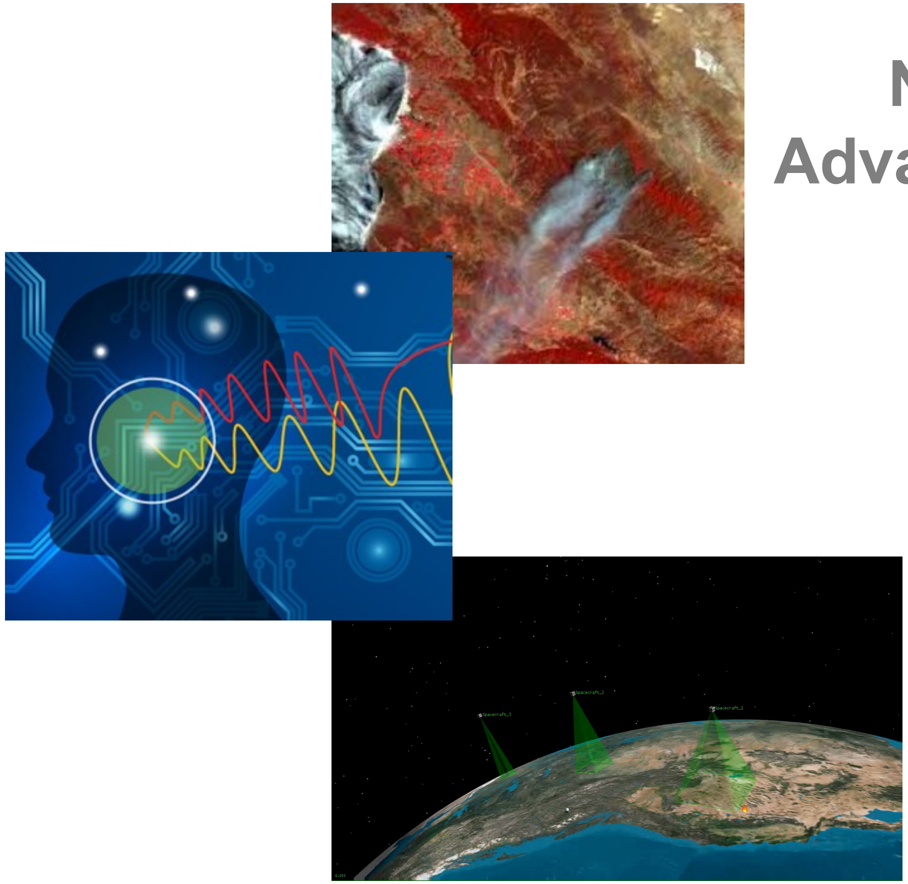


NASA Earth Science Technology Office (ESTO)
Advanced Information Systems Technology (AIST)

New Observing Strategies (NOS)

Annual Technical Reviews

Jacqueline Le Moigne

January 4, 2021

Advanced Information Systems Technology (AIST) Program Management Team

"Investment in information systems that NASA Earth Science will need in the 5 to 10-year timeframe"

Jacqueline Le Moigne, Program Manager
Mike Seablom, Senior Strategist
Marge Cole, Outreach and Validation
<u>Associates:</u> Ian Brosnan, Transitions/Infusions Laura Rogers, Biodiversity & Ocean Nikunj Oza, AI Liaison Ben Smith, Initial NOS-Testbed Demonstration
Jackie Ferguson, Resources Analyst
Bob Connerton, Advisor
Paul Padgett, Communications

NOS and ACF for Science Data Intelligence

Optimize measurement acquisition using many diverse observing capabilities, collaborating across multiple dimensions and creating a unified architecture

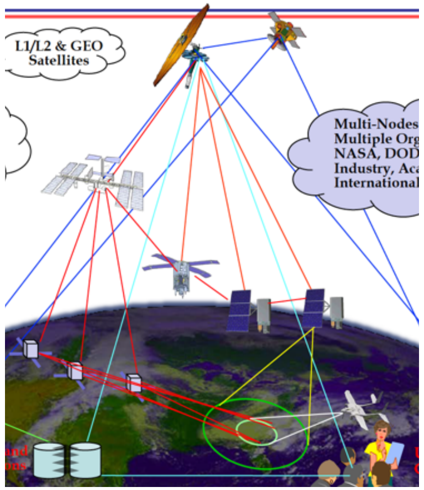
Assimilate Observations

Enhance and enable focused Science investigations by facilitating access, integration and understanding of disparate datasets using pioneering visualization and analytics tools as well as relevant computing environments

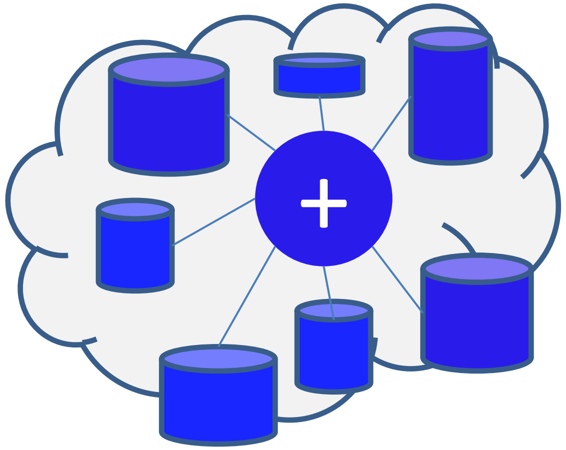
New Observing Strategies (NOS)

Acquire coordinated observations

Track dynamic and spatially distributed phenomena



Analytic Collaborative Frameworks (ACF)



Assimilate many various data into models and analytic workflows.

What additional observations are needed?

Observation Requests

Example: NOS Testbed Demonstration planned for Spring 2021 targeting Mid-West Floods with LIS Models as well as Space and ground observations

Example: OceanWorks, ACF for Ocean Science https://oceanworks.jpl.nasa.gov

NOS+ACF acquires and integrates complementary and coincident data to build a more complete and in-depth picture of science phenomena

NOS for Optimizing Measurements Design and Dynamically Capturing full Science Events

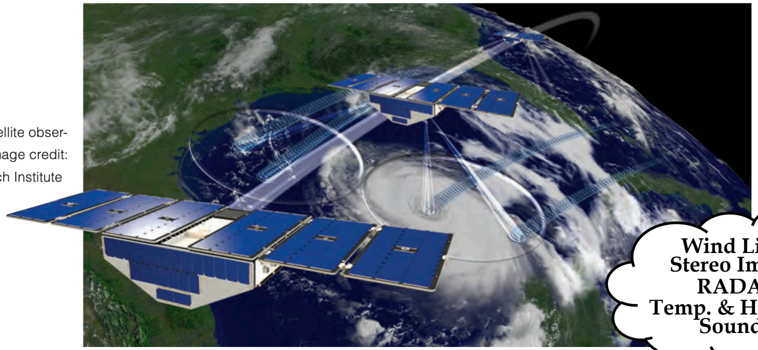
Distributed Spacecraft Missions (DSM):

A Distributed Spacecraft Mission (DSM) is a mission that involves multiple spacecraft to achieve one or more common goals.

Can provide:

- **Multi-perspective observation (angular, spatial, spectral, temporal)**, for fundamental physical understanding of dynamic phenomena
- **Multi-point measurements** for full observation coverage

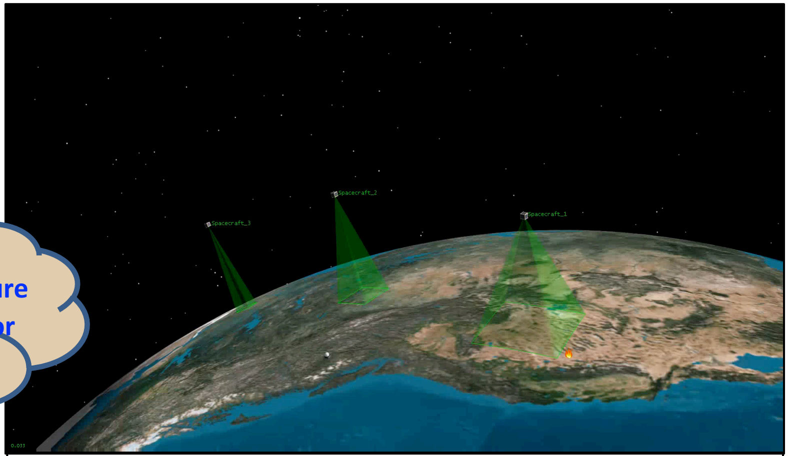
CYGNSS microsatellite observatories in orbit. Image credit: Southwest Research Institute



Using a constellation of eight small satellites enables frequent observations

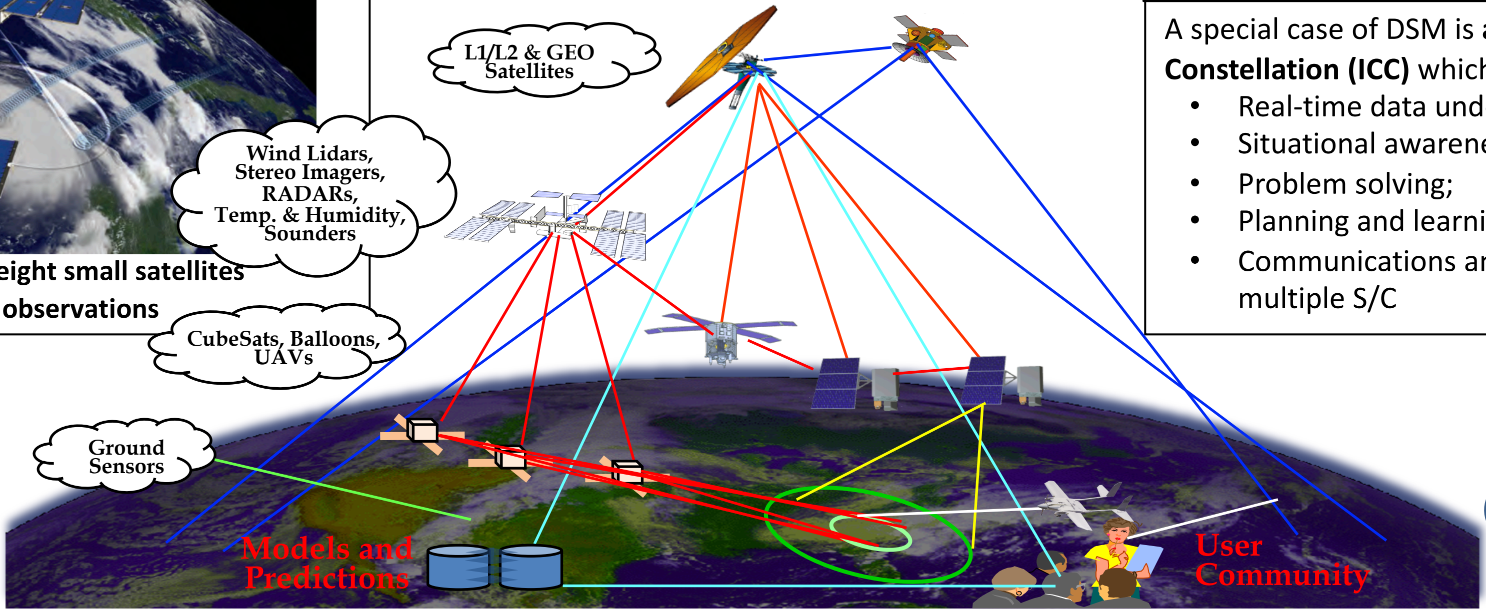
Multiple collaborative nodes from multiple organizations (NASA, OGAs, Industry, Academia, International) from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)

Provide complete picture of physical processes or natural phenomena



A special case of DSM is **an Intelligent and Collaborative Constellation (ICC)** which involves the combination of:

- Real-time data understanding
- Situational awareness
- Problem solving;
- Planning and learning from experience
- Communications and cooperation between multiple S/C



Increased understanding and predictability of dynamic events on Earth.

Actively acquire data in coordination with other sensors, models in response to measurement needs and/or science events

A SensorWeb is a distributed system of ***sensing nodes*** (space, air or ground) that are interconnected by a ***communications fabric*** and that functions as a single, highly coordinated, virtual instrument.

New Observing Strategies (NOS) Objectives

1. Design and develop New Concepts:

- In response to a need that comes from Decadal Survey or a Model or other science data analysis
- Include **various size spacecraft** (CubeSats, SmallSats and Flagships)
- Concepts will be **Systems of systems (or *Internet-of-Space*)** that include constellations, hosted payloads, ISS instruments, HAPS sensors, UAVs, ground sensors, and models (future: IoT sensors, social media & others)
- Take into consideration other **various organizations** (OGAs, industry, academia, international) assets to optimize the development of new NASA assets
- **Make trades** on number & type of sensors, spacecraft and orbits; resolutions (spatial, spectral, temporal, angular); onboard vs. on-the-ground computing; inter-sensor communications, etc.
- System being **designed in advance** as a mission or observing system **or incrementally and dynamically over time** if connected in a feedback loop with a DTE or ACF system

2. Respond to various science and applied science events of interest

- **Various overall observation timeframes**: from real-time to mid-term to long-term events
- **Various area coverages**: from local to regional to global
- **Dynamic** and in response to a specific event (science event or disaster or ...)
- **Real-time SensorWeb response** by:
  - Analyzing which assets could observe the event at the required time, location, angle and resolutions.
  - Scheduling, re-targeting/re-pointing assets, as needed and as possible

NOS Review Schedule

January 4th, 2021 New Observing Strategies (NOS) Technical Annual Reviews					
Tech	**Science**	**Name**	**Title**	**Start**	**Stop**
		Le Moigne	Introductions	11:00 AM	11:20 AM
OSSE / Modeling Systems	Snow / Water & Energy	**Gutmann**	Future Snow Missions: Integrating SnowModel in LIS	11:20 AM	12:00 PM
Modeling systems / data fusion / OSSE	Hydrology / Water & Energy	**Forman**	Next Generation of Land Surface Remote Sensing	12:00 PM	12:40 PM
OSSE / SW Architecture	Weather / Clouds & Aerosols	**Posselt**	Parallel OSSE Toolkit	12:40 PM	1:20 PM
Mission Planning tool / Constellation planning testbed architecture		**Grogan**	Integrating TAT-C, STARS, and VCE / NOS Testbed Architecture	1:20 PM	2:00 PM
Sensor Web / Autonomy / ML	Soil Moisture / Water & Energy	**Nag**	D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions	2:00 PM	2:40 PM
		Break		***2:40 PM***	***2:50 PM***
Onboard processing, Cube-SmallSats	Weather / Winds	**Carr**	StereoBit: Advanced Onboard Science Data Processing to Enable Earth Science	2:50 PM	3:30 PM
Sensor Web / UAV operations	Hydrology / Water & Energy	**Moghaddam**	SPCTOR: Sensing Policy Controller and OptimizeR	3:30 PM	4:10 PM
Ground Station as a service / SW Architecture		**Nguyen**	Ground Stations as a Service (GSaS) for Direct Broadcast Satellite Data	4:10 PM	4:50 PM
Data 3D visualization – CAMP2 EX field campaign		**Di Girolamo**	Data Fusion Visualization for NASA CAMP2 Ex Field Campaign	4:50 PM	5:30 PM

AIST Group Project Review Objectives

- **Regular Annual Reporting Requirements**
  - Individual Programmatic Annual Reviews
  - Technical Annual Reviews Grouped by Topics
- **Establish relationship between awardees**
  - Introduce AIST PIs and their work to one another
  - Enable desired collaborations
  - Potentially share algorithms, codes or cross-cutting ideas
- **Present AIST-18 Projects and PIs to broader community**
  - Present AIST-18 projects to NASA ESD Program Managers and partner organizations
  - Support technology infusions and knowledge transfer of AIST projects upon completion.
- **Review Needs in terms of:**
  - ESIP: Project analysis to improve infusion and transition opportunities
  - SMCE (NASA Science Managed Cloud Environment): AWS system access

ESIP
Earth Science Information Partners

Image Credit: NASA

Image Credit: National Geographic

ESIP TECH EVALUATION

ANNIE BURGESS, PHD

AIST Technical Annual Reviews

Supported by:

ESIP PROVIDES AN EVALUATION FRAMEWORK THAT EXPOSES DEVELOPING TECHNOLOGY TO POTENTIAL END-USERS AND ADOPTERS, ULTIMATELY INCREASING ITS UTILITY AND USABILITY.

FUNDING

Evaluators are compensated for their time, increasing the likelihood of a thorough, comprehensive evaluation.

FACILITATION

ESIP facilitates evaluator calls, development of evaluation plan, communication with PIs.

FRAMEWORK

OBJECTIVES

ESIP works with PIs to set specific objectives taking into consideration TRL.

TECHNICAL EXCHANGE MEETING

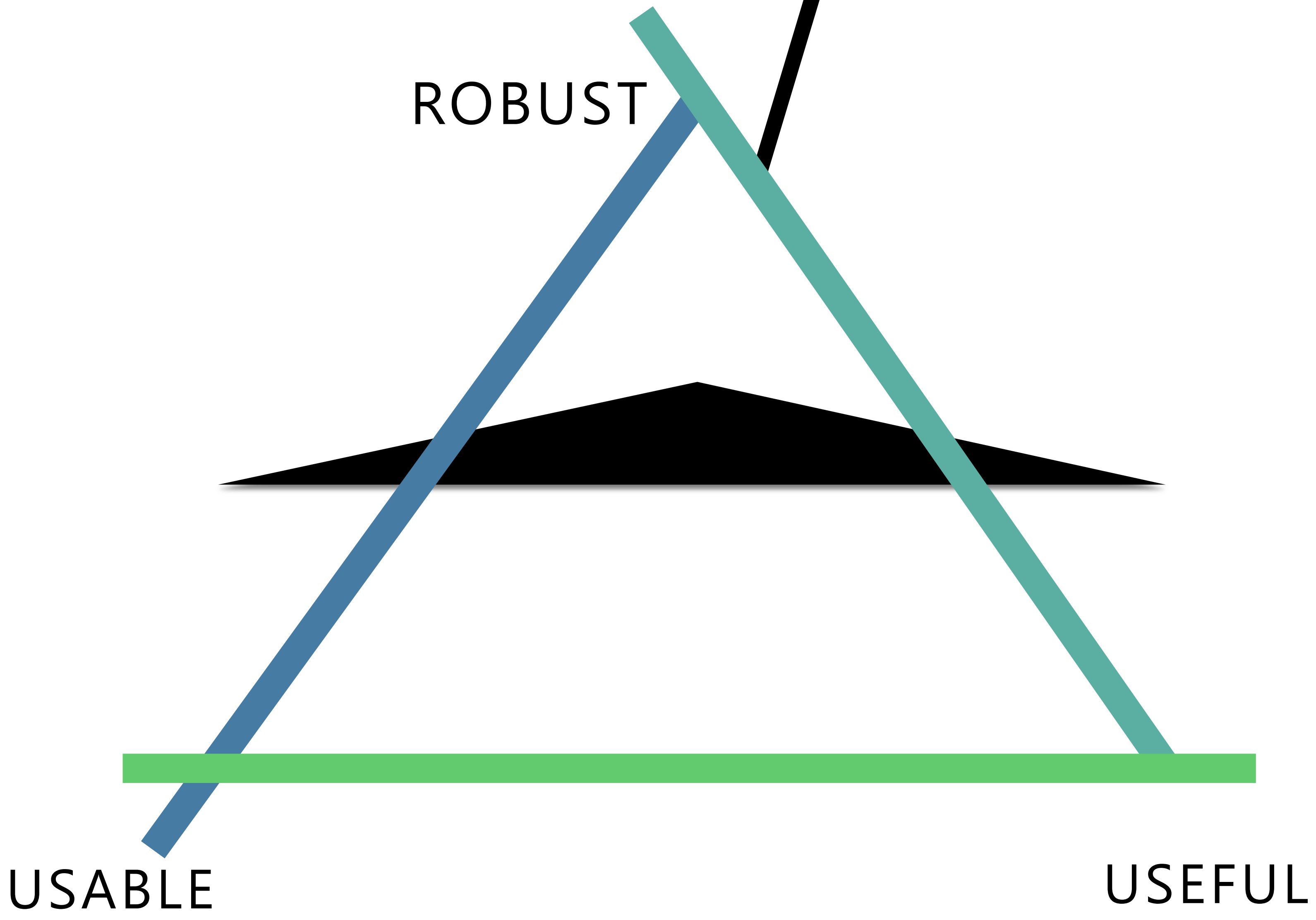
PI team meets evaluators. Big picture to backend... evaluators should have a solid understanding of the purpose and goals of tech.

EVALUATION PERIOD

ESIP coordinates evaluation process. Evaluators meet regularly, requesting information from PIs when necessary.

FINAL REPORT

ESIP works with evaluators to create final report to be shared with PIs & AIST. Reports can be public upon PI request.


ROBUST
USABLE
USEFUL

ESIP

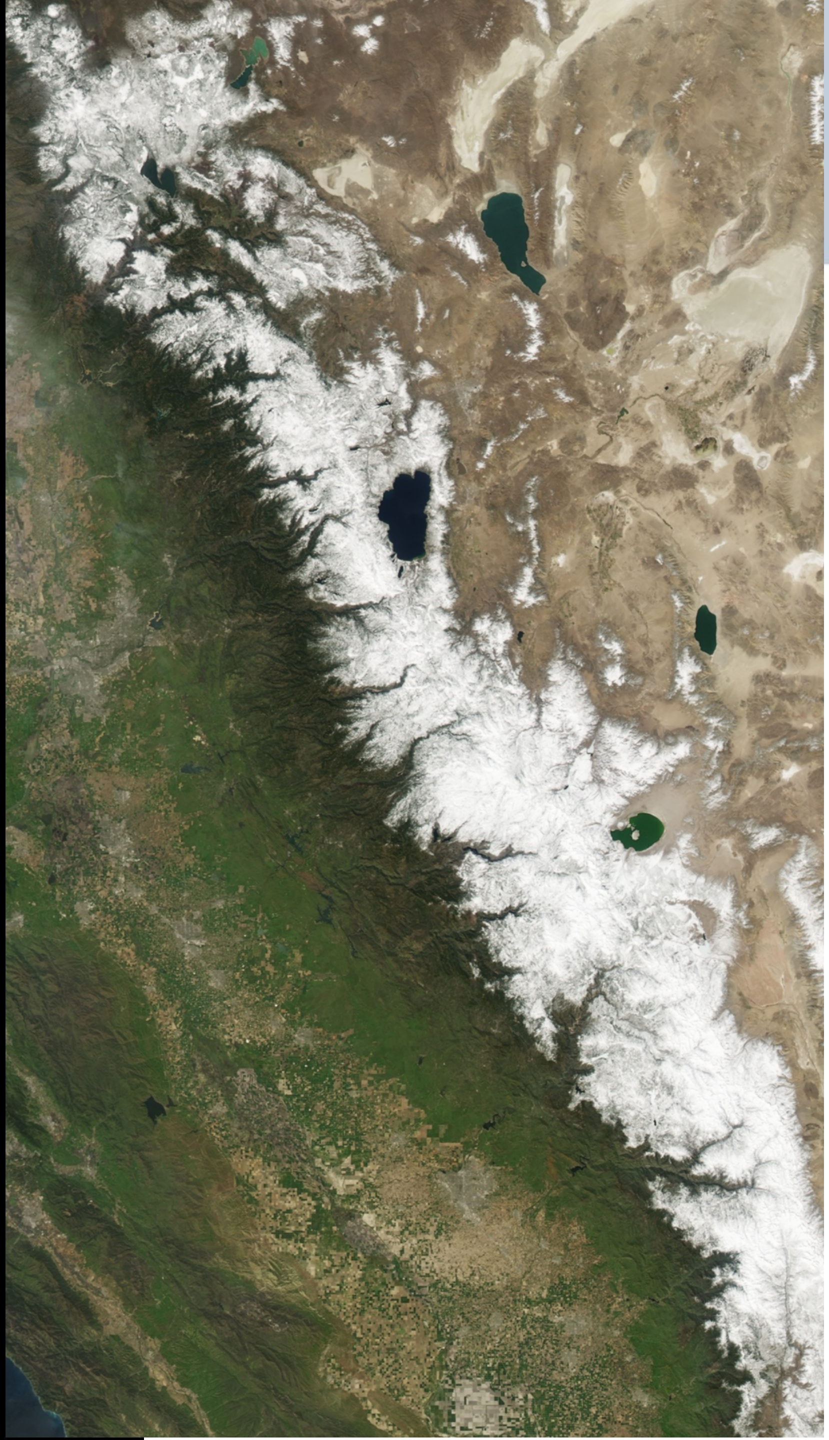
Earth Science Information Partners

esipfed.org | #ESIPfed

THANK YOU

ANNIE BURGESS, PHD

ANNIEBURGESS@ESIPFED.ORG



ESIP is supported by:

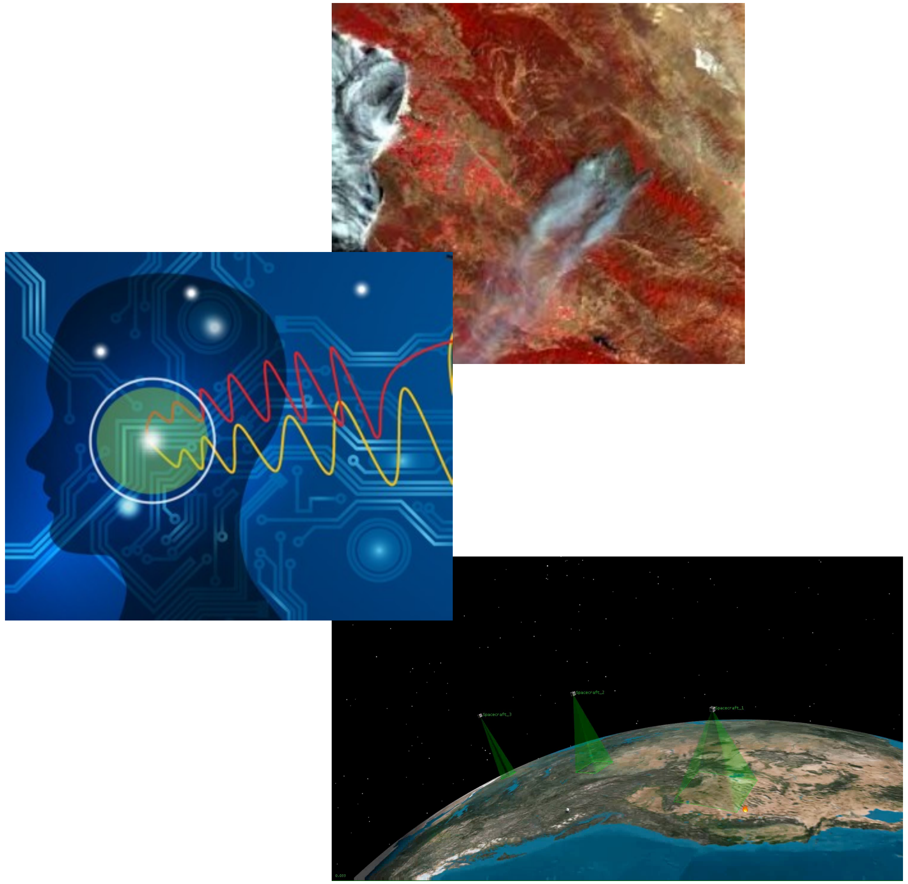
AIST SMCE Options
Marge Cole

- A critical component of the success of AIST projects is access to cost effective, flexible, and scalable compute and storage infrastructure.

- The Science Managed Cloud Environment (SMCE) is a managed Amazon Web Service (AWS) based infrastructure for NASA funded projects that can leverage cloud computing capabilities. This environment is designed to:
    - Provide cloud access to NASA PIs with non-NASA team members.
    - Perform research using new computing capabilities without extensive start-up time.
    - Use new tools and methods from AWS's product catalogue easily and affordably.
    - Scale computing for high-demand, high-bandwidth needs.

- More information at: https://www.nccs.nasa.gov/systems/SMCE

- ***NASA Managed (AWS) Cloud Environment Access***
    - Pay-as-you-go cloud account access with NASA security already built in
    - Enables ease of cloud-based project transition to NASA programs due to NASA level security already requirements already being met.



Introductions

Going Around the Virtual Room

Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS

Ethan Gutmann (PI, NCAR), Glen Liston (Co-I, CSU), Carrie Vuyovich (Co-I, GSFC), Barton Forman (Co-I, UMD), Jessica Lundquist (Co-I, UW)

AIST-18-0045 Annual Technical Review

January 4th 2021

Team listing: Kristi Arsenault (Co-I, GSFC/SAIC),
Melissa Wrzesien (GSFC/USRA), Shugong Wang (Co-I, GSFC/SAIC), Rhae Sung Kim (GSFC/USRA), Adele Reinking (Co-I, CSU), Andy Newman (Co-I, NCAR), Alessandro Fanfarillo (NCAR), Ross Mower (NCAR)

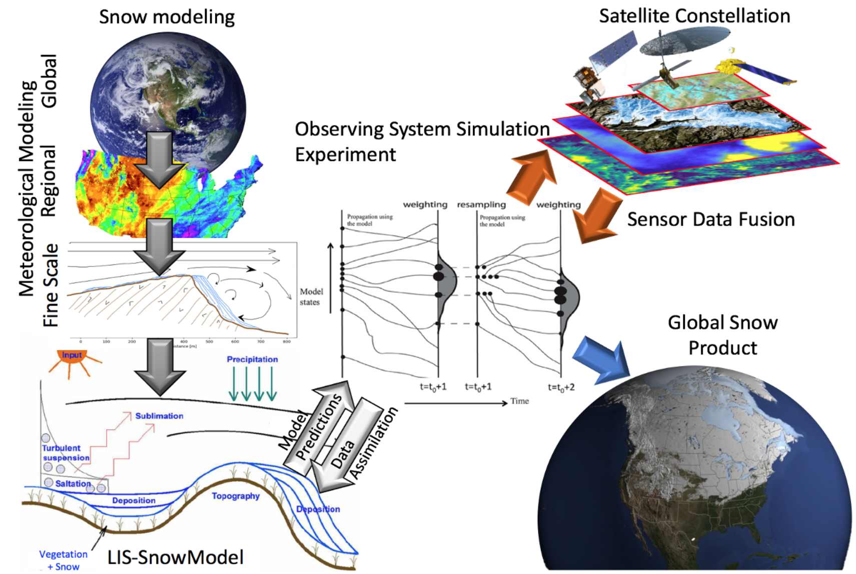
Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS

PI: Ethan Gutmann, National Center for Atmospheric Research

Objectives

Develop an OSSE to improve analysis of snow mission design cost-benefit tradeoffs and extend the NASA Land Information System Framework (LISF) to simulate critical sub-km scale snow variations by:

- Developing a modeling system to produce a realistic fine-scale simulation of snow spatial patterns
- Enhancing LIS-SnowModel system to be capable of continental scale sub-km grid simulations
- Improving local meteorology forcing data for LISF in complex terrain
- Parallelization and optimization for large-domain simulations



Snow Modeling OSSE and Data-Fusion Framework

Approach

Extend the NASA Land Information System Framework (LISF) to simulate critical snow processes:

- Incorporate SnowModel's MicroMet in LISF to enhance the surface meteorological fields produced by LISF
- Add SnowModel's SnowPack and snow redistribution capabilities to extend the snow modeling capabilities in LISF.
- Implement and optimize multi-node parallel computing capability into LISF-SnowModel to permit large, high-resolution simulations.
- Utilize the new LISF-SnowModel capabilities for the NASA-SnowEx Snow Ensemble Uncertainty Project (SEUP) and a dedicated Observing System Simulation Experiment (OSSE).

Co-Is/Partners: B. Forman, UMD; G. Liston, A. Reinking, CSU; J. Lundquist, UW; A. Newman, NCAR; C. Vuyovich, K. Arsenault, S. Wang, S. Kumar, GSFC

Key Milestones

- MicroMet routines integrated in LISF 12/20
- SnowModel is used in LIS to complete a simulation 03/21
- SnowModel is used in LIS to complete a 30-year continental domain simulation. 09/21
- Continental domain LIS-SnowModel simulations used with the synthetic observation operator as the Nature run for NASA-SEUP snow OSSE. 03/22

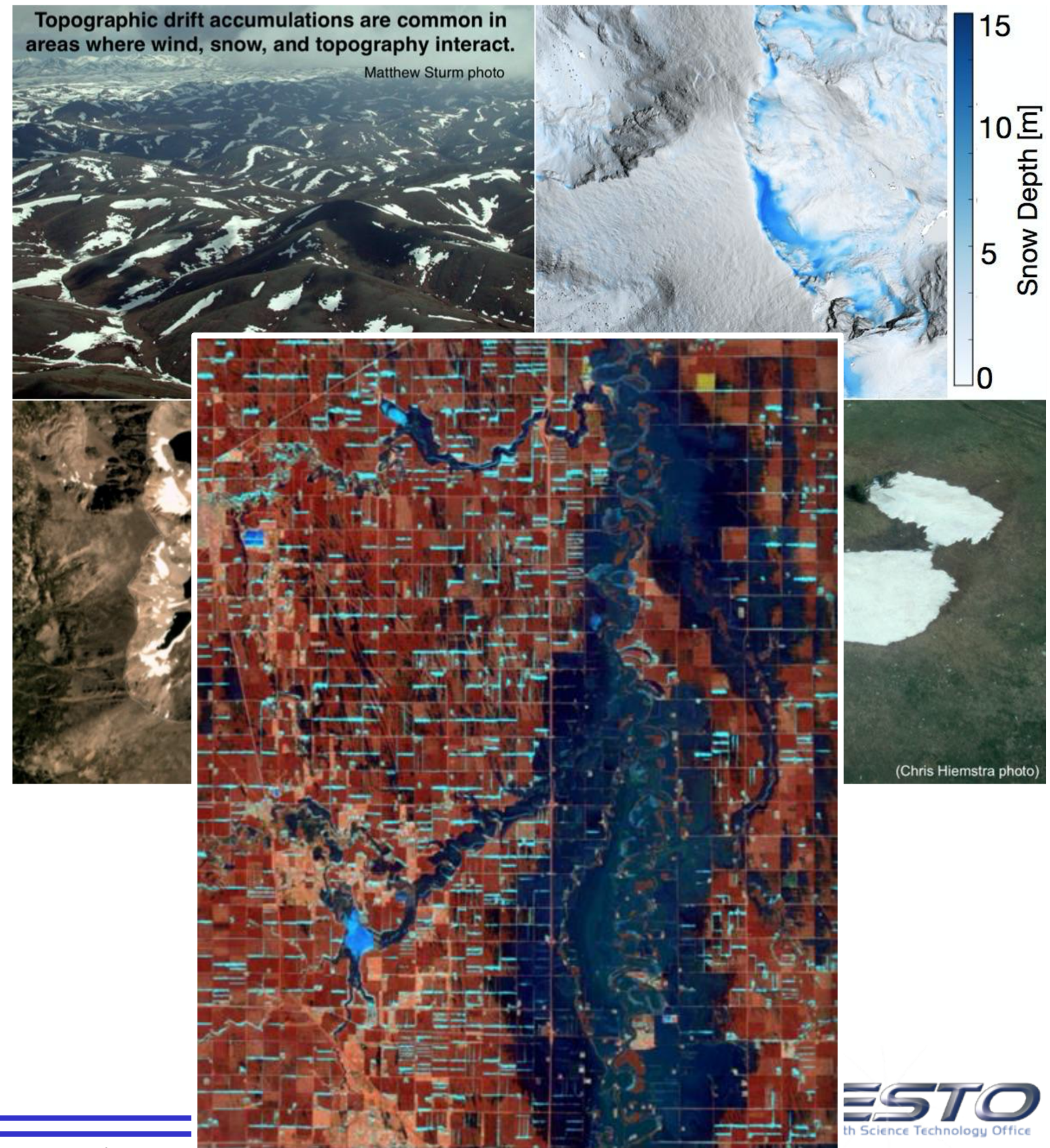
TRL_{in} = 2 **$TRL_{current}$ = 3**

Presentation Contents

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

Why do we need a spatially explicit representation of snow in LIS?

- LIS snow is used for mission planning and model-data fusion
- The representation of snow in LIS now is one dimensional
- Real snow is extremely heterogeneous
- Variability comes from preferential deposition / redistribution / melt
- Occurs on scales of 10-100 m, but has impacts over 10-100 km
- Using LIS as a planning tool for future snow missions thus likely undervalues high spatial resolution and overvalues methods that work well for shallow snowpacks.



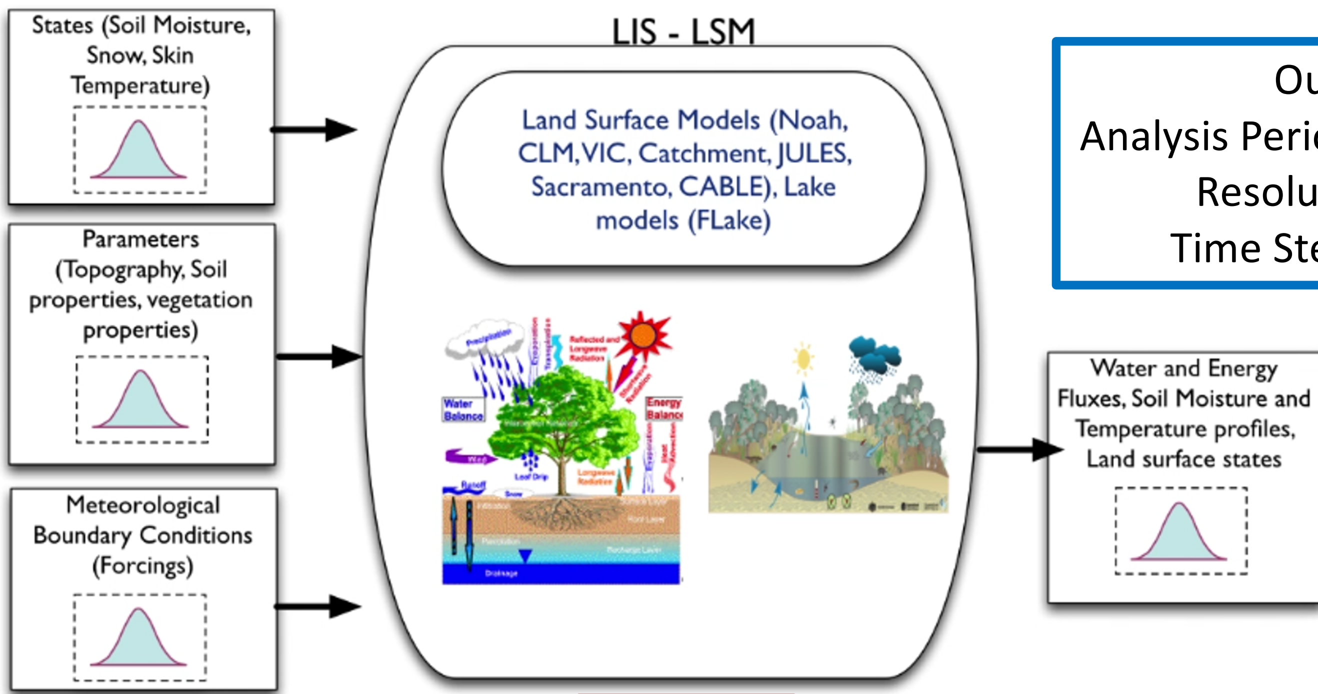
LIS and Snow Ensemble Uncertainty Project

Plan: Use the NASA Land Information System (LIS) framework to run an ensemble of models and forcing datasets to characterize SWE uncertainty across North America to identify regions and temporal periods of high variability.

Downscaling

3 Forcings:

MERRA2
GDAS
ECMWF



4 LSMs:

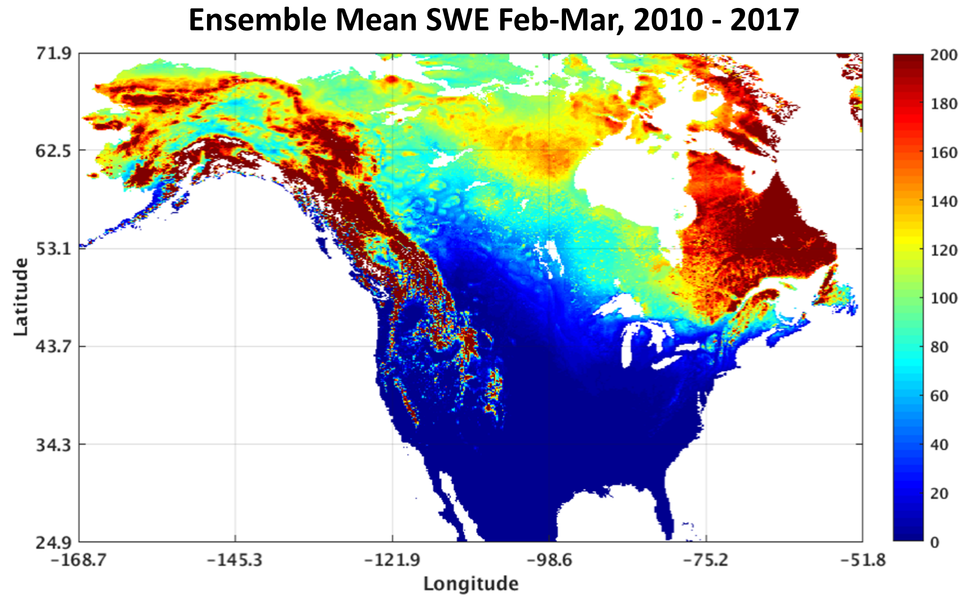
Noah-MP, Noah 2.71, Jules, CLSMF 2.5

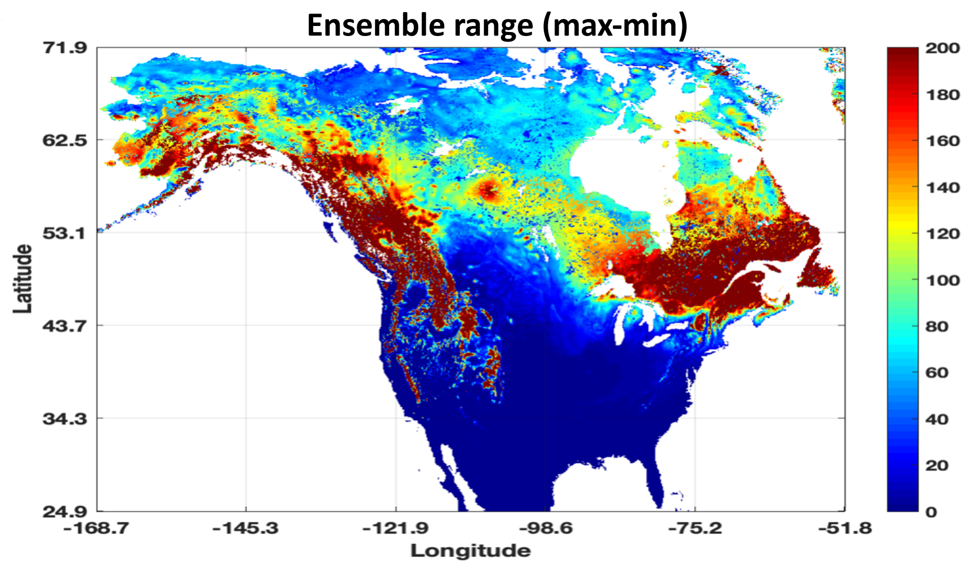
Output:
Analysis Period: 2009 – 2017
Resolution: 5km
Time Step: 3 Hours

SCF
SWE
Evaporation
Surface runoff
Soil Moisture
Rainfall
Snowfall

SEUP Initial Results

1. Tundra region: 43 – 67% of total N. America Snow Water Storage (SWS), high variability in ensemble estimates of SWS.
2. Evergreen/Taiga regions: 17 – 27% of total N. America SWS, with high variability in estimates of SWS and SWE
3. Mountain regions have much greater amount and variability in Snow Water Equivalent (SWE) than non-mountain regions
4. About 75% of the spread stems from the choice of LSM, rather than forcing, though it varies by location.

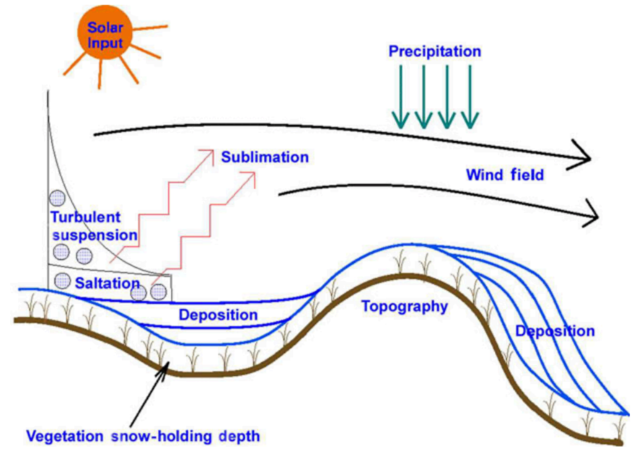




ESTO
Earth Science Technology Office

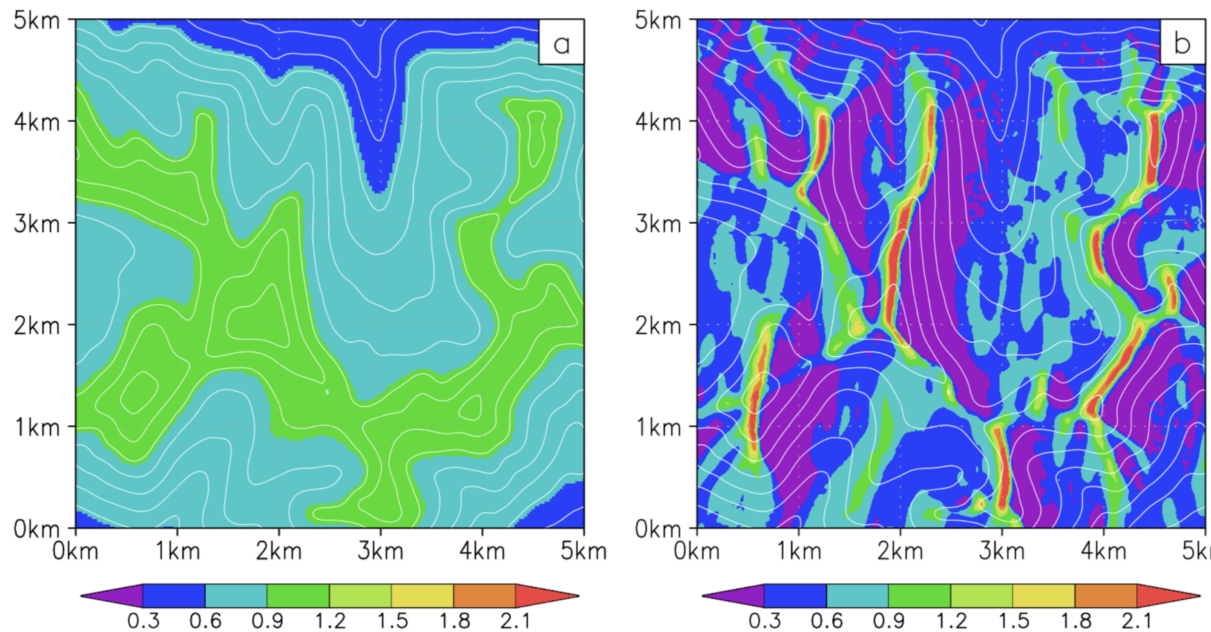
Objective: Improve LIS Snow modeling capabilities

- Couple SnowModel into LIS
  - Snow redistribution capabilities
  - MicroMet: terrain influenced wind, radiation, temperature,…
- Parallelize SnowModel in LIS
- Couple SnowModel to Noah-MP in LIS
- Run continental domain Snow OSSE with LIS-SnowModel



Modeled snow without redistribution

…with redistribution



Presentation Contents

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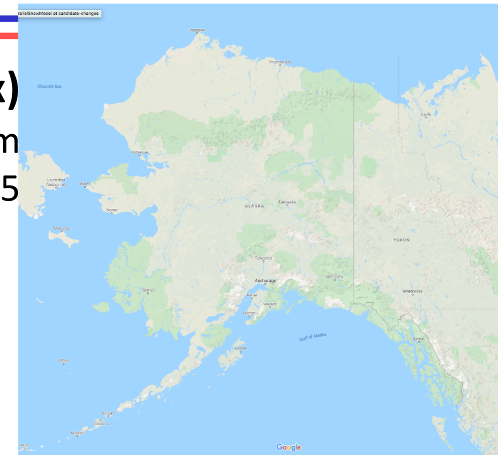
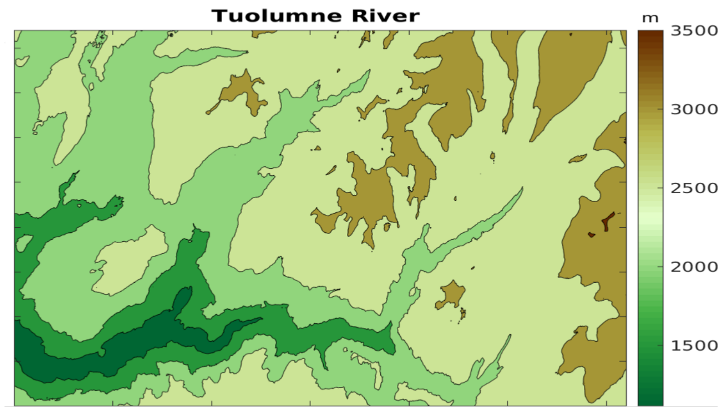
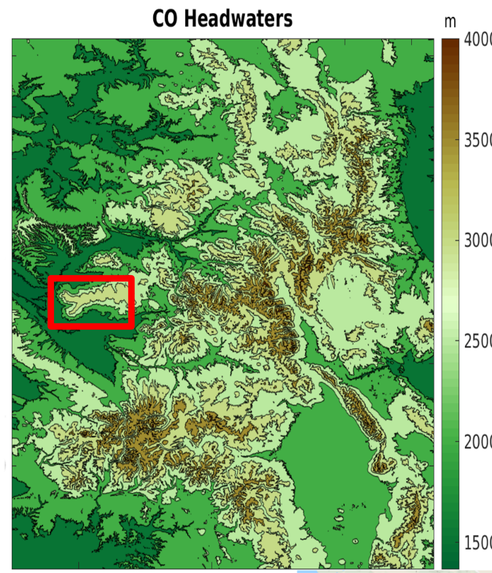
Test Cases

Alaska Domain **(SnowEx)**
250 m
9899x7205



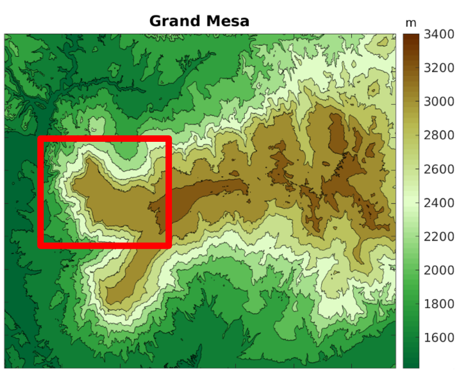
Tuolumne River, California **(SnowEx, ASO)**
100, 25, 10 m
310x168, 1240x672, 3100x1680

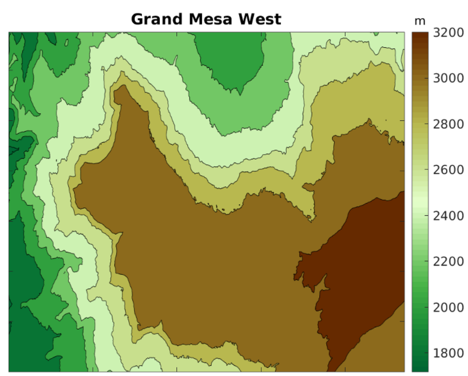




Colorado Headwaters
(Current SEUP OSSE)
100 m, 3166x5167

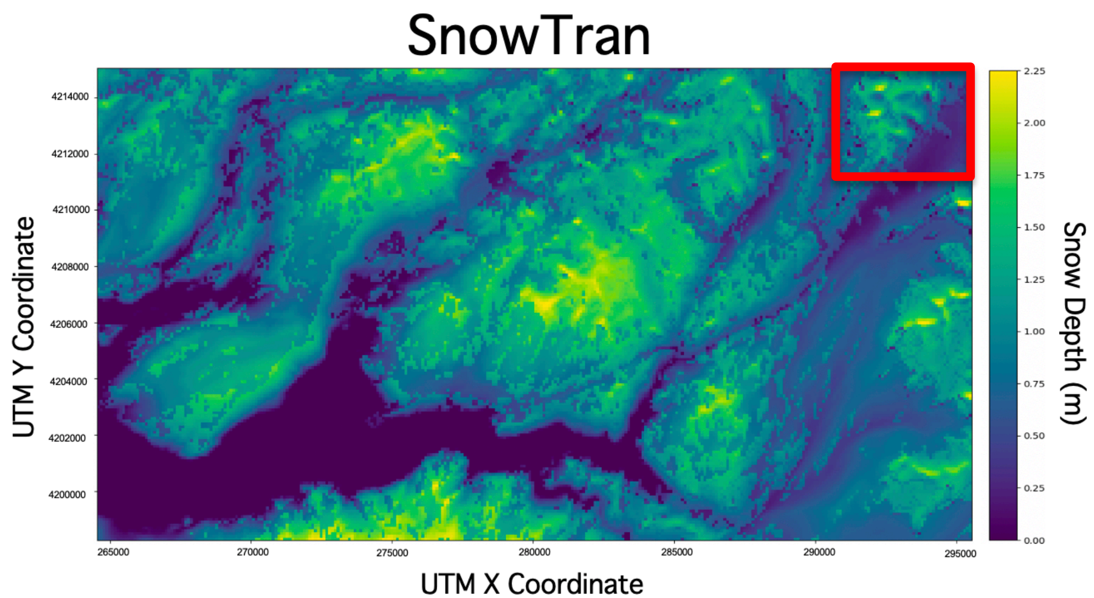
Grand Mesa, Colorado **(SnowEx domain)**
Full and western domains
10 m, 6760x5075, 2351x1351

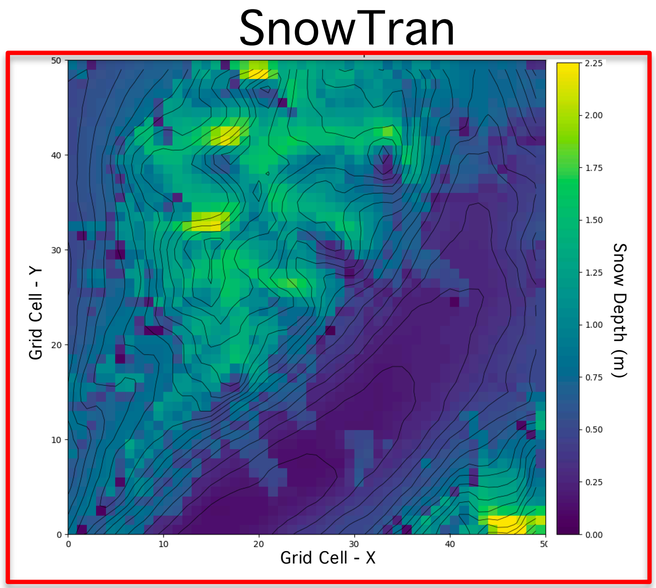


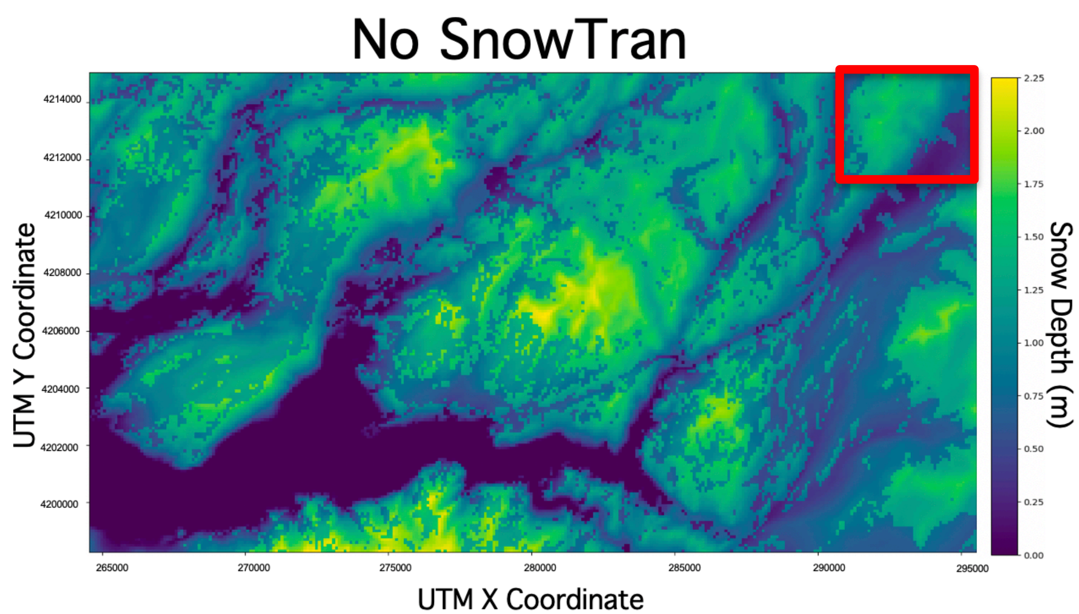


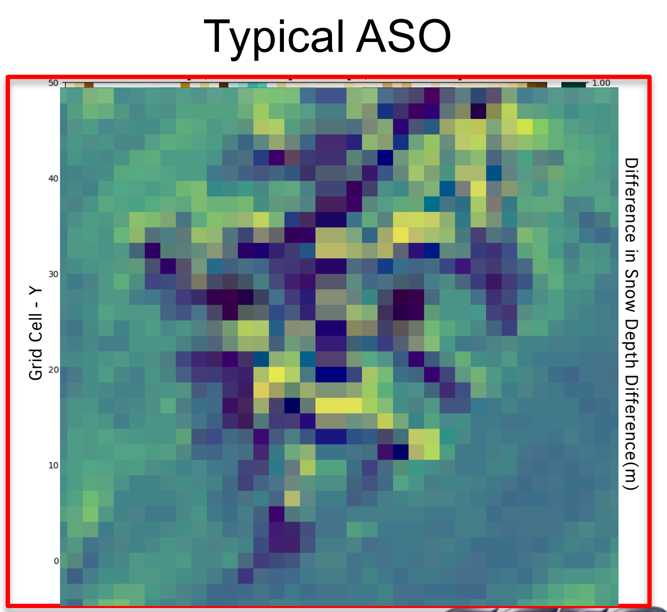
CONUS **End Goal**
100 m
58856 x 29348

SnowTran Snow Depth Subdomain Results

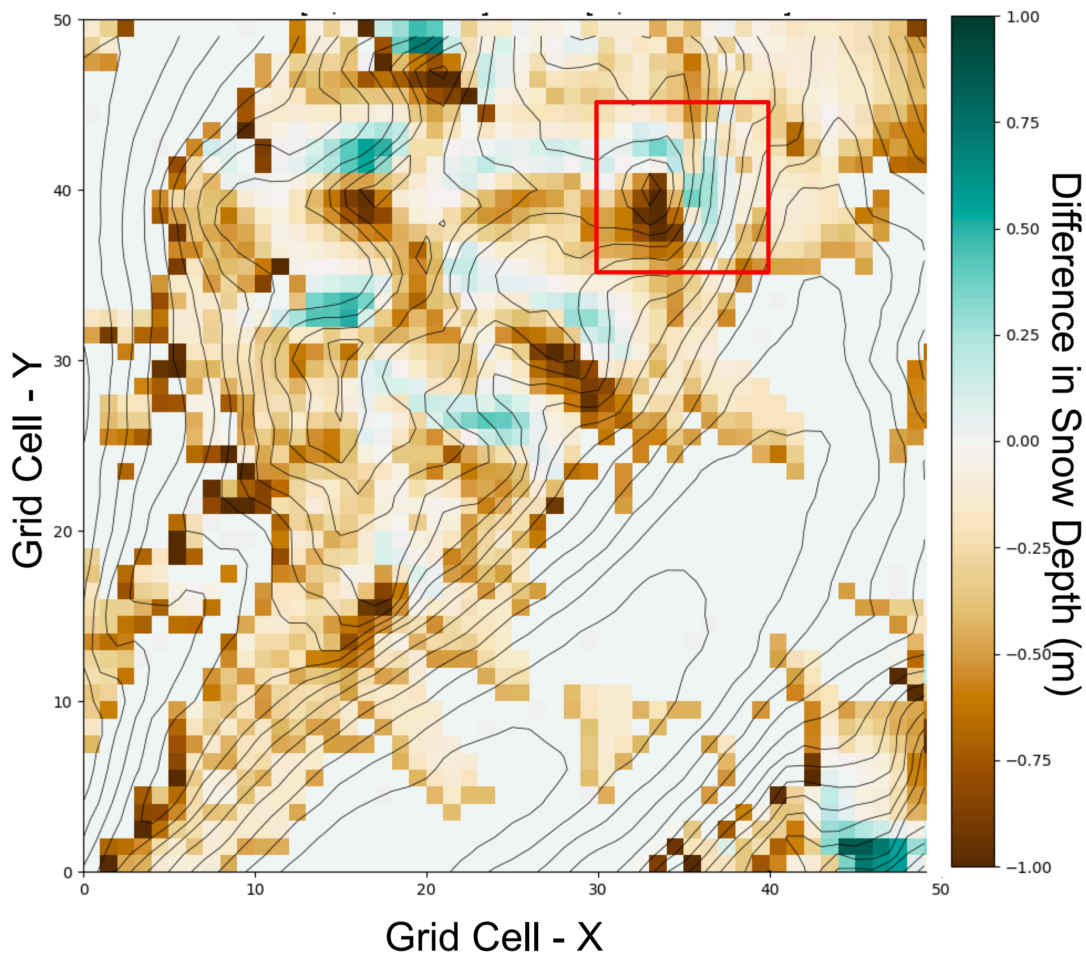


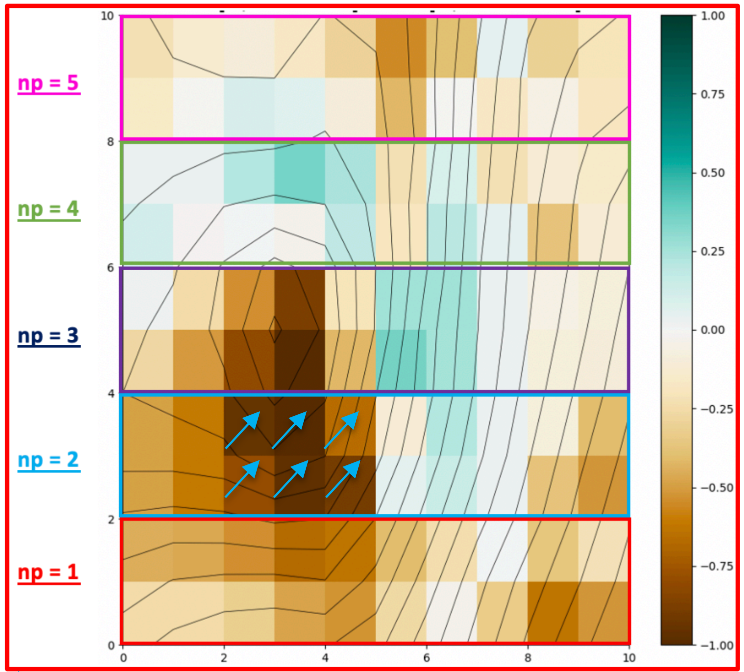






Parallelization Technique

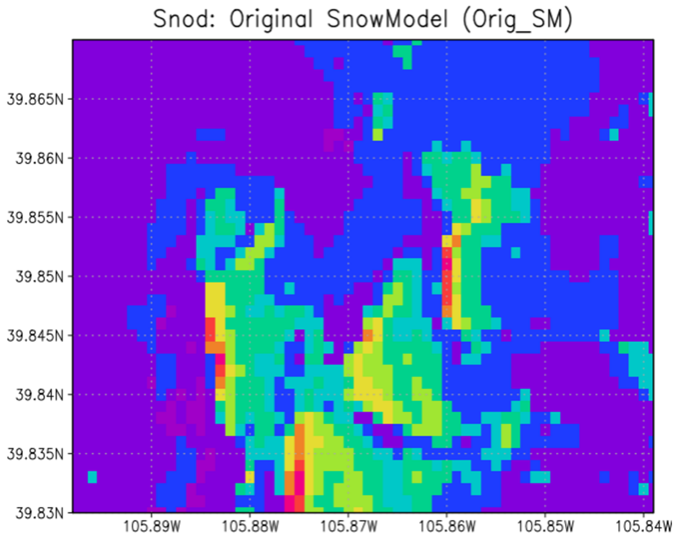


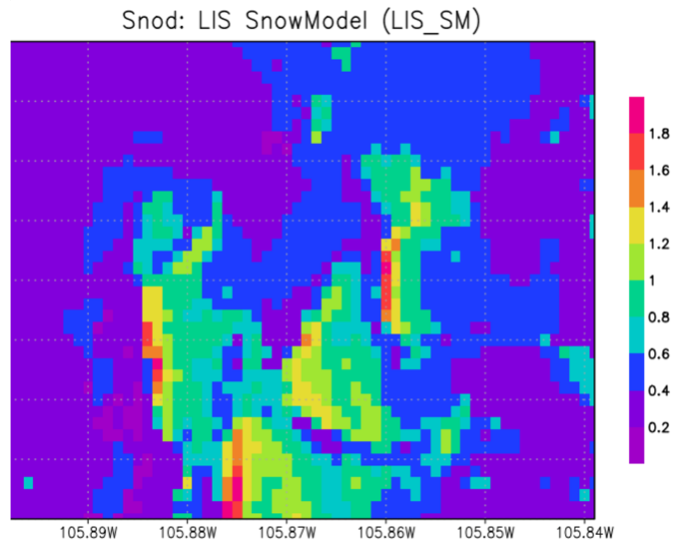


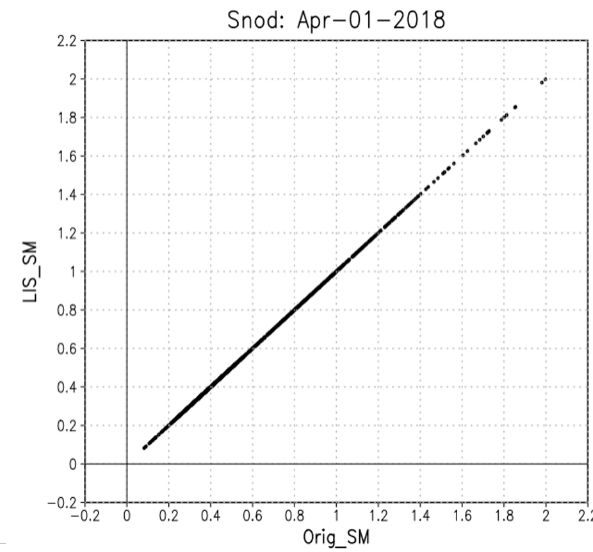
- Local wind direction variable for process #2

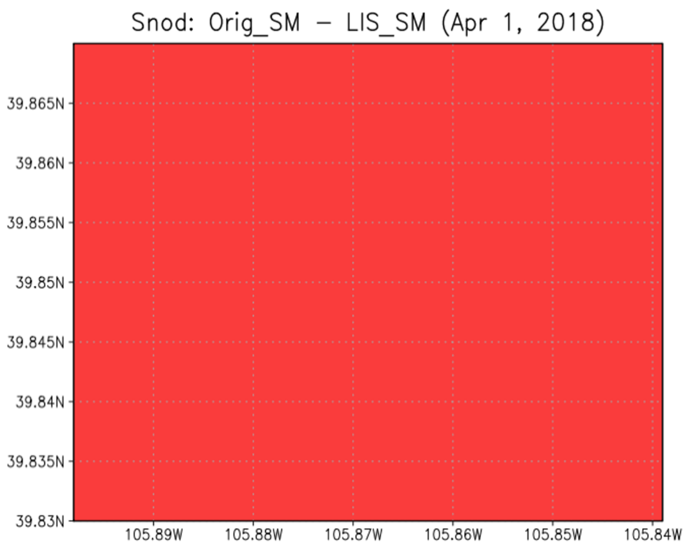
- **Parallelization Advantage**
  - Increase spatial / temporal scales
  - Decrease computational costs
- **Challenges**
  - Efficient communication amongst processes
  - Reduce distribute and gather calls
  - Individual process communication in SnowTran

SnowModel Runs in LIS









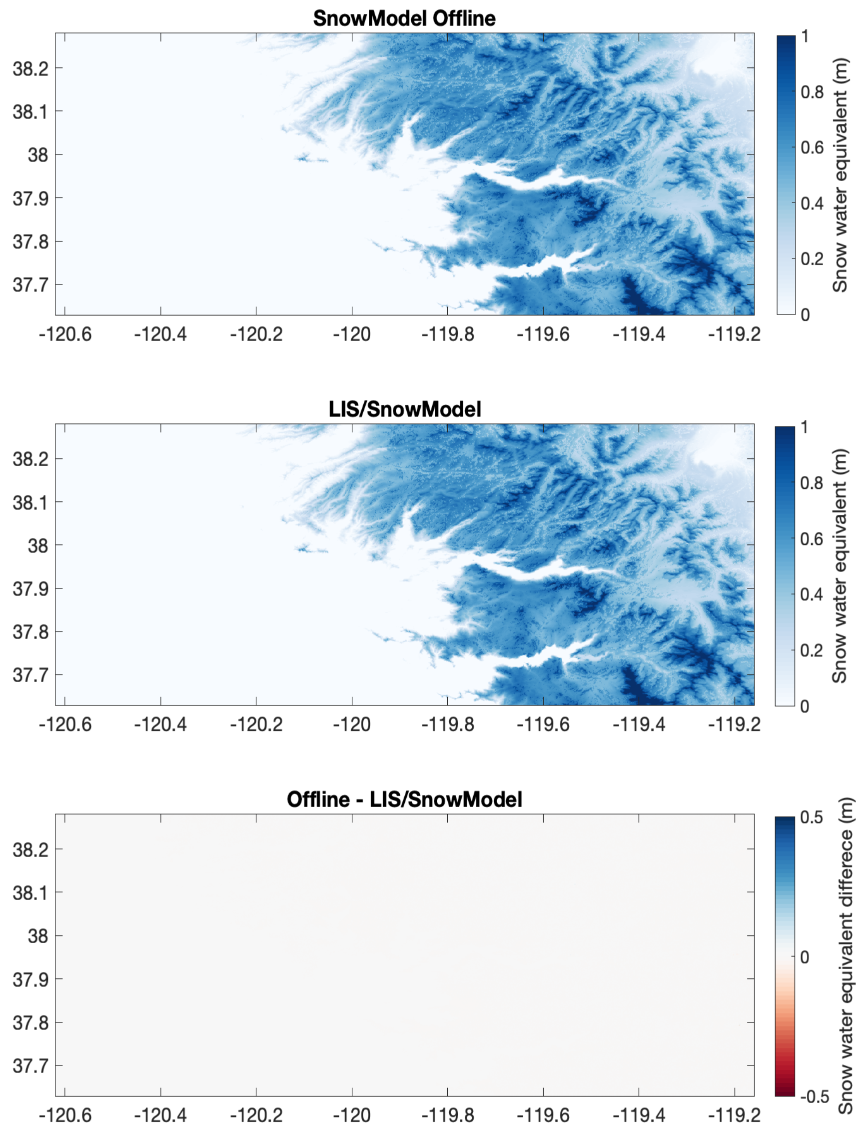
Red = zero difference

SnowModel in LIS matches original version on 1-processor

Snow depth comparison (Apr 1, 2018)

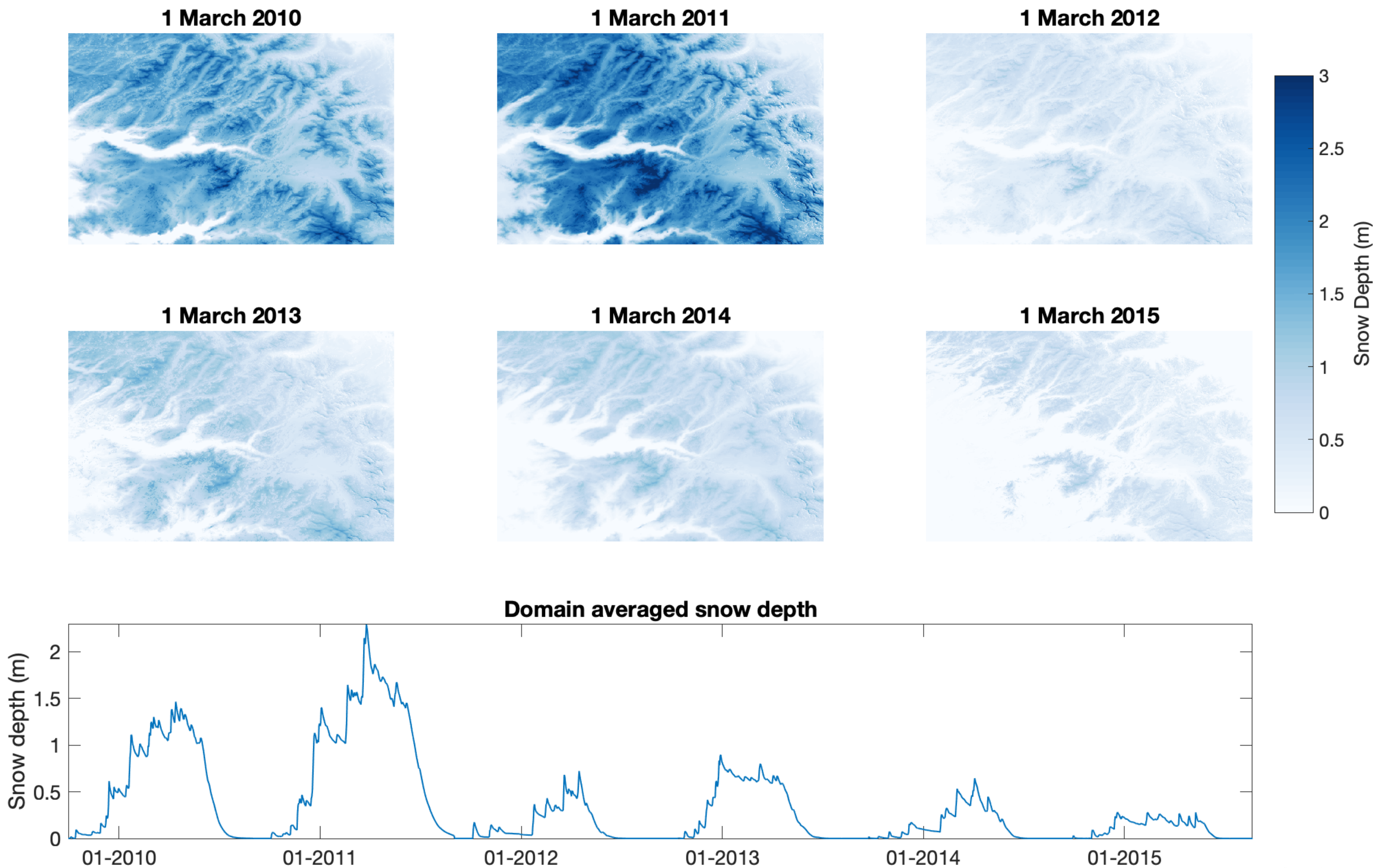
ESTO Earth Science Technology Office

Evaluate offline and coupled SnowModel



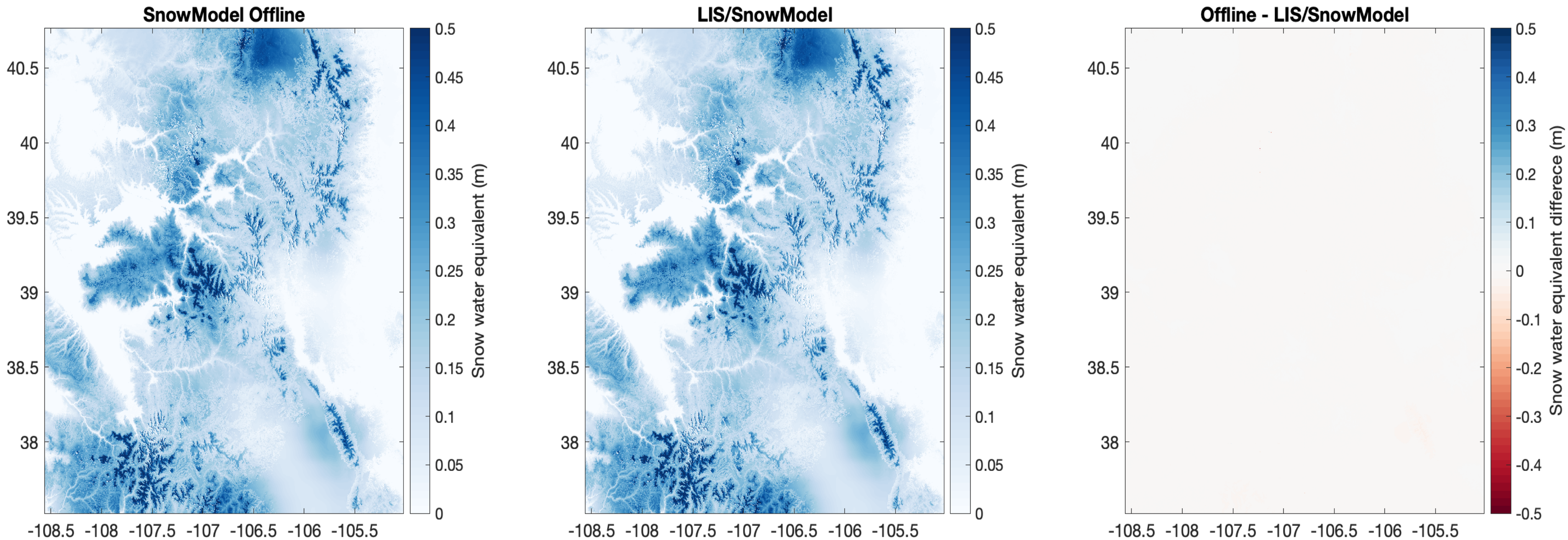
- 'Offline' SnowModel: Original code (or Orig-SM)
- 'Coupled' SnowModel: Added to LIS (or LIS-SM)
- Tuolumne watershed in California for March 1, 2010: SWE
- Domain setup:
  - 100 m spatial resolution
  - 1288 x 723 grid cells

Multi-year simulation of LIS-SnowModel over Upper Tuolumne domain

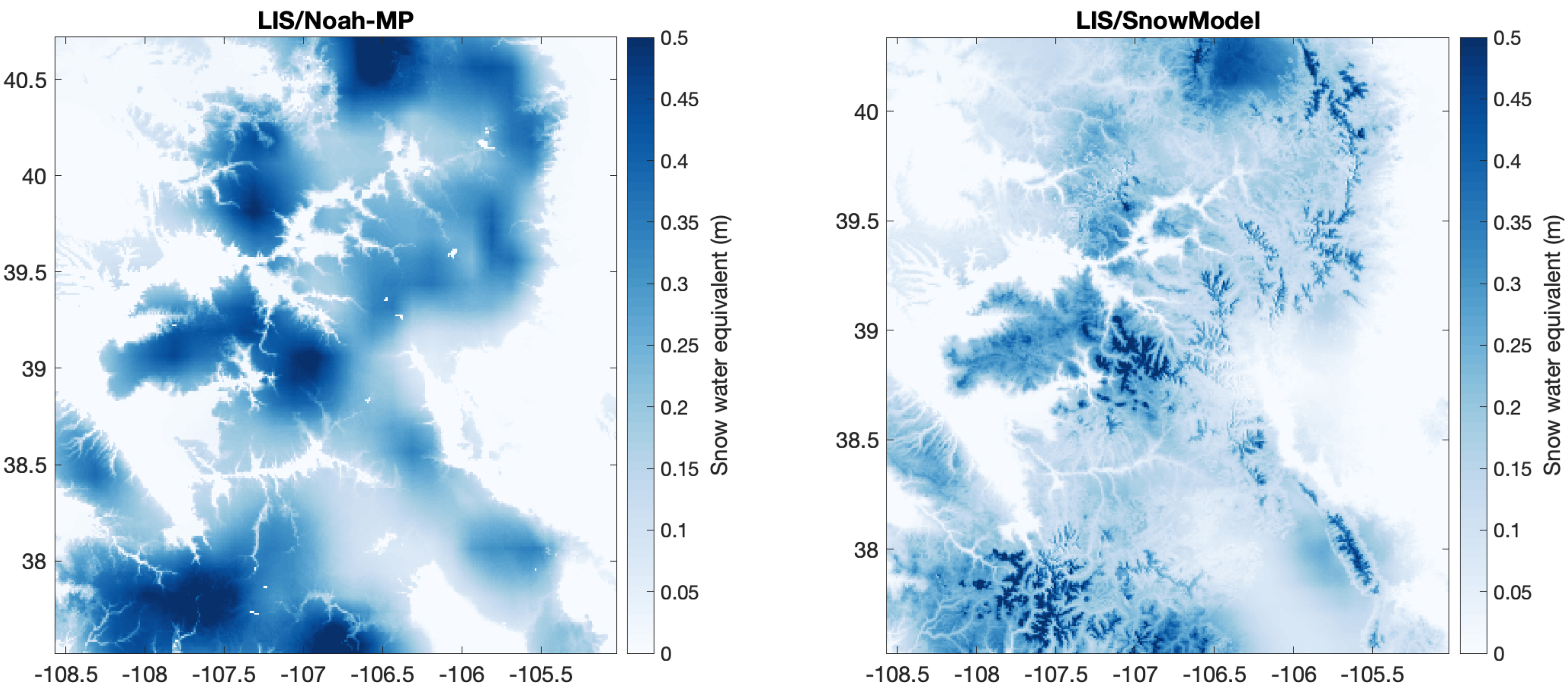


Evaluate offline and coupled SnowModel

- Western Colorado 'OSSE' Domain for March 1, 2017: SWE
- Domain setup: 100 m spatial resolution; **3130 x 3602** grid cells



Noah-MP vs SnowModel comparison



1 March 2017 SWE over western Colorado

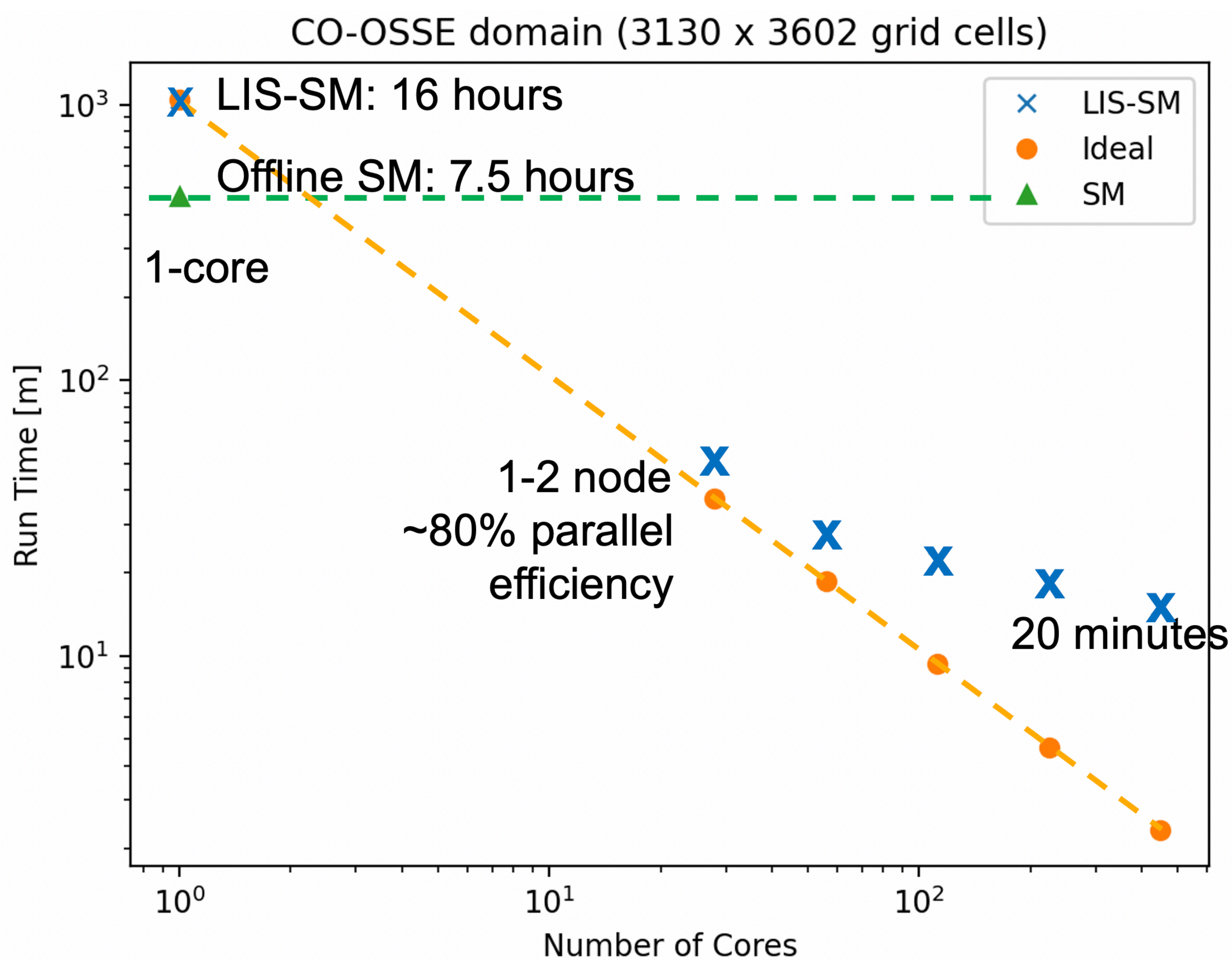
Both simulations approximately 1 km spatial resolution

SnowModel has been aggregated from 100 m to 1 km for this comparison

ESTO Earth Science Technology Office

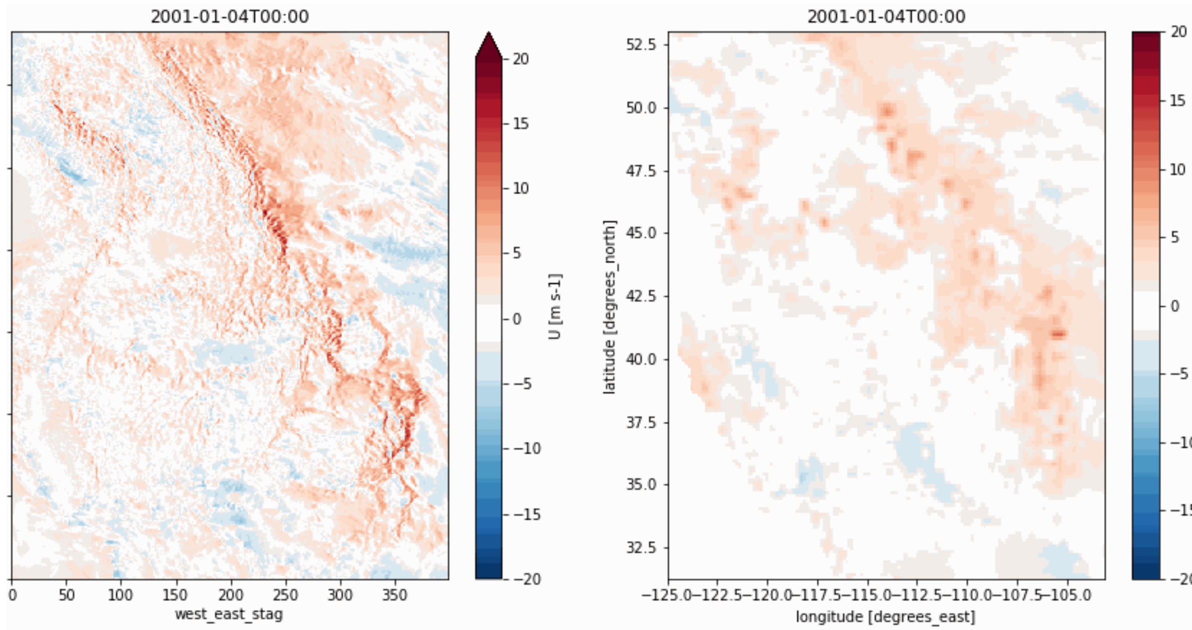
Parallel Runs – Western CO (OSSE) Domain

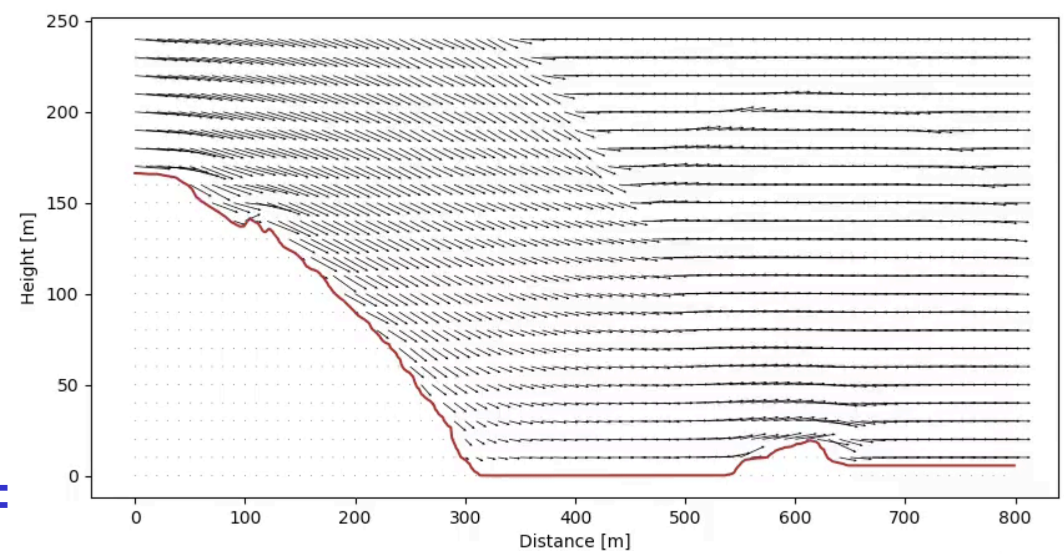
- Simulations conducted on NCCS Discover
- 1 to 16 nodes
  - (28-core Haswells)
- Daily output frequency 7 output fields for duration of ~6 months (Oct 1 to Apr 10)
- Strong scaling analysis
  - Good performance to 2-nodes



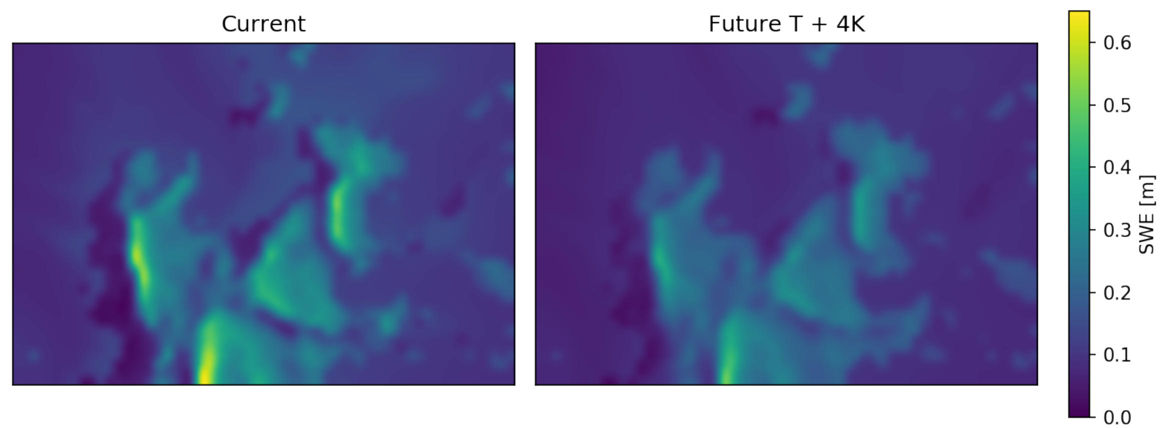
New WRF Forcing Reader and Forcing Dataset Support for SnowModel in LIS

- Insufficient redistribution with NLDAS winds
- WRF 4km forcing dataset
- New reader in LIS to support finer-scale WRF wind data
  - NLDAS2 (12-32km)
- Tested with LIS-NoahMP
- Higher Resolution…?



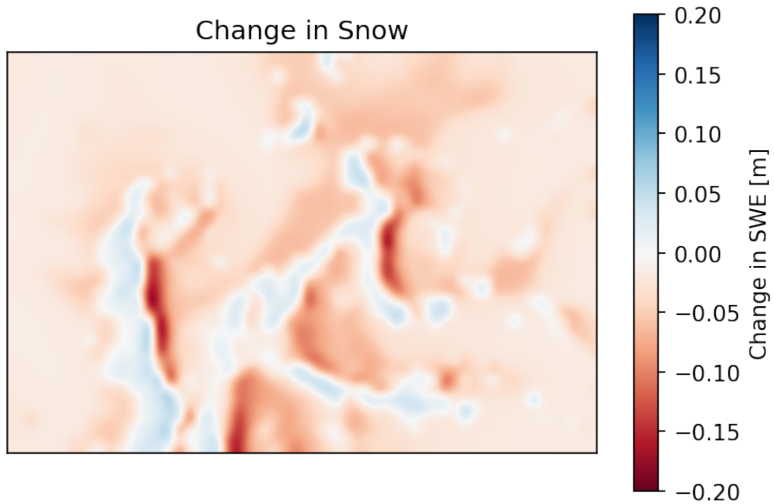


Other Capabilities : Investigating Climate Impacts



With a 4°C increase in air temperature

- Domain wide decrease in snowpack
- Local increases in March SWE in upwind scour zones, but large decreases in drift zones
- In warmer climate snow melts earlier and slower (no surprise)



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- Background and Objectives
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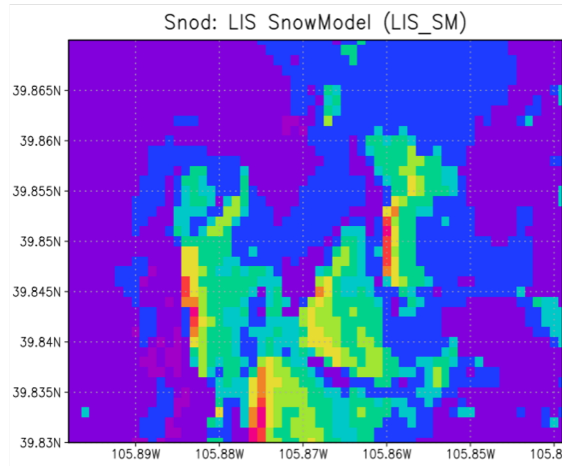
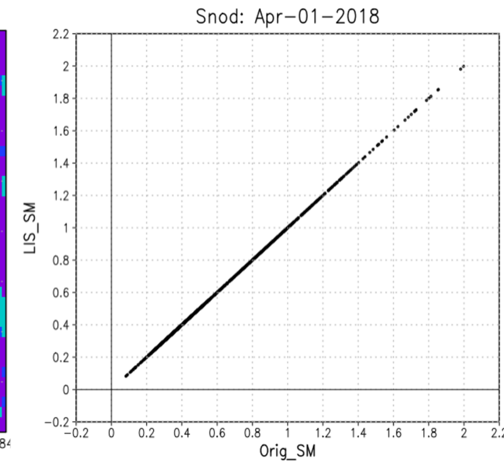
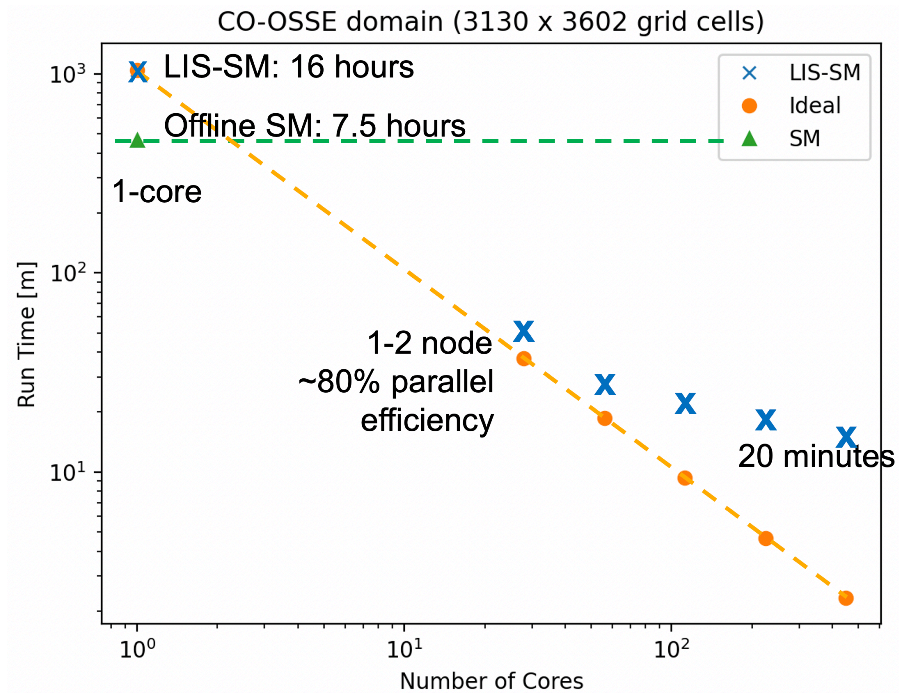
Summary of Accomplishments

- Implementation of SnowModel in LIS reproduces test cases within numerical precision
- Parallelization of offline SnowTran-3D in offline simulations
- Current parallel LIS-SM simulation is >20x faster than original (serial) SnowModel
- Initial simulations suggest importance of improving wind field for CONUS simulations
- Performance of multi-year LIS-SM test cases moving from TRL-2 to TRL-3, and TRL-4 after additional verification of simulations.

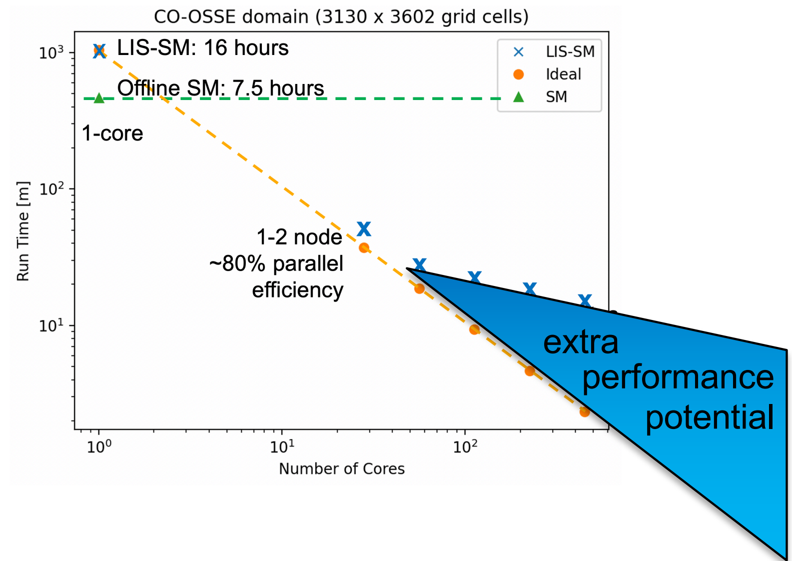




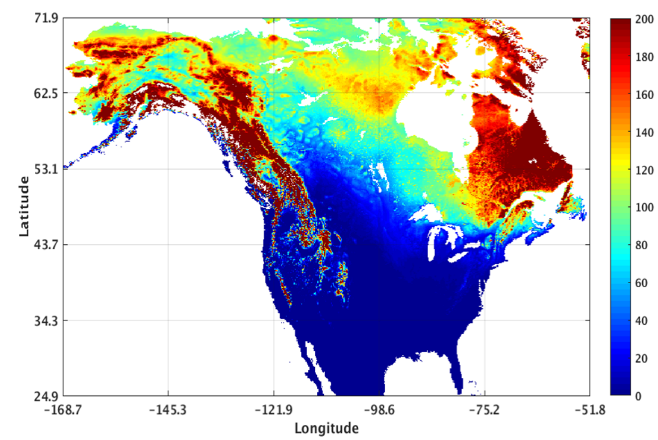


Summary of Future Plans

- Improve parallel efficiency
  - Transport needs parallelization integrated in LIS (currently using a large buffer)
- Test larger domains
  - Does weak scaling permit efficient CONUS domain simulations on 16 nodes
  - Optimizing memory usage
  - Profiling bottlenecks
- Integrate improvements to IO parallelization
- Perform CONUS scale Nature Run
- Perform OSSE to evaluate mission design tradeoffs
- Coordinate with Snow Community on potential for an NOS style mission

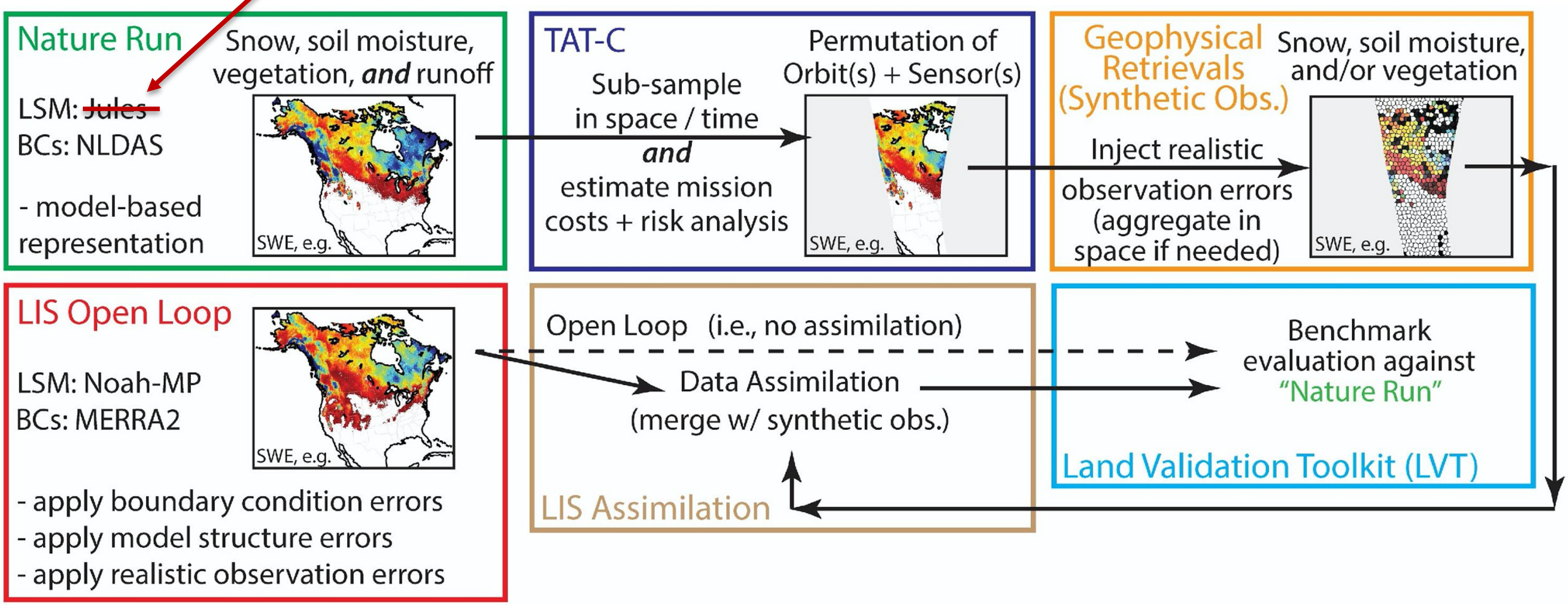


Continental Domain



Technical Development Overview -- OSSE

Bringing SnowModel into a continental scale OSSE



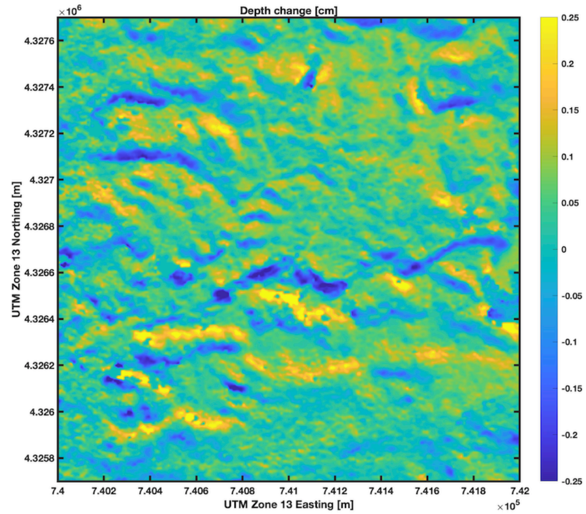
Innovation: **``fraternal twin" experiment rather than "identical twin"** (AIST-16-0024)
Building on OSSE development with AIST-18-0041

Potential for Snow NOS mission

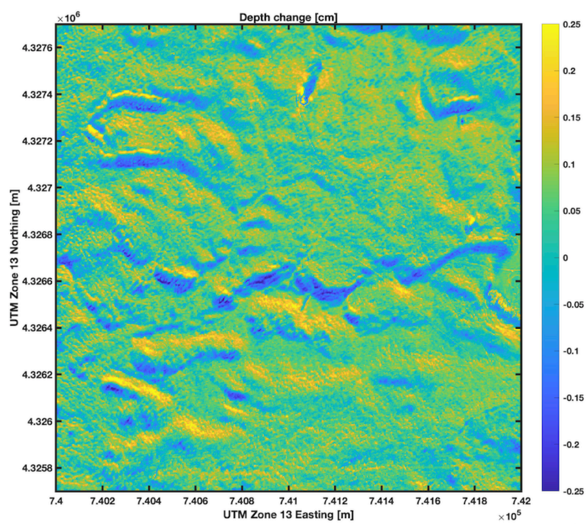
- No single sensor is expected to provide necessary information
- Repeatability of snow patterns + modeling + monitoring sensors can define **where** / when to measure (if point-able sensor)
- Likely proposed pure snow missions will have limitations, e.g.
  - stereo optical with small view area
  - nadir pointing lidar line transect
  - Ku band SAR internal scattering
- Existing and near future satellites can be leveraged
  - NISAR L-band
    - Only measures change in SWE
    - Signal loss with large changes
  - MODIS: Snow Cover
  - GOES: Cloud Cover
- Measure where : no clouds, snow presence, InSAR L-band decorrelation, known precipitation/wind

Grand Mesa SnowEx 2020

L-Band InSAR



Airborne Lidar



Figures from HP Marshall

ESTO Earth Science Technology Office

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Publications / Presentations

Reynolds, D. and J. D. Lundquist, 2020: Evaluating Wind Fields for Use in Basin-Scale Distributed Snow Models, Water Resources Research (accepted) doi:10.1029/2020WR028536.

Kim, R. S., et al. 2020: Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling, The Cryosphere Discuss., doi:10.5194/tc-2020-248, in review.

Presentations

Gutmann et al 2020: Heterogeneity of Mountain Snow: Measurement, Modeling, and Implications. 19th annual AMS Mountain Meteorology Conference Thursday, July 16, 2020.

Wrzesien et al, 2020: Development of a “nature run” for observation system simulation experiments (OSSE) for snow mission development. AGU Fall meeting December, 2020

Gutmann et al 2020: Multi-scale Snow-Atmosphere Interactions Over Mountain Snowpack for Climate Applications (Invited) AGU Fall meeting. December, 2020

Wrzesien et al, 2021: Evaluation of a Calibrated “Nature Run” for Observation System Simulation Experiments (OSSE) against Snow Depth Observations. AMS Annual meeting January, 2021

Kim et al, 2021: Impact evaluation of snow water equivalent uncertainty on streamflow estimation across North America using ensemble land surface modeling. AMS Annual meeting January, 2021

Gutmann et al, 2021: Explicitly Simulating Snow Spatial Variability at Scale to Improve Predictions. AMS Annual meeting January, 2021

List of Acronyms

- ASO Airborne Snow Observatory
- HRRR High Resolution Rapid Refresh model
- CDEC California Data Exchange Center (in situ sites)
- MM MicroMet
- WN Wind Ninja
- DEM Digital Elevation Model
- DS Decadal Survey
- km Kilometer
- SEUP Snow Ensemble Uncertainty Project
- LIS Land Information System
- LDT Land Data Toolkit
- LVT Land Verification Toolkit
- LISF LIS Framework (LIS+LDT+LVT)
- SWE Snow Water Equivalent
- SWS Snow Water Storage
- SCF Snow Cover Fraction
- GDAS Global Data Assimilation System
- NLDAS National Land Data Assimilation System
- MERRA Modern-Era Retrospective Analysis for Research and Applications
- ECMWF European Center for Medium Range Weather Forecasting
- CV Coefficient of Variation
- OSSE Observing System Simulation Experiment
- DA Data Assimilation
- EnKF Ensemble Kalman Filter
- OI Optimal Interpolation
- LSM Land Surface Model
- NCAR National Center for Atmospheric Research
- GSFC Goddard Space Flight Center
- UW University of Washington
- CSU Colorado State University
- UMD University of Maryland

Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals

Prof. Bart Forman (PI, UMD)
Dr. Sujay Kumar (Co-I, GSFC)
Dr. Paul Grogan (Co-I, Stevens Institute)
Dr. Rhae Sung Kim (Co-I, GSFC)
Dr. Yeosang Yoon (Co-I, GSFC)
Dr. Yonghwan Kwon (Co-I, GSFC)
Dr. Melissa Wrezsien (GSFC)
Dr. Jongmin Park (UMD)
Lizhao Wang (UMD)
Jongmin Park (UMD)
Colin McLaughlin (UMD)
Alireza Moghaddasi (UMD)

AIST-18-0041 Annual Review
January 4, 2021

Earth Science Technology Office

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- Quad Chart
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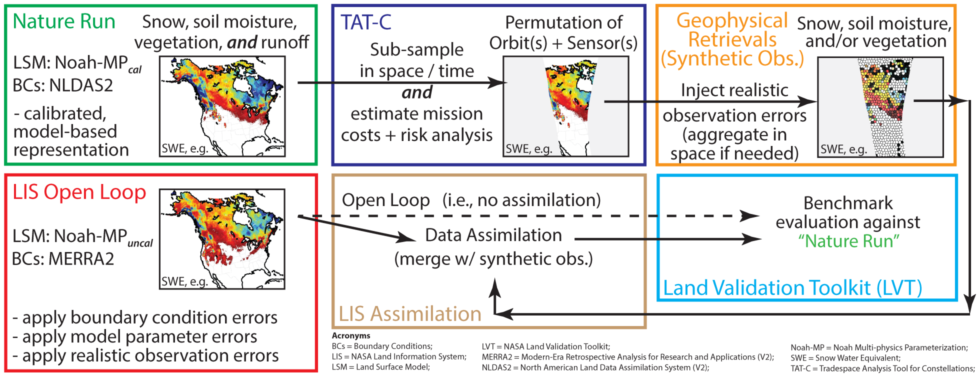
Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals

PI: Barton A. Forman, University of Maryland

Objective

- Create a mission planning tool to help inform experimental design with relevance to global snow, soil moisture, and vegetation in the terrestrial environment
- Use the extensive sensor simulation, orbital configuration, data assimilation, optimization, uncertainty estimation, cost estimation, and risk assessment tools in LIS and TAT-C to harness the information content of Earth science mission data
- Technologies include passive and active microwave remote sensing, optical remote sensing, LiDAR, hydrologic modeling, orbital emulators, adaptive sensor viewing, and data assimilation



Approach:

- Develop a **coupled snow-soil moisture-vegetation observing system simulation experiment (OSSE)** extending the capabilities of LIS and TAT-C
- Conduct end-to-end OSSEs to investigate the impact of **new and future mission concepts** on LIS model efficacy, including the impact of adaptive versus fixed viewing of space-borne sensors
- Conduct end-to-end OSSEs to **characterize tradeoffs in spatiotemporal resolutions and orbital configurations (constellations)**, including mission cost estimates and risk assessments

CoIs: Sujay Kumar, GSFC; Paul Grogan, Stevens Inst.; Rhae Sung Kim, GSFC; Yonghwan Kwon, GSFC; Yeosang Yoon, GSFC;

Key Milestones (start date 01 Jan 2020)

• Data collection and preprocessing	03/20
• Develop Nature Run	06/20
• Develop Geophysical Observation Operators	09/20
• Fixed, Single-sensor DA Experiments	01/21
• Develop Adaptive Sensor Viewing Operator	01/21
• Adaptive, Single-sensor DA Experiments	06/21
• Fixed, Multi-sensor DA Experiments	09/21
• Adaptive, Multi-sensor DA Experiments	12/21
• Project Reporting	Quarterly

$TRL_{in} = 3$ $TRL_{out} = 6$

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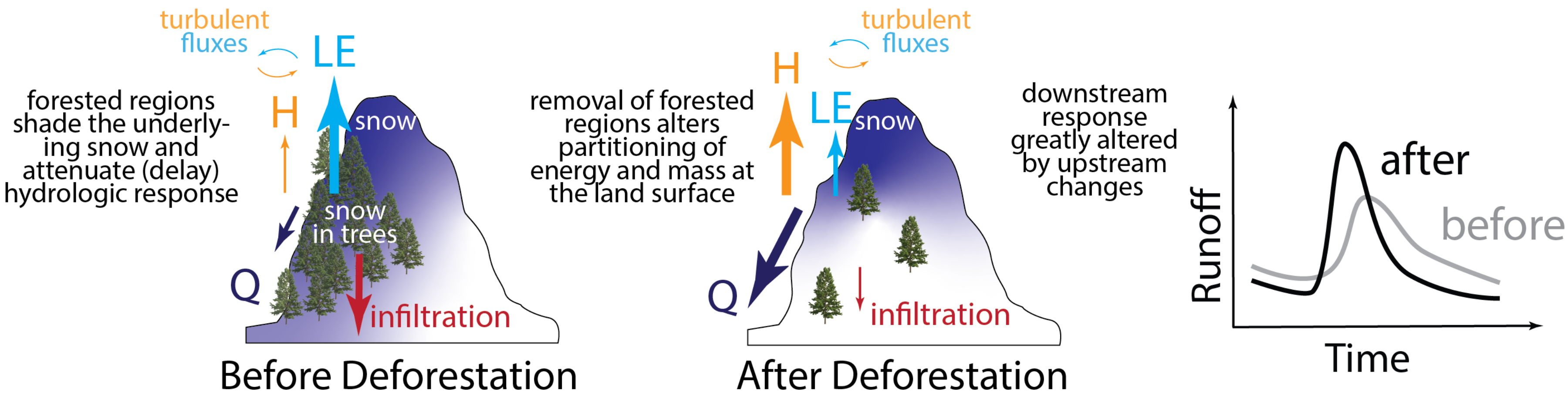
Coupled Snow-Soil Moisture-Vegetation Processes

Coupled Snow-Soil Moisture-Vegetation System

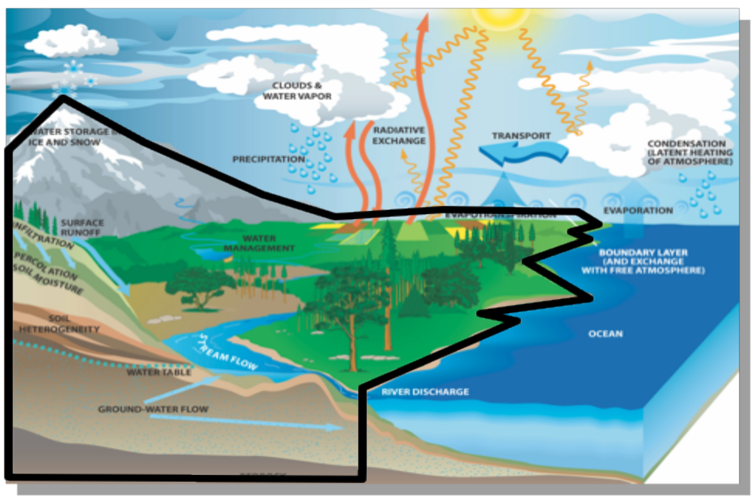


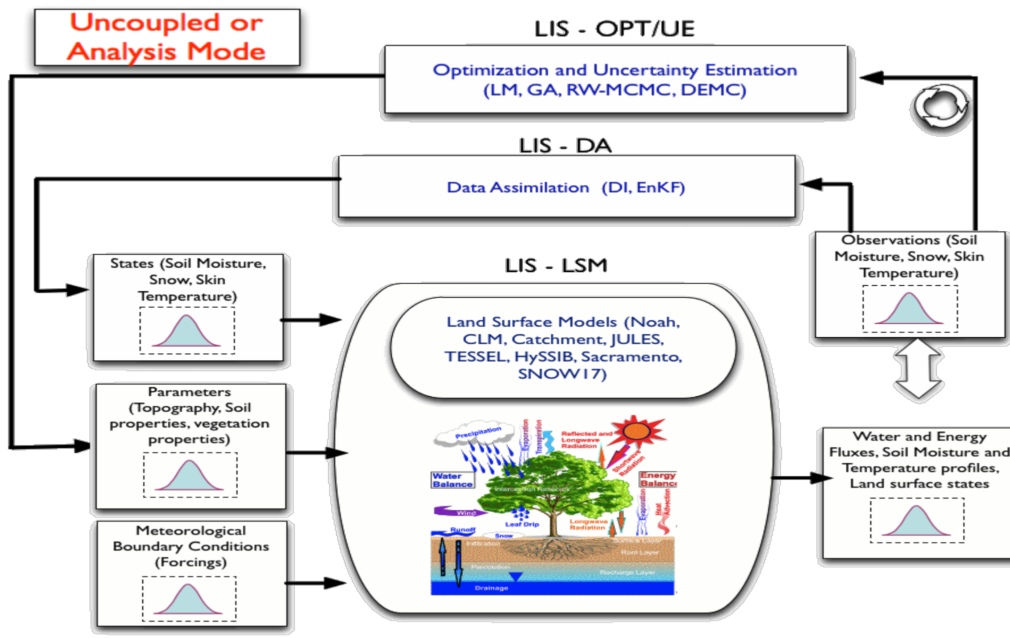
Background and Motivation

- Terrestrial freshwater is a **highly dynamic, coupled** system
  - Requires a **cohesive, physically-consistent** framework
- Leverage suite of remotely-sensed observations
  - **LIDAR** → snow and vegetation information
  - **Passive MW** → snow and soil moisture information
  - **Active MW** → snow, soil moisture, and vegetation information
- Need for observing system simulation experiment (OSSE) to study complex interplay of synergistic effects
  - Use in **data assimilation** framework
- Goal is to **improve coupled snow-soil moisture-vegetation** response across **regional and continental scales** based on **conditional probability, *p(y|z)***

Land Information System (LIS)

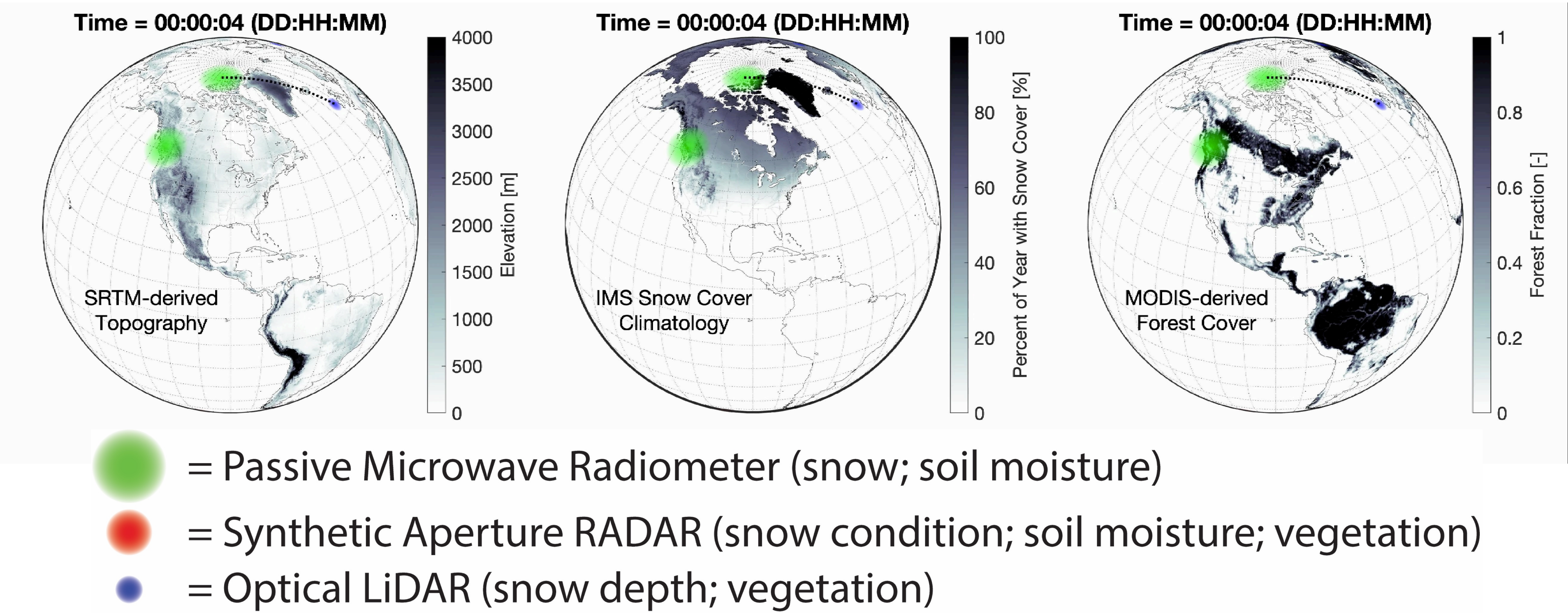
- Study **land surface processes** and land-atmosphere interactions
- Integrates satellite- and ground-based **observational data** products with land surface **modeling techniques**





Kumar et al. (2006), Land Information System: An interoperable framework for high resolution land surface modeling, Environmental Modeling and Software

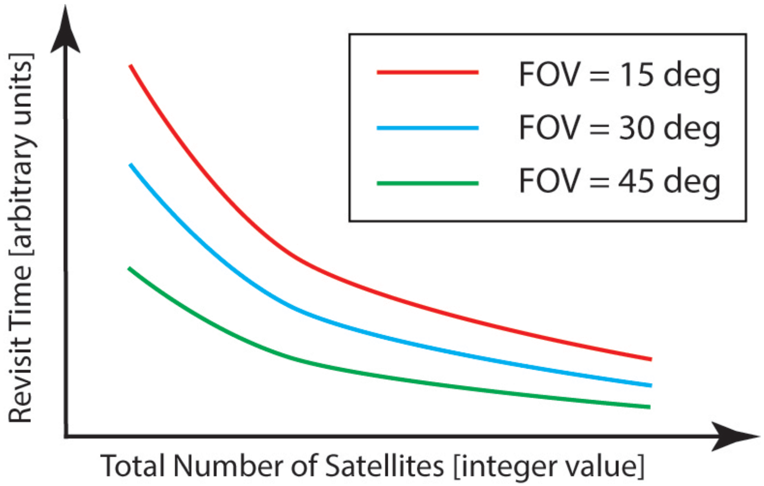
Tradespace Analysis Tool – Constellation (TAT-C)

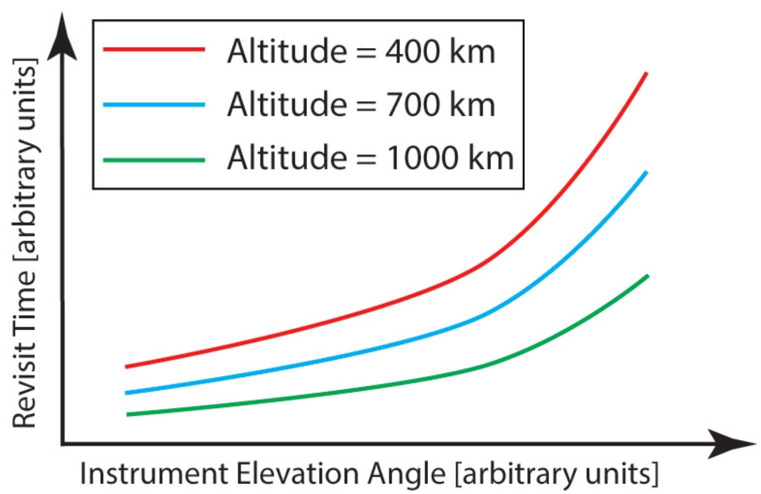


Not Shown:

- irrigable lands directive
- agricultural productivity directive
- Low Earth Orbit (LEO) VIS+NIR sensors

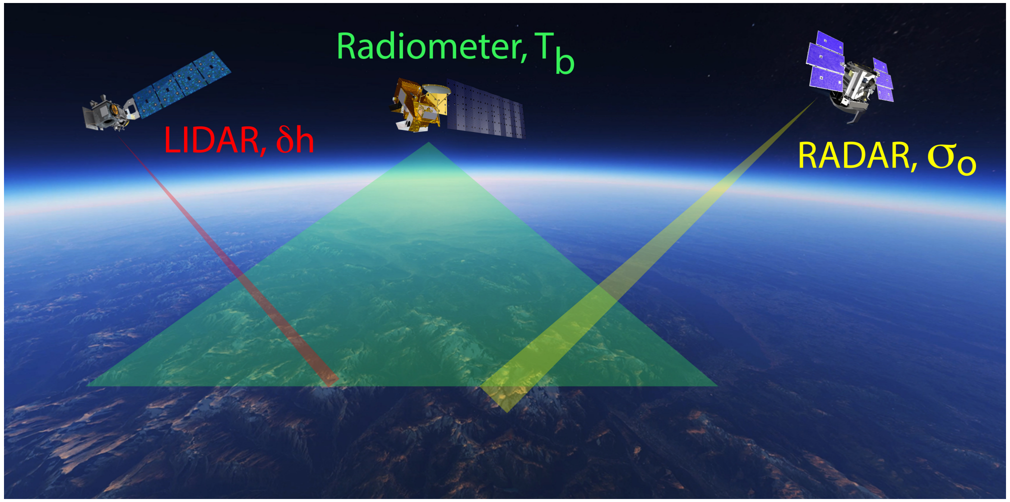
Trade-off Space: Coverage vs. Resolution





- Explore **trade-off** between engineering and science
  - Field-of-View (FOV)?
  - Platform altitude?
  - Repeat cycle?
  - Single platform vs. constellation?
  - Orbital configuration(s)?
- How do we get the most **scientific bang** for our buck?

Data Assimilation via Ensemble Kalman Filter (EnKF)



$$\underbrace{\mathbf{y}_i^+}_{\substack{\text{posterior}\\ \text{SWE}}} = \underbrace{\mathbf{y}_i^-}_{\substack{\text{prior}\\ \text{SWE}}} + \underbrace{\mathbf{K}}_{\substack{\text{Kalman}\\ \text{gain}}} \Big[\underbrace{Z}_{\substack{\text{synthetic}\\ \text{measurements}\\ \text{LIDAR snow depth}\\ \text{and/or}\\ \text{LIDAR vegetation}\\ \text{and/or}\\ \text{C-band SAR snow condition}\\ \text{and/or}\\ \text{C-band SAR soil moisture}\\ \text{and/or}\\ \text{C-band SAR vegetation}\\ \text{and/or}\\ \text{PMW soil moisture}\\ \text{and/or}\\ \text{PMW snow}}} - \underbrace{\mathbf{H}\mathbf{y}_i^-}_{\substack{\text{observation}\\ \text{operator}\\ \text{spatiotemporal } \mathbf{H}}} \Big]$$

Not Shown: Low Earth Orbit (LEO) visible and near-infrared sensors

Geophysical Retrievals

Sensor Type	Spectral Band(s)	Geophysical Retrievals	Satellite Proxy
Passive Optical	VIS / NIR	Snow-covered extent; surface albedo; skin temperature;	MODIS / VIIRS
Passive MW	Ka-, Ku-, and X-	SWE; soil moisture (~1 cm)	AMSR-E / AMSR2
	L-band	Soil moisture (~5 cm); vegetation optical depth;	SMAP / SMOS
Active MW	C-band	SWE; leaf area index; vegetation density;	Sentinel 1A/1B
	Ku- and Ka-	Snow depth; SWE; near-surface soil moisture (~1 cm)	CoReH20
	L-band	Soil moisture (~5 cm); vegetation optical depth;	SMAP
	S- and P-	Soil moisture (~1 m); freeze-thaw state;	SMAP (or upscaled AirMOSS)
LiDAR	Thermal IR Optical (green)	Snow depth; forest height; leaf area density; biomass;	GEDI (or upscaled ASO)

MW=Microwave; SWE=Snow Water Equivalent; SAR=Synthetic Aperture RADAR;

Satellite **proxy used for volume, weight, and power requirements** to install sensor into orbit

Earth Science Technology Office

Research Objectives

Science and mission planning questions

1) What observational records are needed (in space and time) to maximize coupled snow-soil moisture-vegetation utility?
2) How might observations be coordinated (in space and time) to maximize this utility?
3) What is the additional utility associated with an additional observation?
4) How can future mission costs be minimized while ensuring Science requirements are fulfilled?

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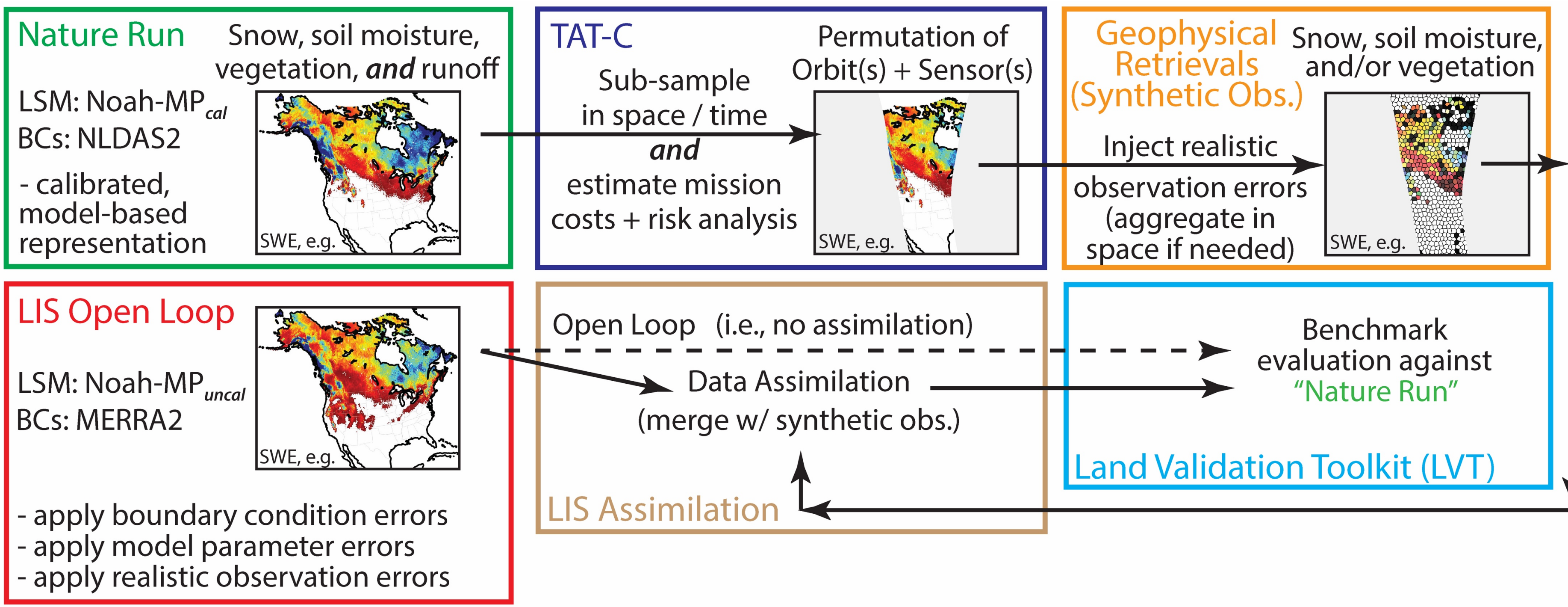
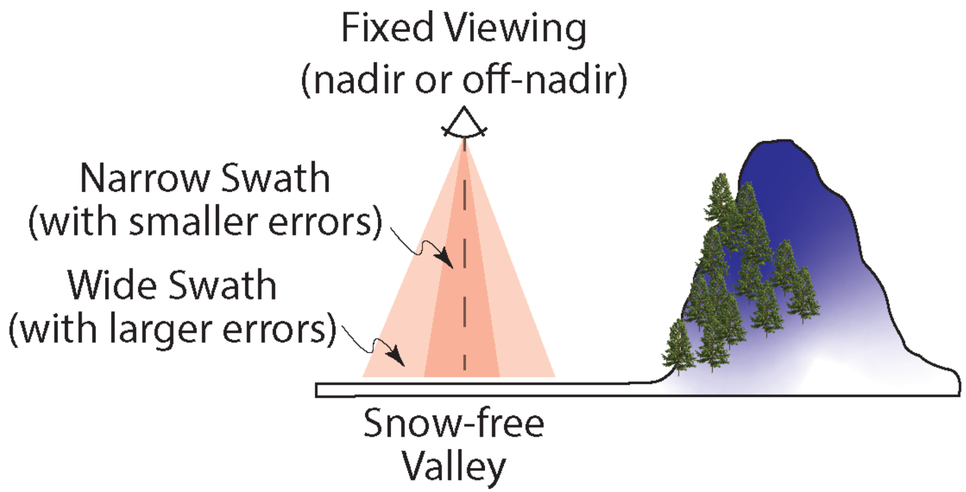
Technical Development Overview – OSSE



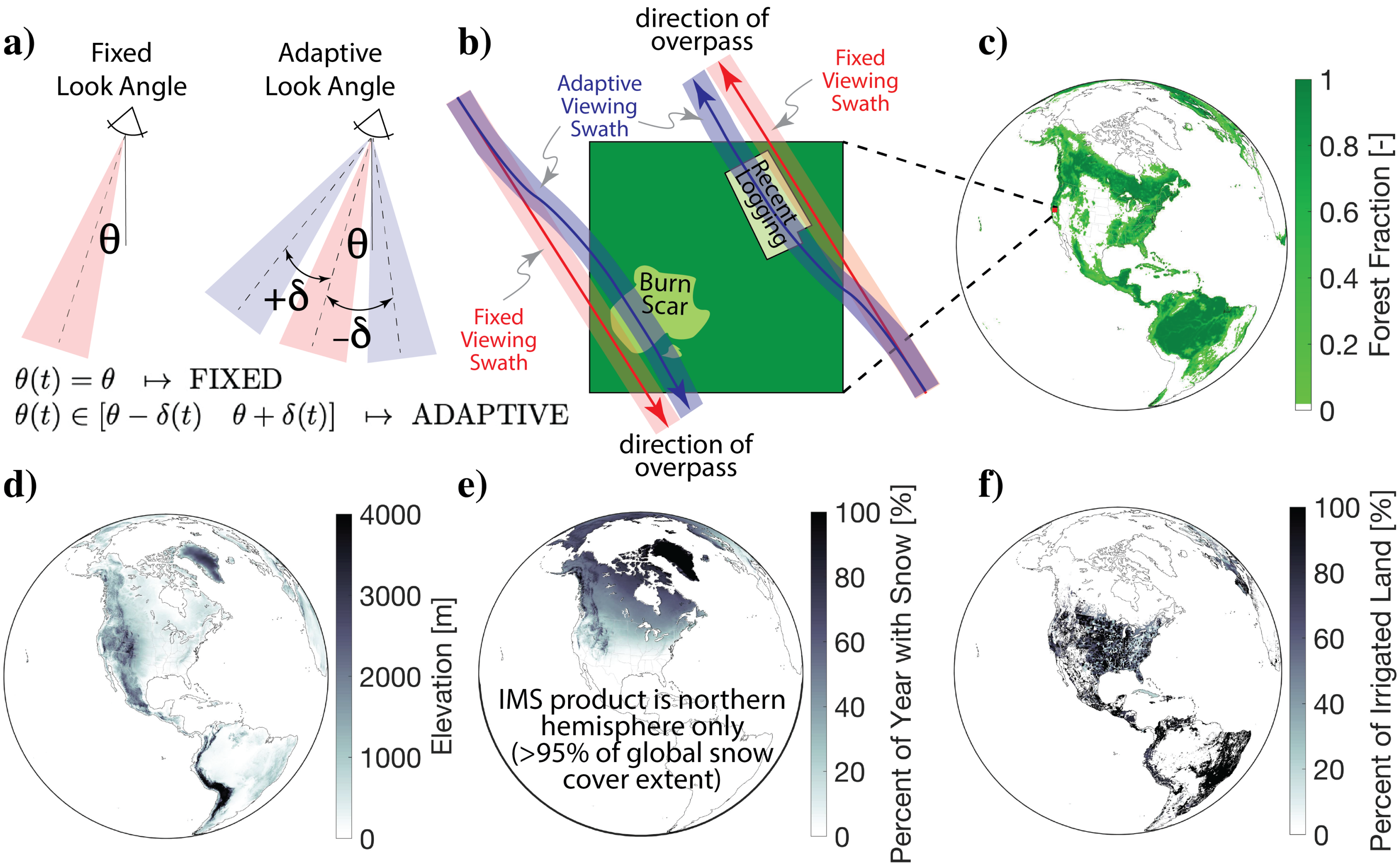
<u>Innovations from AIST-16-0024:</u>

1. **``fraternal twin" experiment** rather than "identical twin"
2. **snow-soil moisture-vegetation focus** rather than snow only focus

Technical Development – Adaptive Viewing (1 of 2)



Technical Development – Adaptive Viewing (2 of 2)



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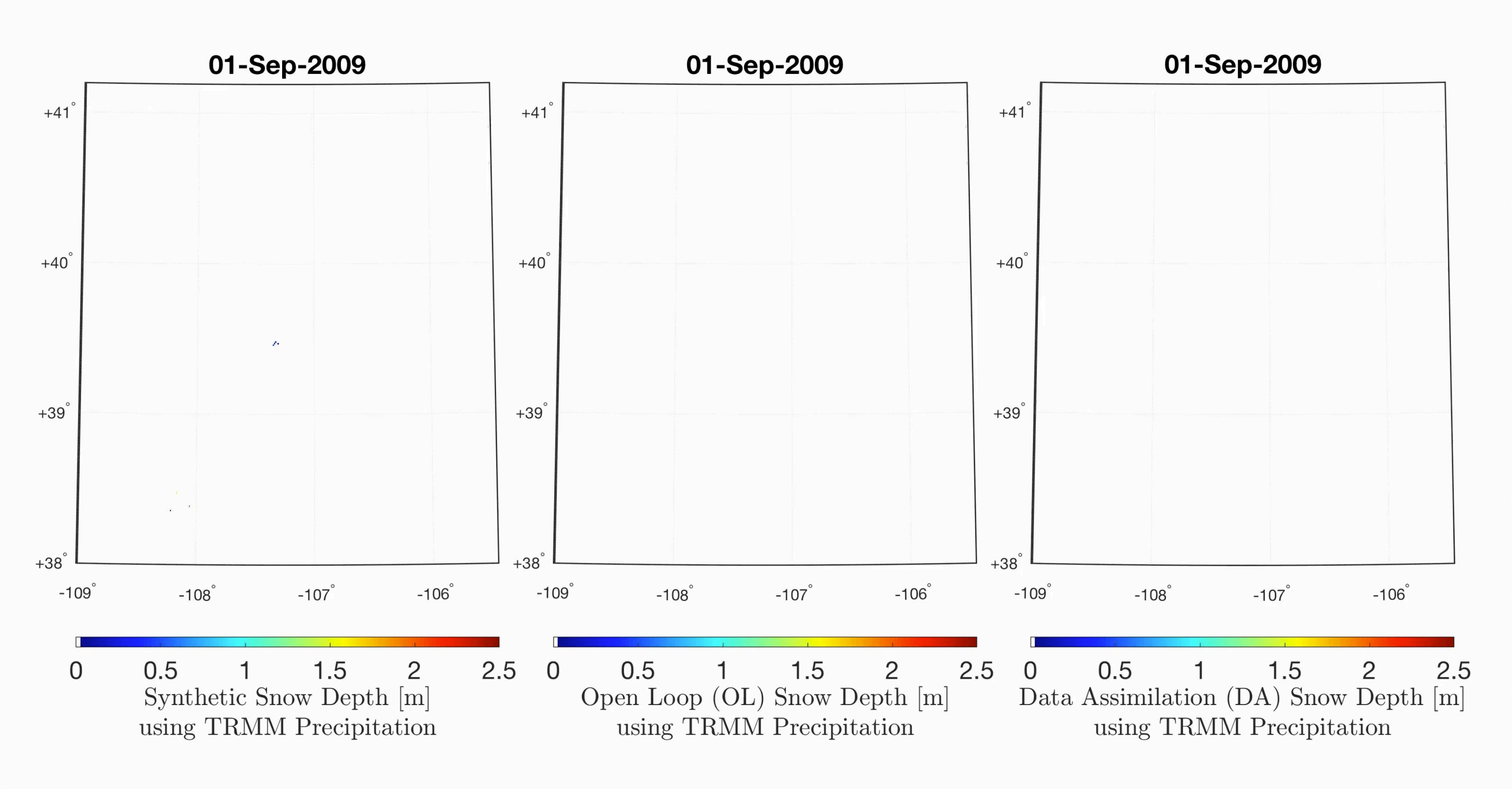
LiDAR-based Snow Depth Assimilation

Videos courtesy of Lizhao Wang and Alireza Moghaddasi (Ph.D. Students)



Synthetic Truth

OL
(no assimilation)

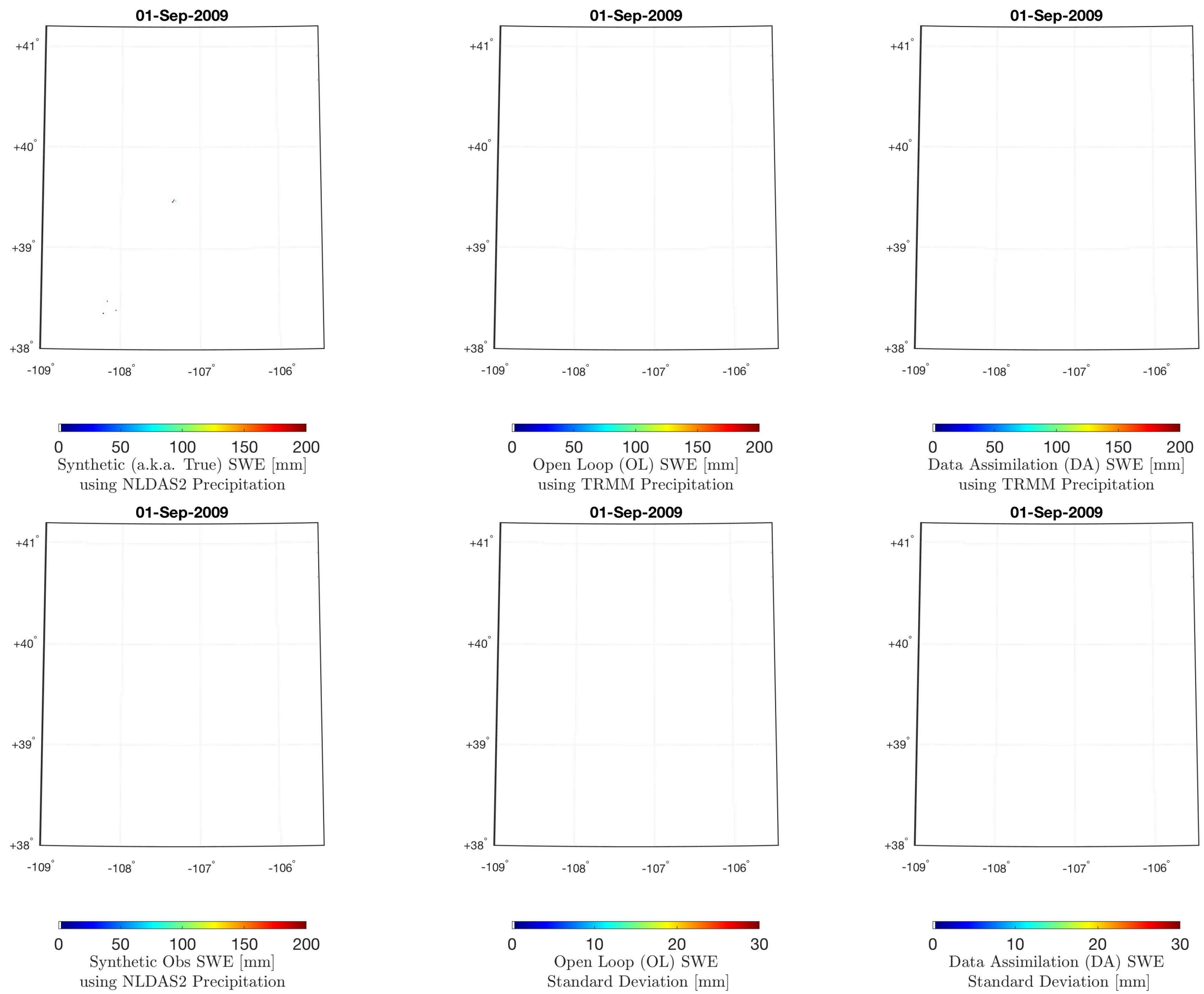
DA
(with assimilation)

NOTE: preliminary testing assumes **idealized viewing during cloud-free conditions**

C-band SWE Assimilation

Videos courtesy of Lizhao Wang and Alireza Moghaddasi (Ph.D. Students)

Synthetic Truth | OL | DA

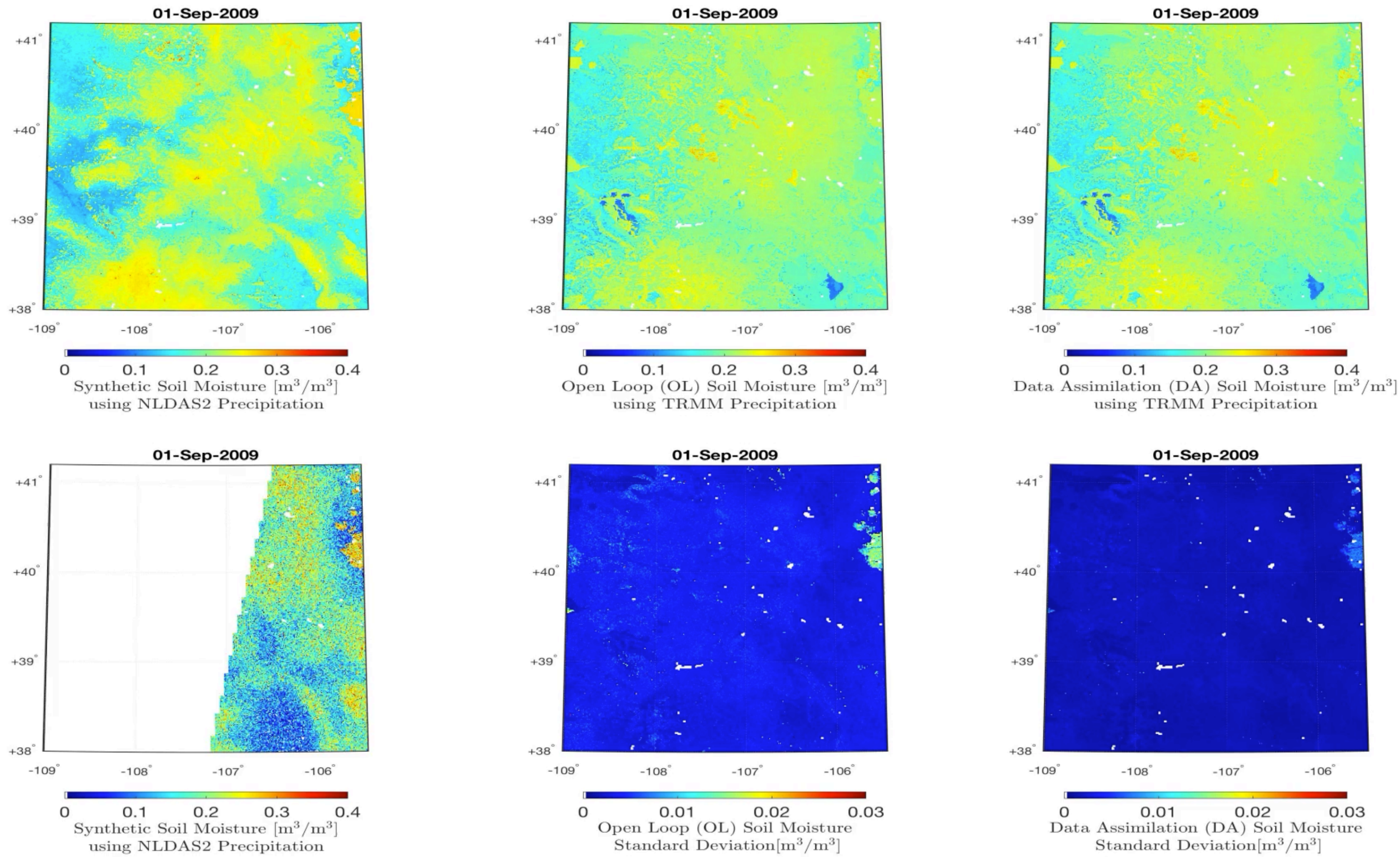


Synthetic Obs. | OL Uncertainty | DA Uncertainty

L-band Soil Moisture Assimilation

Videos courtesy of Lizhao Wang and Alireza Moghaddasi (Ph.D. Students)

Synthetic Truth | OL | DA



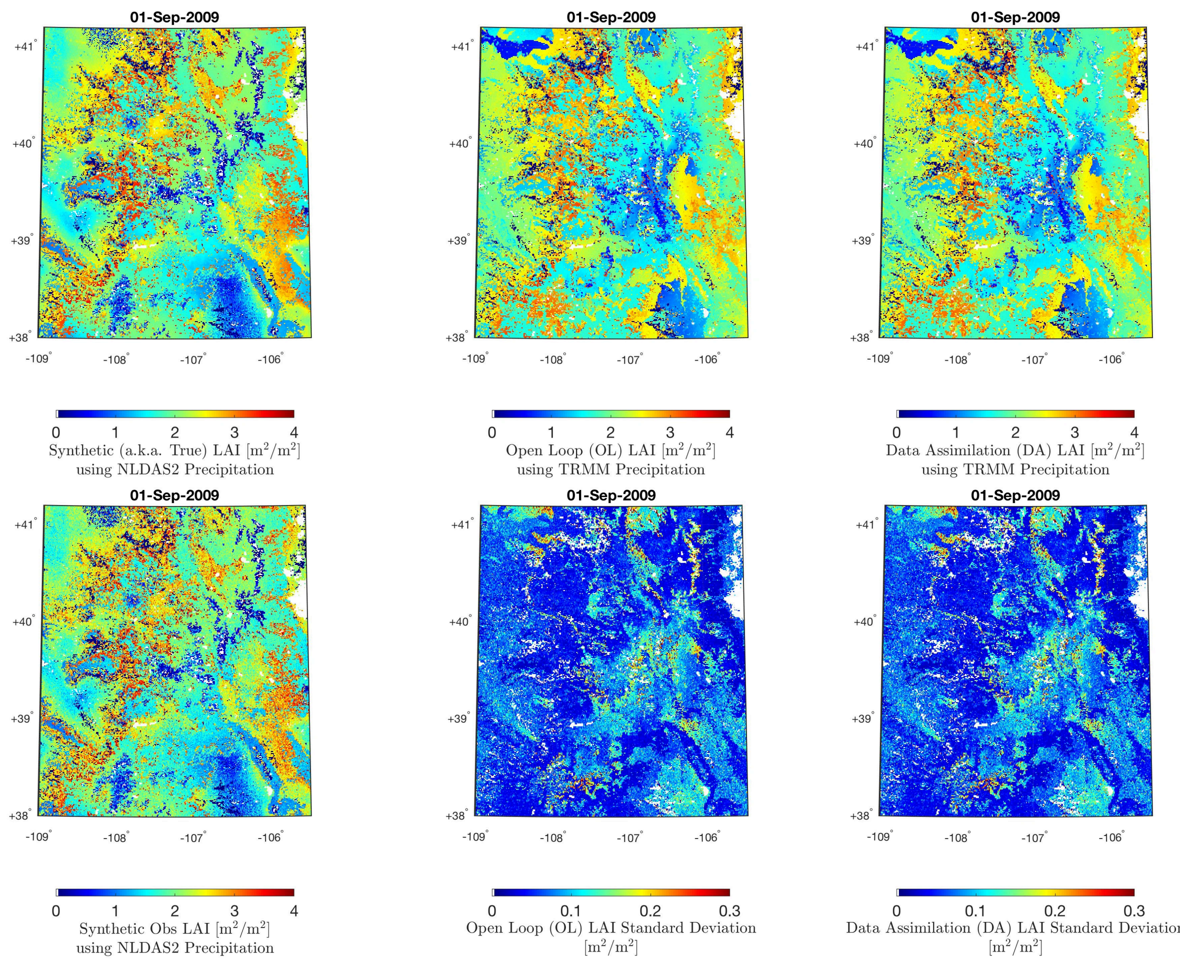
Synthetic Obs. | OL Uncertainty | DA Uncertainty

NOTE: **frozen soil conditions masked** out from synthetic observations

Multi-variate (Snow Depth + LAI) Assimilation

Videos courtesy of Lizhao Wang and Alireza Moghaddasi (Ph.D. Students)

Synthetic Truth | OL | DA

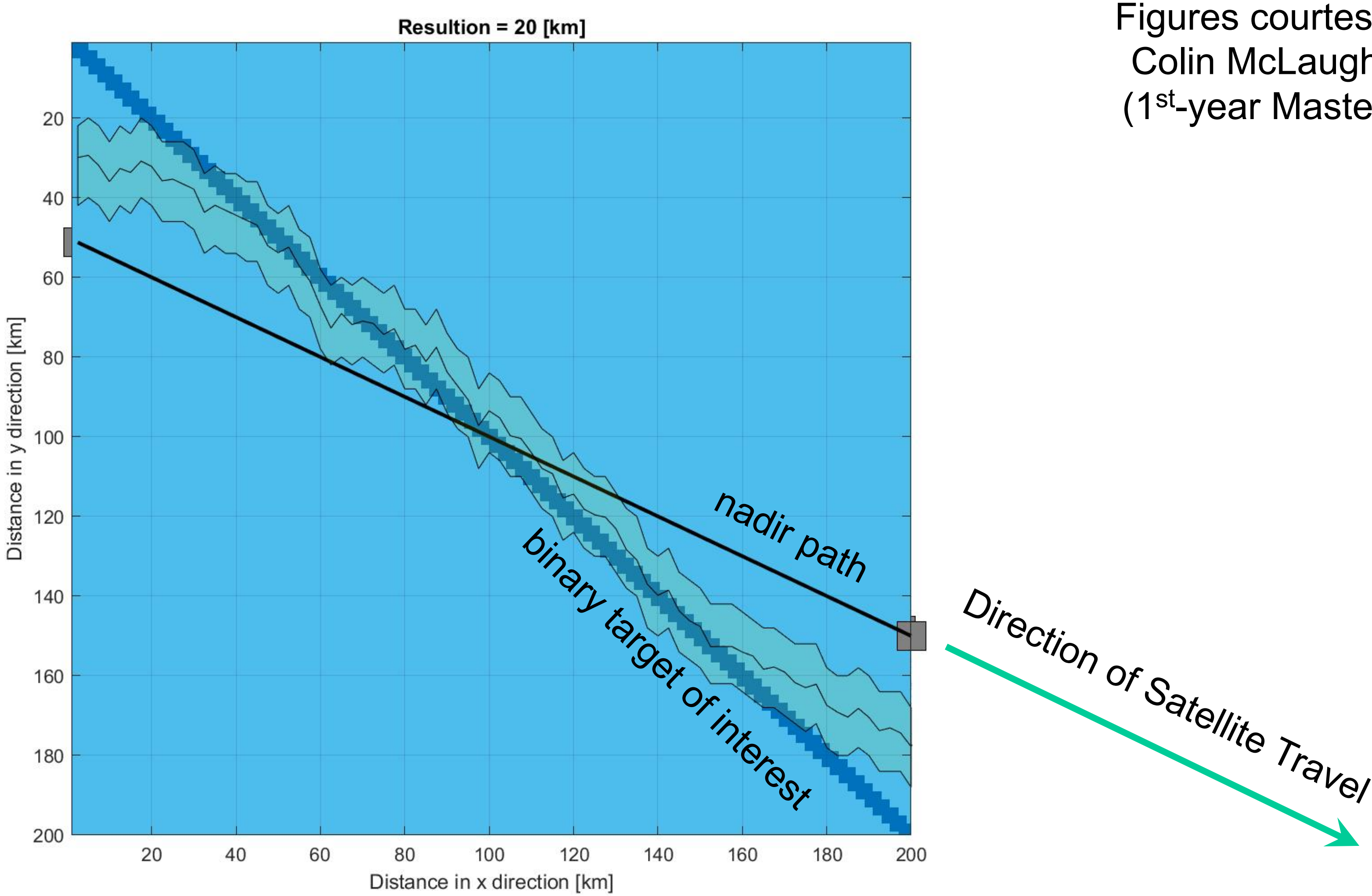


Synthetic Obs. | OL Uncertainty | DA Uncertainty

NOTE: preliminary testing assumes **idealized viewing during cloud-free conditions**

Adaptive Viewing for LiDAR, SAR, and Radiometry

Figures courtesy of
Colin McLaughlin
(1st-year Master's)



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Accomplishments – Year #1

- Completed **Nature Run** (including parameter calibration)
- Completed **Open Loop** (OL) simulation
- **Univariate assimilation** experiments
  - Snow depth assimilation (LiDAR)
  - SWE assimilation (PMW and C-band SAR)
  - LAI assimilation (LiDAR and VIS/NIR radiometry)
  - Soil moisture assimilation (PMW and C-band SAR)
- **Multivariate assimilation** experiments
  - Dual assimilation of LiDAR-based snow depth and LAI
- Initial development of **adaptive viewing** algorithm
  - Random walk employing periodic re-initialization
- Incorporated **two (2) new graduate students** into the project team in Fall 2020

Future Plans

Near Future

- Expand **multi-variate** assimilation experiments
- Refine geophysical **retrieval error** characterization
- Incorporate **adaptive sensor** viewing into OSSE framework
- Utilization of **cost + risk** information in "TAT-C Lite"

Further Down the Road (out-of-scope wish list)

- **L-band InSAR** for snow mass
  - Change detection algorithm impact on snow mass estimation?
- **LiDAR "imager"**
  - Physics of pointing error(s) likely prohibitive for space-borne application
- **GRACE2** constellation
  - Enhanced TWS resolution impact on water cycle characterization?

Thank You!

Questions and/or comments?

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Publications

Journal Papers (graduate students & postdocs shown in **bold**)

Two (2) papers in review; two (2) papers in preparation;

1. **Park, J.**, B. A. Forman, and H. Lievens. ``Prediction of active microwave backscatter over snow-covered terrain across Western Colorado using a land surface model and support vector machine regression" *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Major Revisions.

2. Kwon, Y., Y. Yoon, B. A. Forman, S. V. Kumar, and **L. Wang**. ``Quantifying the observational requirements of a space-borne LiDAR snow mission", *Remote Sensing of Environment*, In Review.

3. **Park, J.**, B. A. Forman, and S. V. Kumar. ``Estimation of snow mass information through assimilation of C-band synthetic aperture radar observations using an advanced land surface model and support vector machine regressions", *Water Resources Research,* In Preparation.

4. **Wang, L.**, B. A. Forman, and E. Kim. ``Exploring the spatiotemporal coverage of terrestrial snow mass using a suite of satellite constellation configurations", *Remote Sensing*, In Preparation.

Dissertations

One (1) Ph.D. dissertation and one (1) Master's thesis

1. Lizhao Wang (coupled snow-soil moisture-vegetation OSSE experiment)
2. Colin McLaughlin (adaptive sensor viewing)

Conference Papers / Presentations (graduate students & postdocs shown in **bold**)

1. Forman, B. A., S. V. Kumar, P. Grogan, **L. Wang**, Y. Kwon, P. Grogan, R. S. Kim, and Y. Yoon. Exploring the next generation of land surface remote sensing: A comparative analysis of passive optical, passive microwave, active microwave, and LiDAR Retrievals, NASA Earth Science Technology Forum, Dulles, Virginia, United States, 2020.

2. Forman, B. A., S. V. Kumar, P. Grogan, **L. Wang**, Y. Kwon, R. S. Kim, and Y. Yoon. What is the optimal mixture of space-borne sensors for remote sensing of terrestrial freshwater?: A comparative analysis of passive optical, passive microwave, active microwave, and LiDAR retrievals, American Geophysical Union Annual Meeting, San Francisco, California, United States, 2020.

3. **Wang, L**., B. A. Forman, S. V. Kumar, Y. Kwon, P. Grogan, R. S. Kim, and Y. Yoon. Towards an integrated terrestrial freshwater remote sensing system using the NASA Land Information System (LIS), data assimilation and synthetic retrievals of snow, soil moisture, and vegetation, American Geophysical Union Annual Meeting, San Francisco, California, United States, 2020.

4. Wrzesien, M. L., S. V. Kumar, C. Vuyovich, E. D. Gutmann, R. S. Kim, B. A. Forman, M. Durand, M. Raleigh, R. Webb, and P. Houser. Development of a ``nature run" for observation system simulation experiments (OSSE) for snow mission development, American Geophysical Union Annual Meeting, San Francisco, California, United States, 2020.

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List of Acronyms

DA	Data Assimilation
EnKF	Ensemble Kalman Filter
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
LIS	Land Information System
LSM	Land Surface Model
MERRA2	Modern-Era Retrospective Analysis for Research and Applications, Version 2
NLDAS2	North American Land Data Assimilation System project phase 2
Noah-MP	Noah – Multi Parameterization Land Surface Model
OL	Open Loop
OSSE	Observing System Simulation Experiment
PMW	Passive Microwave
RADAR	Radio Detection and Ranging
SAR	Synthetic Aperture RADAR
SWE	Snow Water Equivalent
TAT-C	Tradespace Analysis Tool – Constellations

A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design

Derek J. Posselt (PI)[1]
Brian Wilson (Co-I)[1]

AIST-18-0009 Annual Technical Review
04 January 2021

Team listing:

Rachel Storer[2], Derek Tropf[1], Noppasin Niamsuwan[1], Matt Lebsock[1], George Duffy[1], Vishal Lall[1], Simone Tanelli[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

[2]University of California, Los Angeles, CA

A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design

PI: Derek J. Posselt, JPL

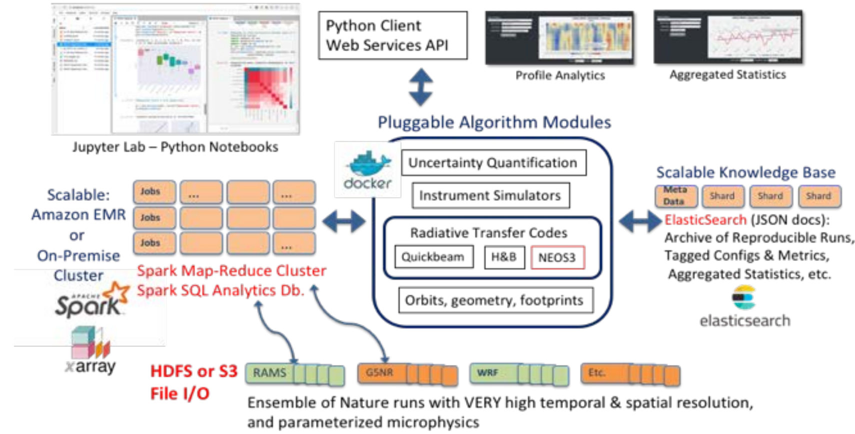
Objective

Develop a fast-turnaround, scalable OSSE Toolkit that can support both rapid and thorough exploration of the mission design trade space, with full assessment of the science fidelity and retrieval uncertainty.

Couple instrument simulators with a scalable parallel computing framework utilizing the Apache PySpark (Map-Reduce analytics) and xarray/dask technologies.

Produce quantitative estimates of geophysical variable uncertainty, and provide information on mission architecture sufficiency

Architecture of the Parallel OSSE Framework



The basic architecture of the OSSE system, including the Map-Reduce compute cluster (Apache Spark & xarray), the scalable Knowledge Base (ElasticSearch), a set of "pluggable" code modules, and python Live Notebooks as one of several front-ends.

Approach

Use a PySpark framework, coupled with state of the art instrument simulators and a Bayesian retrieval algorithm to assess possible mission architectures

1. Use a database of high resolution and high fidelity convection resolving simulations as nature runs
2. Apply measurement simulators with varying fidelity, and with variation in tunable model parameters to assess uncertainty in simulated measurements
3. Vary observation parameters (e.g., footprint, sensitivity, and frequency) and produce simulated retrievals using a well tested Bayesian optimal estimation algorithm

Co-Is/Partners: Brian Wilson, JPL; Rachel Storer, UCLA; Matt Lebsock, JPL; Noppasin Niamsuwan, JPL; Simone Tanelli, JPL; George Duffy, JPL; Derek Tropf, JPL; Vishal Lall, JPL

Key Milestones

- PySpark MAP connected to all forward models, on-premise Spark cluster operational, Knowledge Base collecting run data — 6/20
- Production of simulated measurement database complete. PySpark REDUCE implemented on measurement database. — 12/20
- Spark SQL implemented for data-intensive analytics, Knowledge Base operational for "scaled up" runs, first Kibana dashboards. — 12/20
- Measurement UQ complete. PySpark MAP with OE retrieval single profile tests complete. Production OE runs begin. — 6/21
- Parallel OSSE system deployed on AMCE using an AWS Elastic Map Reduce (EMR) cluster, ElasticSearch service, & Docker containers — 6/21
- PySpark REDUCE analytics implemented for the single profile OE test cases. Production runs of the OE algorithm complete. — 9/21
- Full system running on premise and on AMCE. Analysis of the OE retrieval database complete.
  Final software versions delivered as open source — 12/21

$TRL_{in} = 4$ $TRL_{current} = 5$

Team Members: Scientists

Derek Posselt, PI, Scientist, JPL

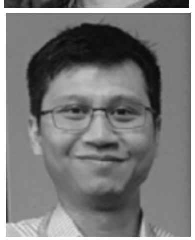
Role: Project PI. Oversee all aspects of the project, provide guidance on high resolution modeling, Bayesian retrievals, and uncertainty quantification. Connect project research to ACCP study.

Rachel Storer, Co-I, Scientist, University of California, Los Angeles

Role: Production of cloud and convection Nature Run data, testing and implementation of fast radar simulators, testing and implementation of optimal estimation retrieval algorithm.

Matt Lebsock, Co-I, Scientist, JPL

Role: Testing and implementation of fast radar and passive microwave simulators, testing and implementation of optimal estimation retrieval algorithm.



Noppasin Niamsuwan, Co-I, Scientist, JPL

Role: Implementation of NEOS3 radar and passive microwave simulator, production of high fidelity instrument simulations

Simone Tanelli, Co-I, Scientist, JPL

Role: Work with PI Posselt and Co-I Storer to implement optimal estimation retrievals. Connect parallel OSSE work with operational GPM retrievals

Team Members: Data Scientists

Brian Wilson, Co-I, Principal Data Scientist, JPL

Role: Provide the parallel Map-Reduce framework, Knowledge database, and sharable Jupyter eNotebooks; educate the scientists in Python map-reduce computing; architect & implement key metadata and workflows.

Derek Tropf, Contractor, JPL

Role: Work with Co-I Wilson to implement workflows, Jupyter notebooks, and knowledgebase / elasticsearch software. Work with PI Posselt to conduct sensitivity experiments and test new retrieval algorithms

Vishal Lall, Data Scientist, JPL

Role: Work with Co-I Wilson to implement workflows and simulators on Amazon Web Services

Team Members: Students and Post-Docs

George Duffy, Post-Doc, JPL

Role: Implement ice scattering properties in radar forward models, conduct forward modeling and retrieval experiments, analyze results.

Presentation Contents

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

Background / Objectives / Tech Advance

Project Summary: Objectives, Technology, and Science Goals

- **Objective**: Construct a software architecture capable of rapidly and thoroughly evaluating mission science objectives / architecture components (OSSE)
- **Technology**: Pluggable instrument simulators connected to Spark MAP-REDUCE analytics, Jupyter notebook workflows, and ElasticSearch database
- **Science Goals**: Evaluate spaceborne radar/radiometer measurements of hydrometeors and dynamics in shallow and deep convection

R&A and Applications Science Goals for *Weather* and *Water & Energy*

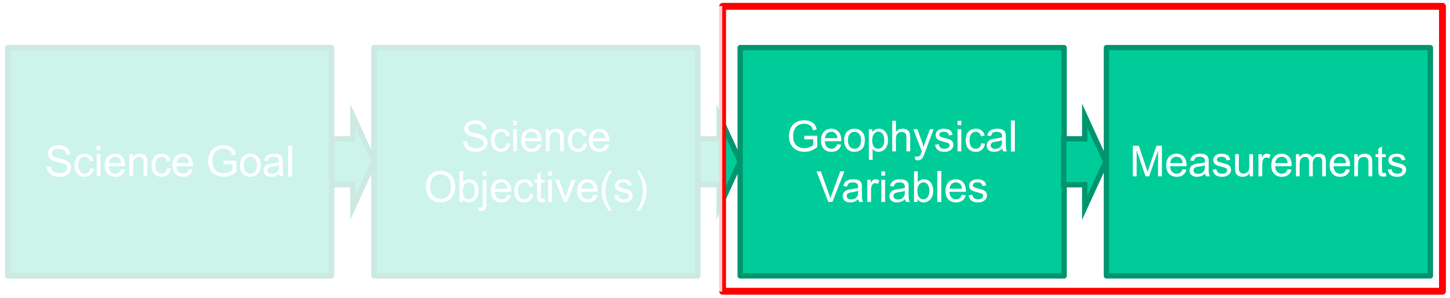
- Advances in understanding the dynamics of weather systems, and their transport of water and energy will require new observing systems and new measurement techniques
- The parallel OSSE toolkit provides a quantitative means for evaluation of new measurement techniques and observing systems, in the context of a SATM

2017 Decadal Survey Aerosols and Clouds, Convection and Precipitation

- Radar/radiometer retrievals and uncertainty quantification directly relevant to all four cloud-related science objectives

Scientific Challenge

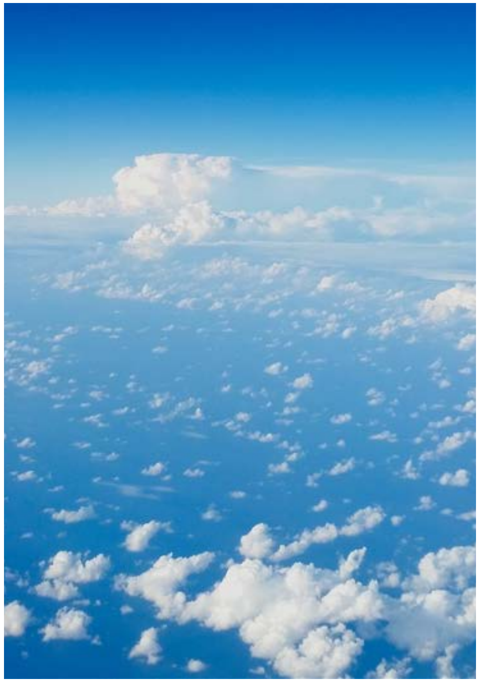
- Clouds and precipitation are central to climate and weather
- After decades of space-borne measurements,
  key processes are still missing
- Goal: design a new observing system (e.g. ACCP*)
  - Address specific science objectives
  - Consider the vast array of possible measurements
  - Rigorously quantify uncertainties



*Aerosols and Clouds, Convection, and Precipitation
https://science.nasa.gov/earth-science/decadal-accp

Technical Challenge

- The design trade-space is *large* and clouds are *diverse*
- Dimensionality of the mission design problem is *immense*
  - Multiple different geophysical scenarios (different cloud types)
  - Diversity of measurement types (active, passive, single-point, distributed)
  - Multiple sources of uncertainty (instrument noise, forward models, sampling characteristics)
- **Computational challenge: identify suitable candidates**



For each geophysical variable → For each cloud type → For each combination of measurements → Considering all sources of uncertainty → Determine whether measurements meet mission requirements

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Technical Advances

- **Build a flexible system that is applicable to a broad variety of mission concepts**
- Combine measurement simulators and Bayesian retrieval with a Parallel Map-Reduce framework
  ➔ Pervasive parallel computing
- Containers for Pluggable measurement simulators
  – "app store" of pluggable algorithms
- Flexible Knowledge Database
  – Search for & group experiment outputs by tags & run metadata
  – Fast ensemble statistics, comparisons, drill-down
- Map-Reduce framework & cluster/GPU computing to:
  – Generate large database of simulations – geophysical variable (retrieval) pairs
  – Compute analytics to determine whether measurements satisfy mission requirements

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OSSE Infrastructure Design

Technologists:
PI Brian Wilson
Derek Tropf
Vishal Lall

Computing Technologies

Apache PySpark
SciSpark – AIST14
Py Mat/Vec for GPU

Instrument Simulation Codes

QuickBeam
H&B
NEOS3
Statistical Analysis

OSSE Team:
Derek Posselt
Rachel Storer
George Duffy
Matt Lebsock
Noppasin Niamsuwan
Derek Tropf

Parallel OSSE Toolkit for Mission Design

Spark Cluster

GPUs

Integrated Toolkit in Python
End-to-end automated analysis
16 to 1024-way Ensemble Parallelism
"Quick look" Exploration
High-Fidelity Simulations
Parallel Analytics (or on GPU)
Explore larger Science Trade-Space

Applications:
- 2017 Decadal Survey-proposed CCP "required" observations
- Radar constellations
- All future instrument simulation & mission design at JPL

Details of OSSE Infrastructure

- Knowledge Base
  - ElasticSearch JSON doc. database, on-premise or at Amazon
  - Kibana dashboard to keep track of experiments in-flight or completed
  - Traceability for all experiment runs by configuration
  - Metadata: user tags, timestamps, code versions, input configs.
  - Sub-docs. for details of ensemble, instrument, retrieval parameters
- Workflows and Notebooks
  - Exploratory statistics, visualizations, and code development in Jupyter Notebooks
  - Production workflows in version-controlled Python scripts
- Pluggable Codes
  - Binary executables called from Python (“wrapped”): QuickBeam, H&B
  - Thin Python clients calling into Docker container: NEOS3
- Deployment on parallel backends
  - Codes written once using PARMAP Python library
  - Deploy by changing config. “string” to Spark/Dask cluster or Lambdas

Overview of Progress & Accomplishments

Science: Completed all proposed 0-12 month milestones
- Forward models of varying complexity coupled with nature run database
- Radar simulations completed for nature run database
- Completed multi-frequency radar and radiometer uncertainty experiments

Science: Augmentation (no additional cost)
- Expanded forward models to include active (radar) and passive (radiometer) microwave
- Detailed ice crystal scattering calculations in radar and radiometer forward models

Technical Details:
- Connected pyspark MAP to three different radar instrument models
- Python-based workflow established to map over cloud microphysics uncertainty
- Jupyter hub up and running and available to project personnel
- Elasticsearch database connected with workflows, tagging, tracking of simulations
- JSON configuration documents and Elasticsearch database connected with workflows; tagging and tracking of simulations; analysis and plotting of run data
- Bayesian (optimal estimation) radar-based retrieval of cloud properties constructed for ACCP shallow cloud objective
- Initial tests of forward models and containers on AWS

Programmatic Notes:
- Working with AIST / NOS Tradespace Analysis Tool for Constellations (TAT-C) to conduct sampling OSSEs for ACCP deep convection objective
- Providing input to guide NOS atmosphere use cases

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OSSE Requirements

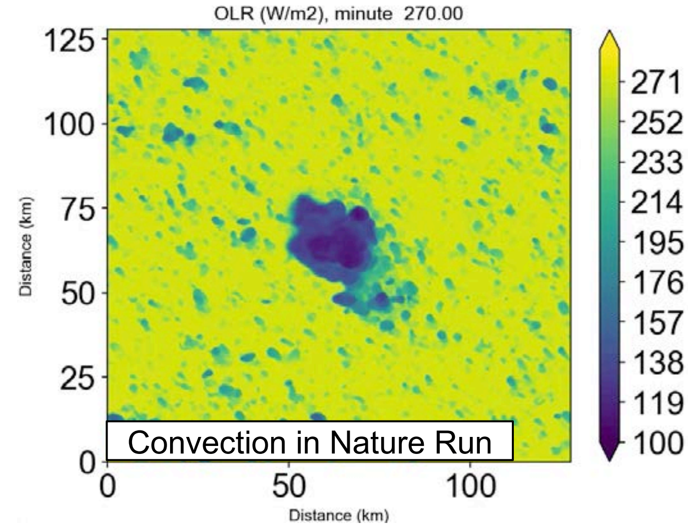
Any observing system simulation experiment (OSSE) requires at least three components:

1. Nature run:
   - Starting point for any OSSE
   - A highly realistic representation of the real world
2. Instrument simulators:
   - Simulating measurements = high fidelity model (slow)
   - Estimating geophysical variables = fast (low fidelity)
3. Quantifying uncertainty:
   - Incorporate measurement (instrument) noise
   - Model the effect of real-world uncertainty

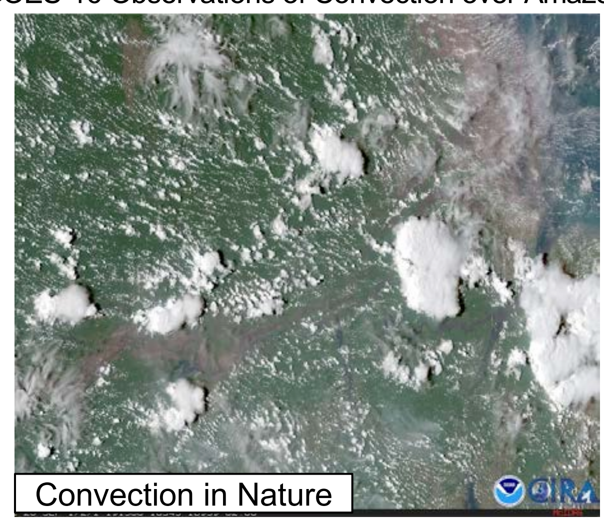
Nature Run: Shallow and Deep Convection

- Nature run consists of library of highly realistic simulations of convection
- Simulate radar observations
- Implement a Bayesian retrieval
- Quantify uncertainty
- Assess effect of mission design parameters on retrievals and uncertainty

Simulation of Convection over Amazon



GOES-16 Observations of Convection over Amazon



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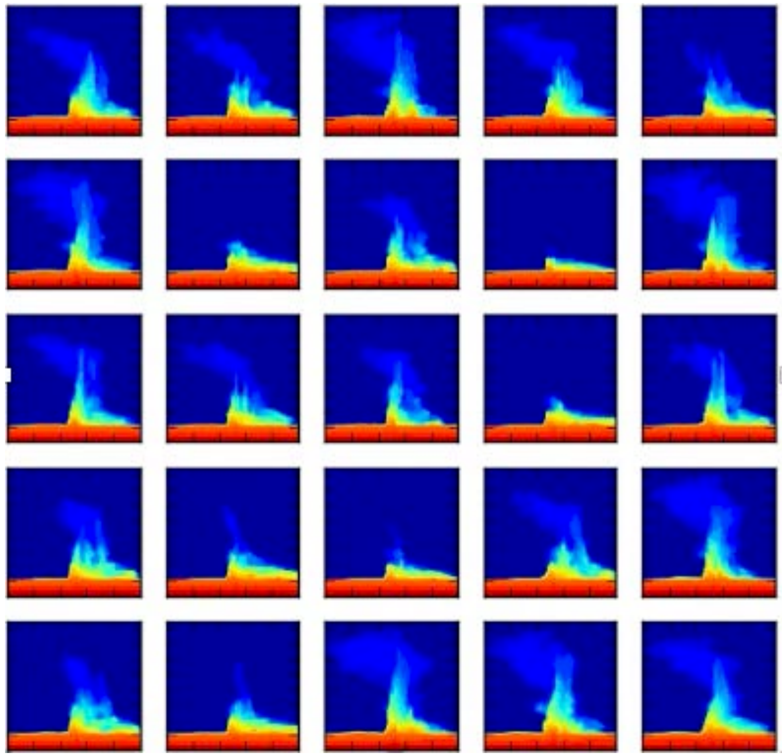

Cross-section through ensemble of 25 simulations of deep convection, showing transport of pollution from the boundary layer upward into the free troposphere.

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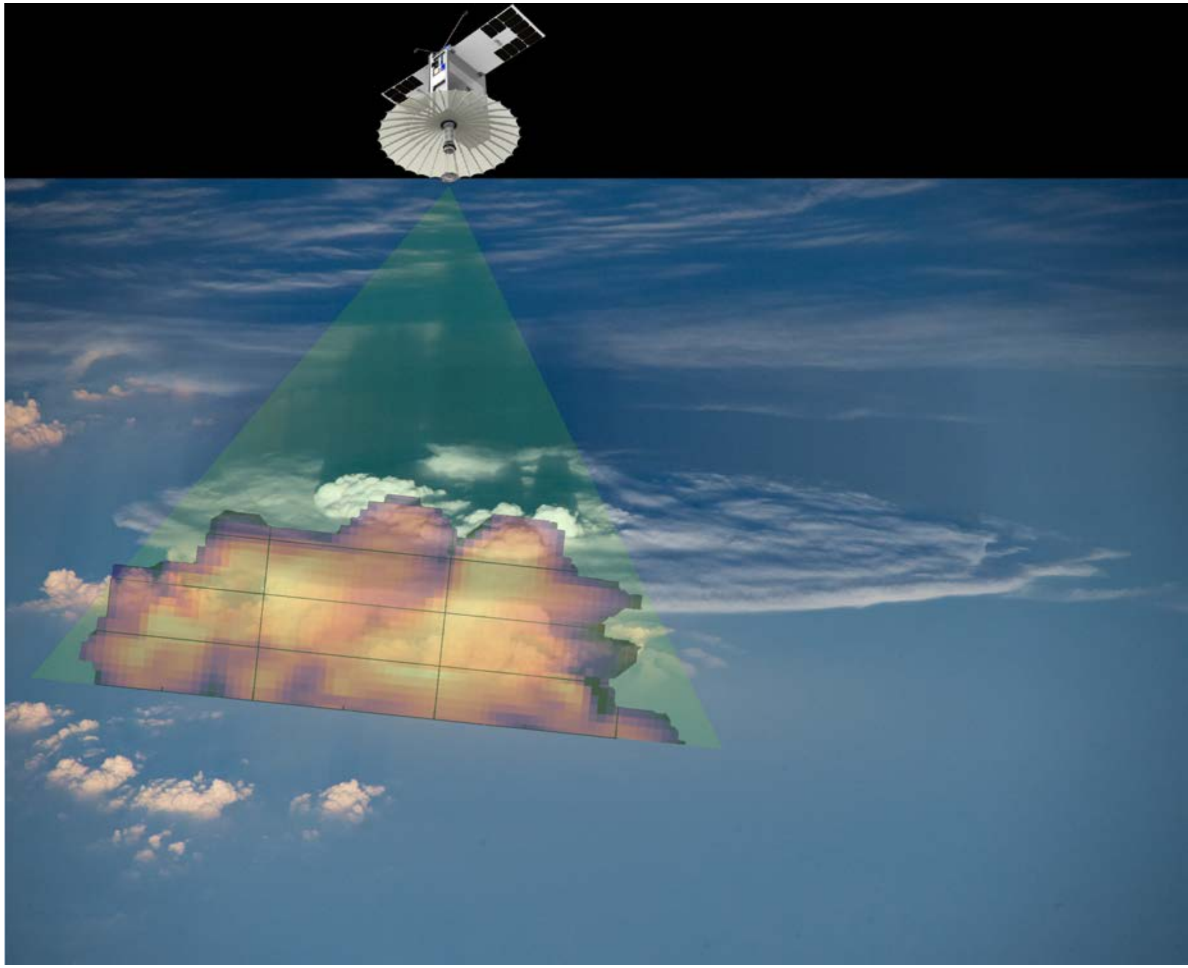
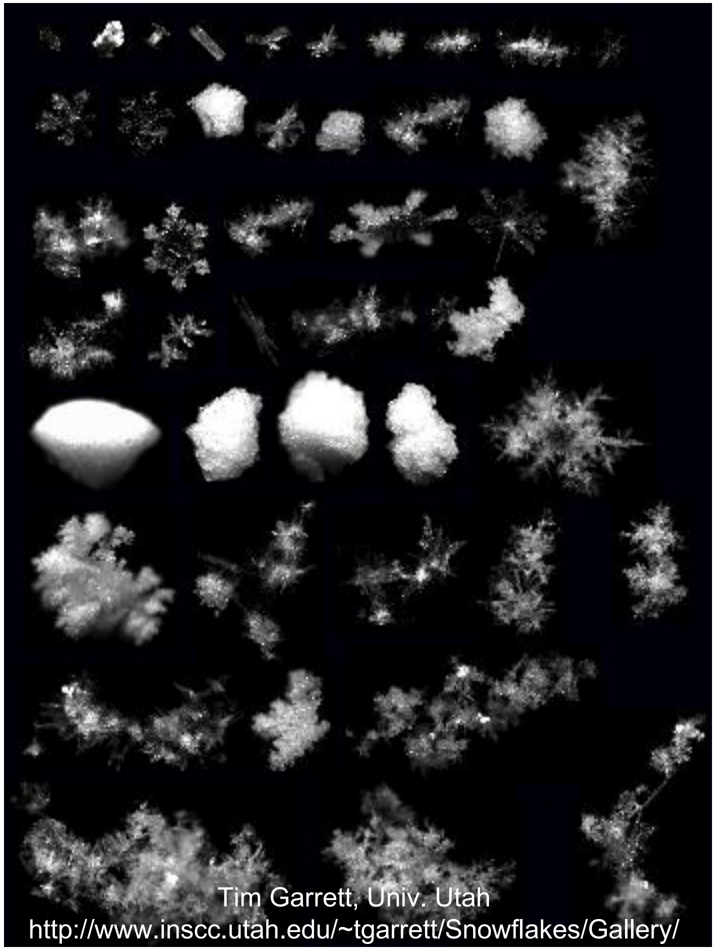
Instrument Simulators and Uncertainty Quantification

- Simulating radar reflectivity, doppler velocity, and microwave radiometer brightness temperature in deep convection
- OSSEs must consider sources of uncertainty
  - Instrument noise (radar/radiometer)
  - Geophysical uncertainty (ice crystal shapes)



Quantifying Ice Cloud Uncertainty: Crystal Shape
(ACCP Objective O3 (O2,O4))

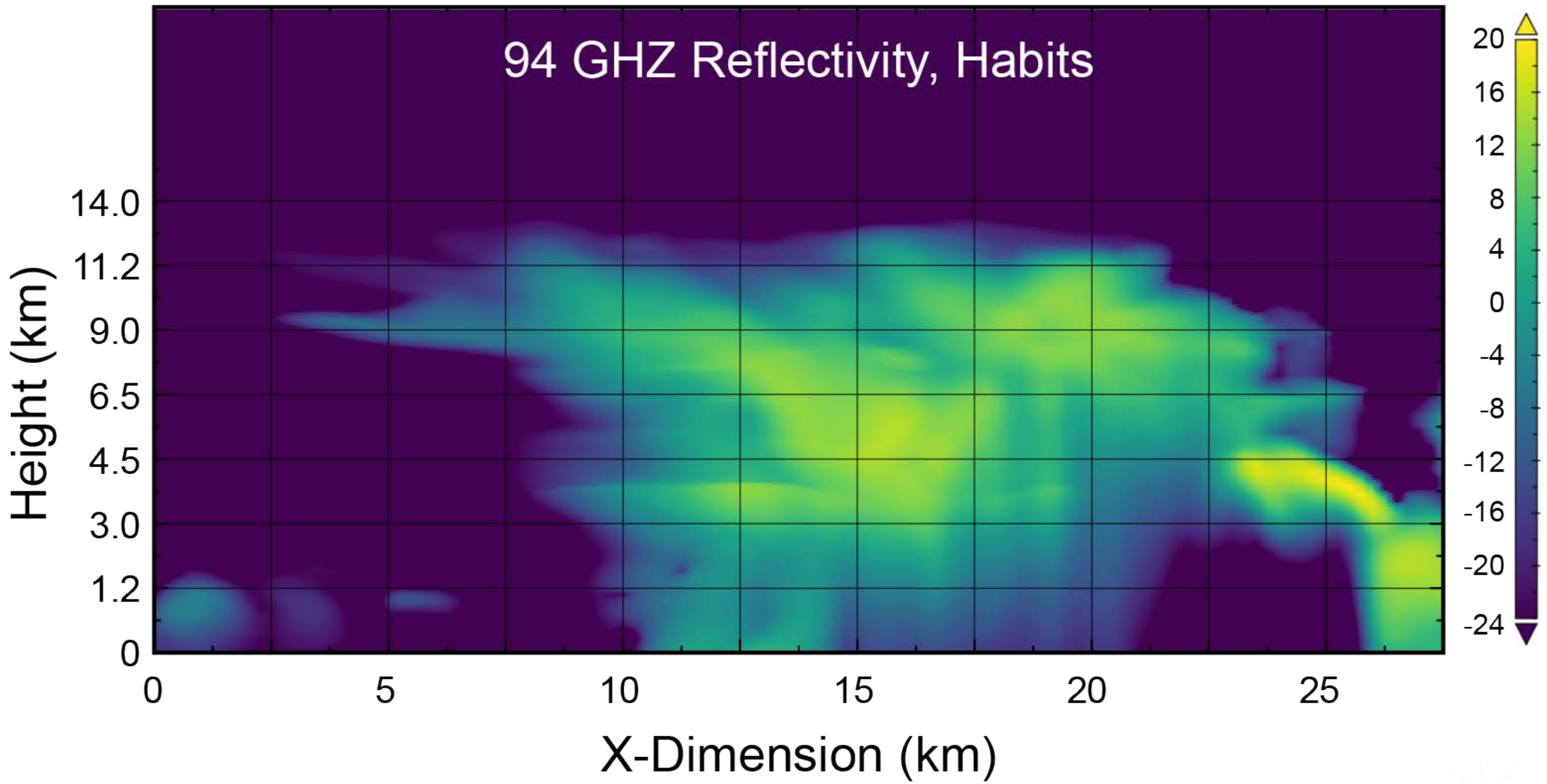
- Tremendous variety of ice crystal shapes inside clouds
- Radar observations of ice clouds are sensitive to the crystal shape
- Organized a variety of scattering codes to simulate Z and Tb with different degrees of freedom for ice crystals.
- Organized size distributions, *in-situ* properties, particle morphological information, and collocated reflectivity from four NASA GPM ground validation campaigns.
  - OLYMPEX, GCPEX, MC3E, IPHEX
- Implemented these in radar/radiometer forward models



Tim Garrett, Univ. Utah
http://www.inscc.utah.edu/~tgarrett/Snowflakes/Gallery/

Ice Crystal Shape Uncertainty

- Run radar simulator using two different sets of ice shapes (spheres vs multiple habits)



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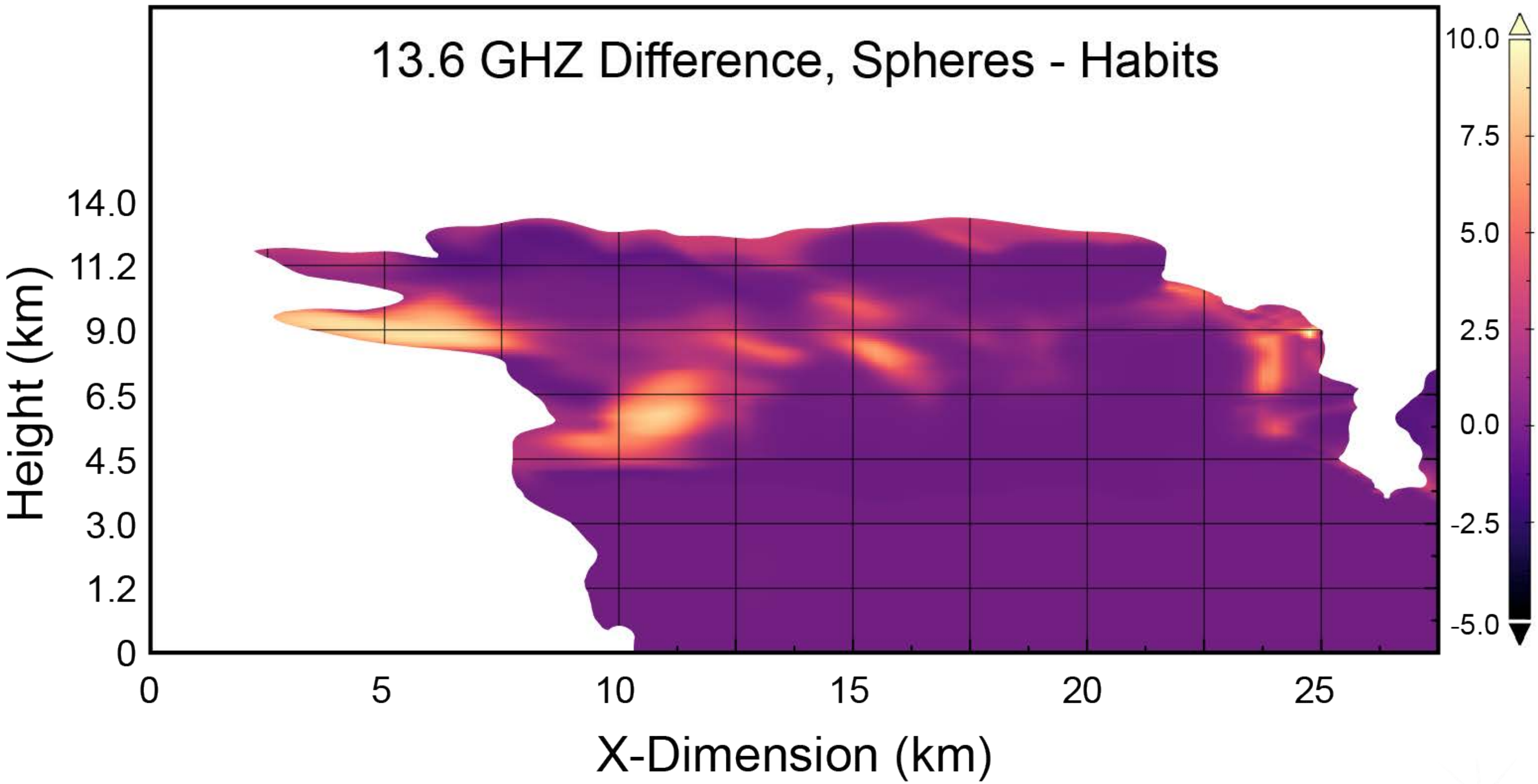

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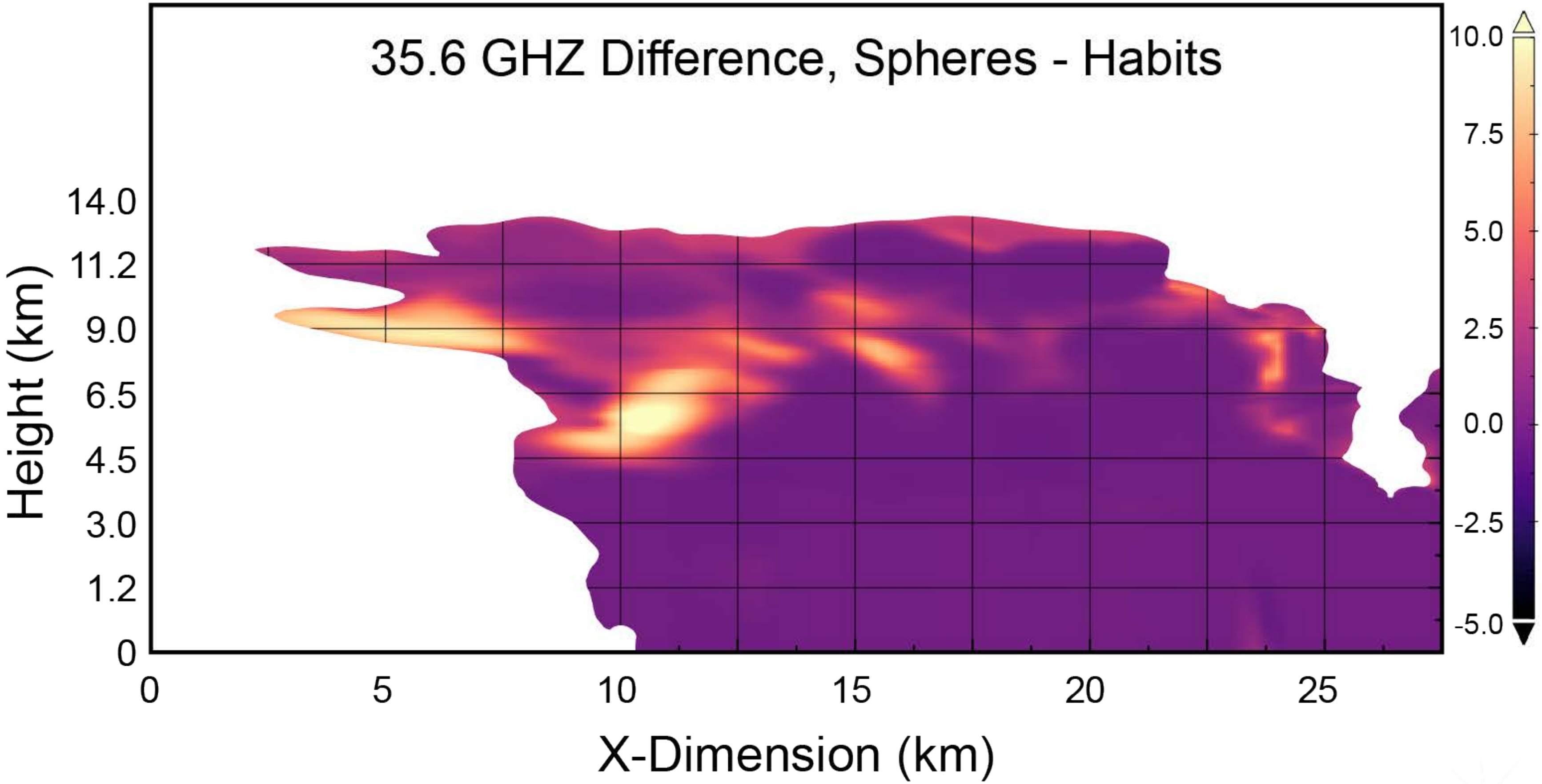

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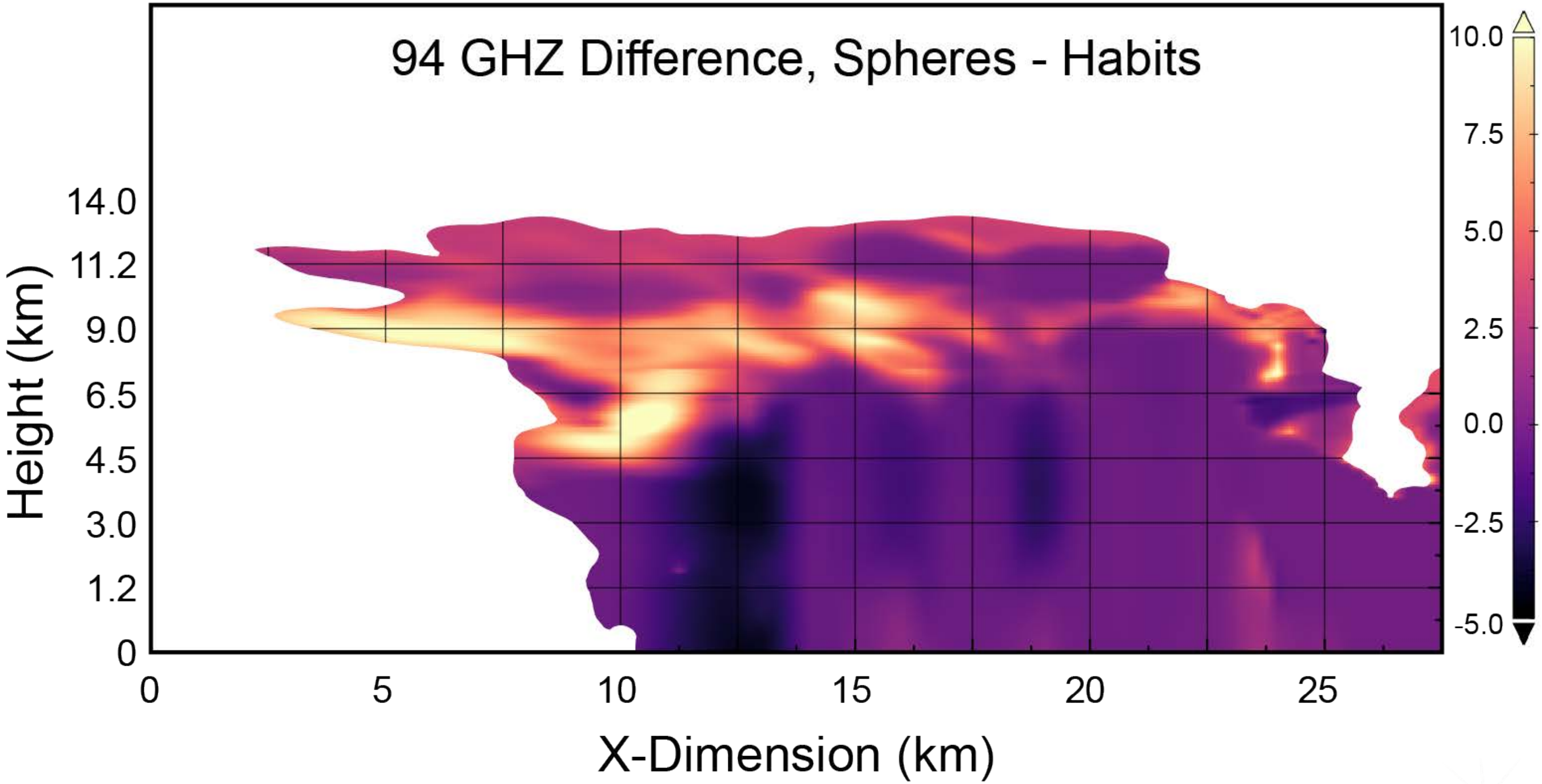


End-to-End Sensitivity Experiment for Convection (ACCP O3)

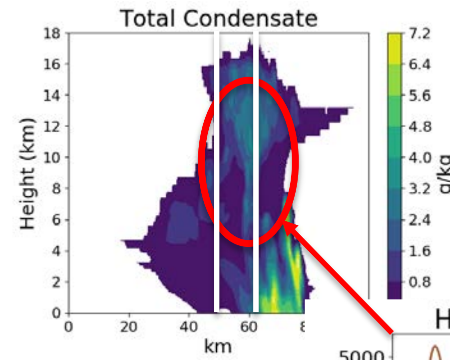
Components implemented:

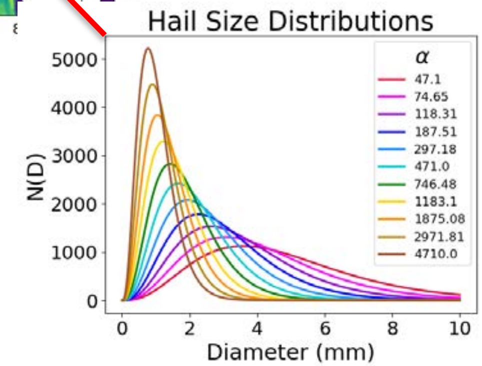
1. Python handler for running mesurement simulator executables (QuickBeam and H&B)
2. Python code for Bayesian retrieval of cloud and rain water
3. Wrappers (also in Python) allowing 1. and 2. to be fully configurable in JSON; the wrappers upload all relevant metadata (such as path of model output) to Elasticsearch
4. MAP function transforming experiment trade space to a list of embarrassingly-parallel run configurations
5. PARMAP library providing parallelization capability
6. Analytics capability: query Elasticsearch, retrieve data, and generate statistics/visualizations (REDUCE)
7. Finalized I/O format and constructd a top-level function/object
8. Conducted an end-to-end convective cloud sensitivity experiment

Sensitivity Experiment:
Radar Observations of Convection (ACCP O3)

Experiment Configuration:

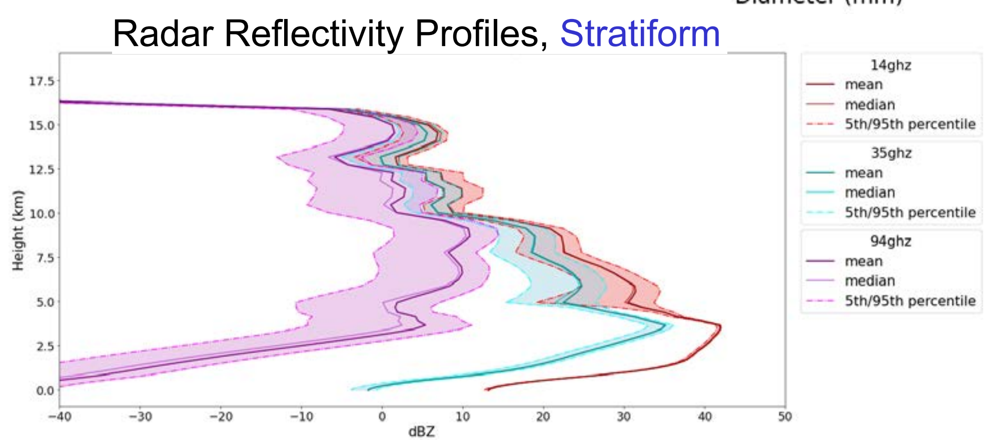
- 2 input model profiles (1 convective, 1 stratiform)
- 3 radar frequencies (Ku, Ka, W)
- 5 uncertain parameters, 11 possible values each
- $2 \times 3 \times 11^5 = 966{,}306$ forward model runs
- Per profile time elapsed: 18 hours single processor, 40 minutes parallel





- Inputs:
  - Nature run profiles
  - Range of uncertainty

- Outputs:
  - Ensemble of possible radar profiles for each input model profile and frequency
  - Improved understanding of uncertainty in radar observations of convection



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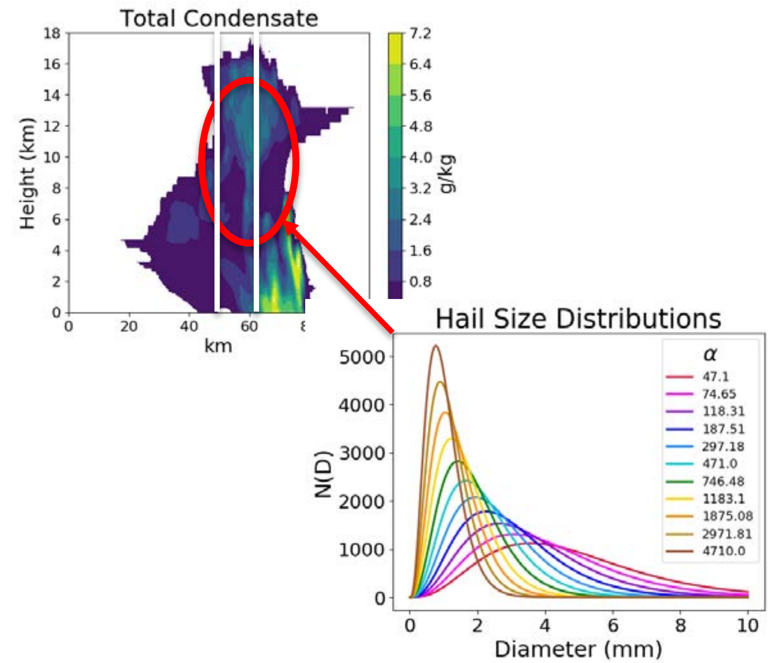

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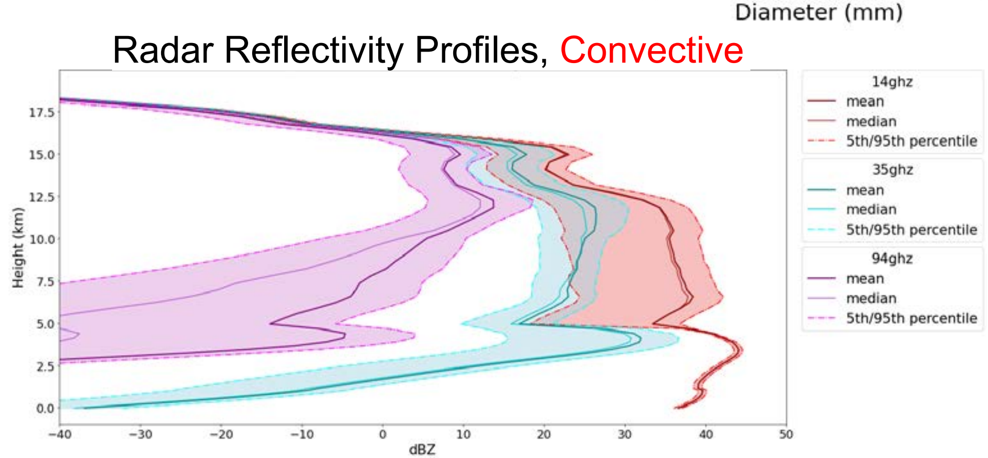


Shallow Cloud Rain Retrieval
(ACCP O1)

- Next step: apply framework to radar-based retrievals
- Application: evaluate measurement effectiveness for geophysical variables (direct quantification of science traceability)
- Specific example: shallow convection rain retrieval
  - Sensitive to radar design parameters (sensitivity, footprint, surface clutter)
  - Important for hydrologic cycle and climate radiation feedbacks
  - Smaller / easier problem (relative to convection)
- Constructed an optimal estimation (Bayesian) retrieval based on the CloudSat algorithm
- Conducted first test of retrieval uncertainty using 6000 shallow rain profiles from nature run
- Results presented at Fall 2020 AGU meeting

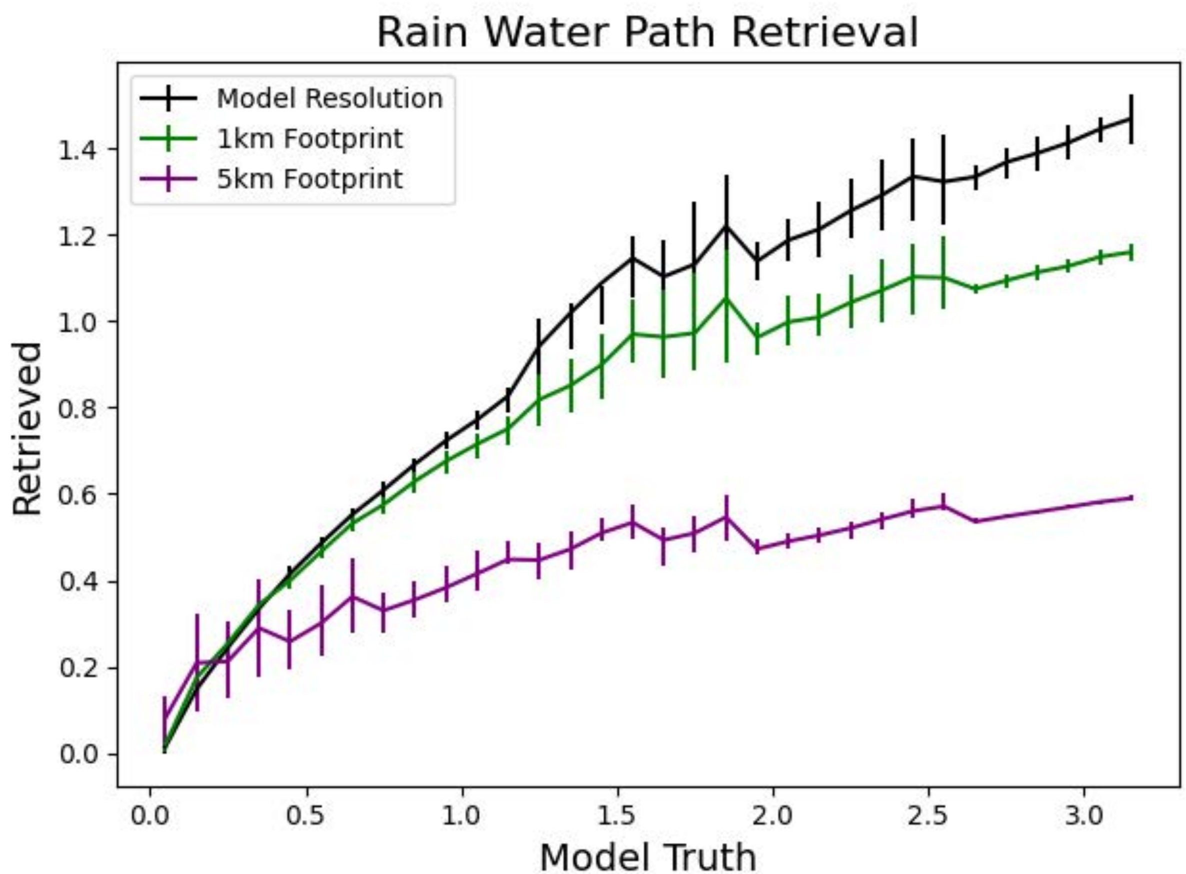
Shallow Cloud Rain Retrieval
(ACCP O1)

Key results:

- Underestimate of rain water with increasing radar footprint size
- Bias in rain water with increasing amounts of rain

Next steps:

- Apply radar clutter and sensitivity
- Retrieval diagnostics



Progress on Implementation of the ParOSSE Framework

- Developed Framework for ‘wrapping’ executables into Python
  - Exewrap Python library
  - Strategy for Parallelizing runs over ensembles using PARMAP library
- Pluggable Radar Simulators
  - QuickBeam and H&B (Fortran) into Python Exewrap
  - Integrated Python client for calling into NEOS3 Docker container
  - Currently running using on-premise cluster
- Deployed 1st version of KnowledgeBase (KB running on-prem)
  - ElasticSearch JSON document database, Kibana dashboards
  - Later will also use AWS ElasticSearch service

Progress on Implementation of the ParOSSE Framework (II)

- Have a set of initial 'tags' for run traceability & GroupByKey statistics
  - JSON key/value documents inserted into KB
  - These will be expanded as new sources of uncertainty are added
- Notebook Analytics
  - Deployed Jupyter Hub (on-prem)
  - Shareable Python notebooks for the team
  - Later will deploy on AWS
- Applying PARMAP 'easy' Map-Reduce library
  - Selectable Python parallelization over multicore, Dask cluster, Spark cluster, AWS Lambda functions, and eventually GPU
  - Currently using 7-node, 294-core on-prem cluster
- **Have run an end-to-end sensitivity experiment, meeting year 1 goals, and advancing to TRL5**

Creating a Larger and More Flexible OSSE Framework: ParOSSE + TAT-C

- The ParOSSE framework examines the ability of measurements to meet science goals
- It does not address questions of orbit, sampling, data sufficiency, etc. All of which are equally important (especially when considering constellations)
- We have begun a partnership with Prof. Paul Grogan to connect ParOSSE with the Tradespace Analysis Toolkit for Constellations (TAT-C)
  - TAT-C: explores whether various orbits produce sufficient samples of features of interest (e.g., convection)
  - ParOSSE: determines whether measurements made on each platform can address the observational needs of the mission
- The two frameworks are highly complementary
- Extensible to missions beyond ACCP – submitted response to RFI for PBL Incubation Study

TAT-C and ParOSSE Complementary Contributions

- ParOSSE:
  Do the measurements provide enough information to satisfy science requirements?
  - Parallel architecture allows for rapid and iterative exploration of the effect of instrument trades on measurement and retrieval information
  - Pluggable forward models allow flexibility in instrument configurations
  - Returns quantitative estimates of uncertainty in geophysical variables to assess retrieval quality vs mission desired capability
  - Parallelism allows thorough measurement tradespace evaluation and uncertainty quantification

- TAT-C:
  Do the orbits, swaths, and space and time resolution meet the science objectives?
  - Evaluate combinations of orbits and swaths to quantify sampling
  - Information content measures are flexible: accommodate the full distribution and also various environmental conditions (e.g., day / night, stable / unstable)
  - Architecture allows diverse orbits and robust measures of information

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Summary

- Proposed goals for year 1:
  - PySpark MAP connected to all forward models (Quickbeam, H&B, and NEOS3). (**DONE**)
  - On-premise Spark cluster operational, Knowledge Base (ElasticSearch db) collecting run data, Jupyter Hub providing Python Notebooks. (**DONE**)
  - First end-to-end use of the ParOSSE system to quantify radar sensitivity (**DONE**)
- Stretch goals accomplished
  - Retrieval framework already being tested
  - Additional forward model implemented (H&B)
  - Interface build to detailed ice crystal scattering database
- Programmatic relevance
  - Infrastructure and results informing ACCP DO study
  - Connection established to AIST-funded TAT-C project
  - Input provided to NOS atmosphere use cases

Future Plans

- Optimal Estimation retrieval uncertainty quantification
  - Begin with precipitation retrievals from shallow clouds (directly relevant to ACCP Objective 1)
  - Extend to for convective / stratiform profiles (directly relevant to ACCP Objective 3)
- Scale up to additional nature run databases for different environmental contexts
- Apply uncertainty quantification metrics to tagged database of retrieval simulations
  - Which are the largest sources of uncertainty?
  - Which additional observations may be used to reduce uncertainty?
  - Which combinations of measurements meet desired uncertainty metrics?

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Publications

Conference Papers:

2020 American Meteorological Society Annual Meeting, Boston, MA

- Posselt, D. J., M. Lebsock, R. L. Storer, M. Minamide, J. Mace, and Z. Xu, *Observing System Simulation Experiments for Convective Clouds*. Talk presented in the 24th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface at the 2020 American Meteorological Society Annual Meeting, Boston, MA, 12-16 January 2020.

- Posselt, D. J., B. D. Wilson, R. L. Storer, E. L. Nelson, N. Niamsuwan, and S. Tanelli, *Observation-Based Cloud and Precipitation Properties from Spaceborne Measurements Using a Parallel Bayesian Retrieval Framework*. Talk presented in the 26th Conference on Probability and Statistics at the 2020 American Meteorological Society Annual Meeting, Boston, MA, 12-16 January 2020.

2020 Fall American Geophysical Union Meeting, Online / Virtual

- Posselt, D. J., B. D. Wilson, R. L. Storer, M. D. Lebsock, G. Duffy, B. Chen, N. Niamsuwan, and S. Tanelli, *Exploring Uncertainty in Bayesian Retrievals of Cloud and Precipitation Properties*, Poster presented at the 2020 Fall American Geophysical Union Meeting, Virtual, 1-17 December 2020.

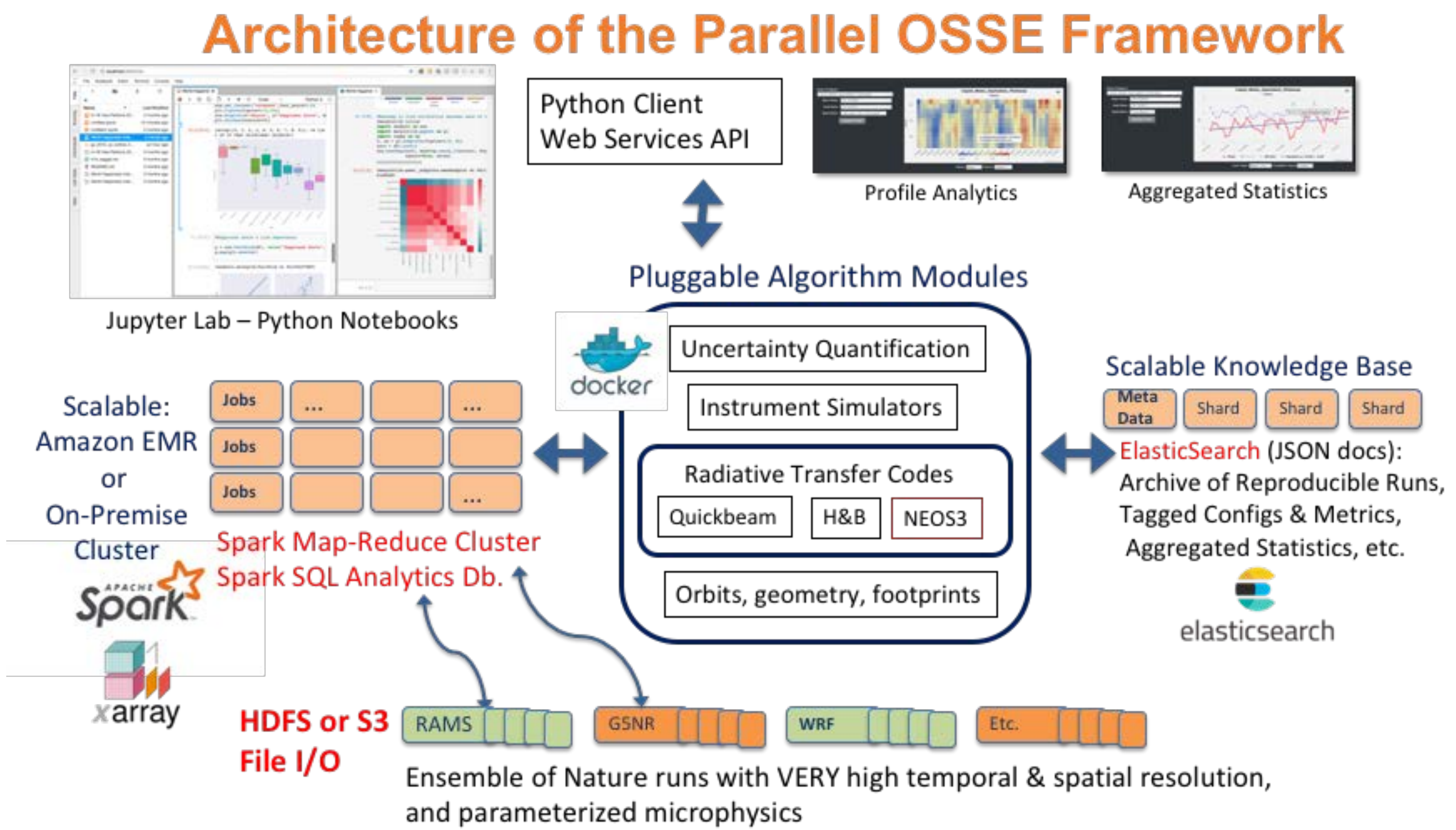
- Storer, R. L., M. D. Lebsock, and D. J. Posselt, *Quantifying the Effects of Radar Resolution on a Warm Rain Retrieval*, Poster presented at the 2020 Fall American Geophysical Union Meeting, Virtual, 1-17 December 2020.

List of Acronyms

ACCP	Aerosol, Clouds, Convection, and Precipitation
DO	Designated Observable
DS	Decadal Survey
G5NR	GEOS-5 Nature Run
GEOS	Global Earth Observing System
NEOS3	NASA Earth Observing System Simulator Suite
OSSE	Observing System Simulation Experiment
ParOSSE	Parallel OSSE
RAMS	Regional Atmospheric Modeling System
TAT-C	Tradespace Analysis Toolkit for Constellations
TBC	To Be Completed
UQ	Uncertainty Quantification
WRF	Weather Research and Forecasting model

Backup Slides

Parallel OSSE Architecture



Deploy using on-premise hardware cluster AND at Amazon.

Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design

Paul T. Grogan (PI, Stevens Institute of Technology)

QRS-20-0001 Group Technical Review
Grant No. 80NSSC20K1118
January 4, 2021

Joel Johnson, Christopher Ball,
Andrew O'Brien (Ohio State University)
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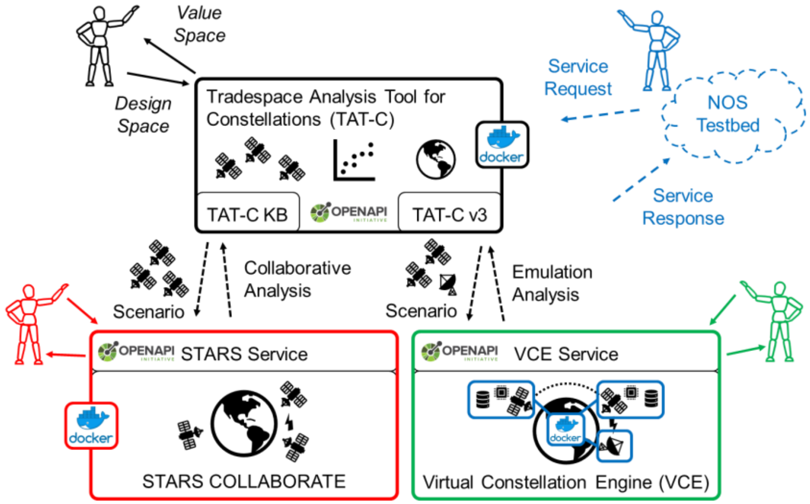
Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design

PI: Paul Grogan, Stevens Institute of Technology

Objective

- Inform selection and maturation of Pre-Phase A distributed space mission concepts
  - TAT-C: architecture enumeration and high-level evaluation (cost, coverage, quality)
  - STARS: autonomous/adaptive sensor interaction (COLLABORATE)
  - VCE: onboard computing and networking
- Expose tools as services to NOS Testbed efforts
  - Tools accessed individually or in concert to support concept development
  - Loosely-coupled service-oriented API



STARS and VCE support TAT-C and all interface with NOS-T

Approach

- Identify initial set of services to expose
- Define and align interface vocabulary
- Refactor tool interfaces: sequential operation
  - Use TAT-C output as STARS/VCE input
  - Broad set of loosely-coupled services
- Refactor tool interfaces: integrated operation
  - Call STARS/VCE in TAT-C workflow
  - Selective set of tightly-coupled services
- Documentation and deployment/release

Co-Is: J. Johnson, C. Ball, A. O'Brien / OSU, M. French and M. Paolieri / USC ISI

Key Milestones

- Develop service API vocabulary (v1): Sep '20
  - Adopted OpenAPI (REST/HTTP)
  - JSON Object Schema
- Demonstrate sequential operation: Dec '20
  - Development servers operational
  - Virtualization containers (Docker)
- Demonstrate integrated operation : Mar '21
- Release updated software tools: Jun '21

Entry TRL: 3, Current TRL: 4

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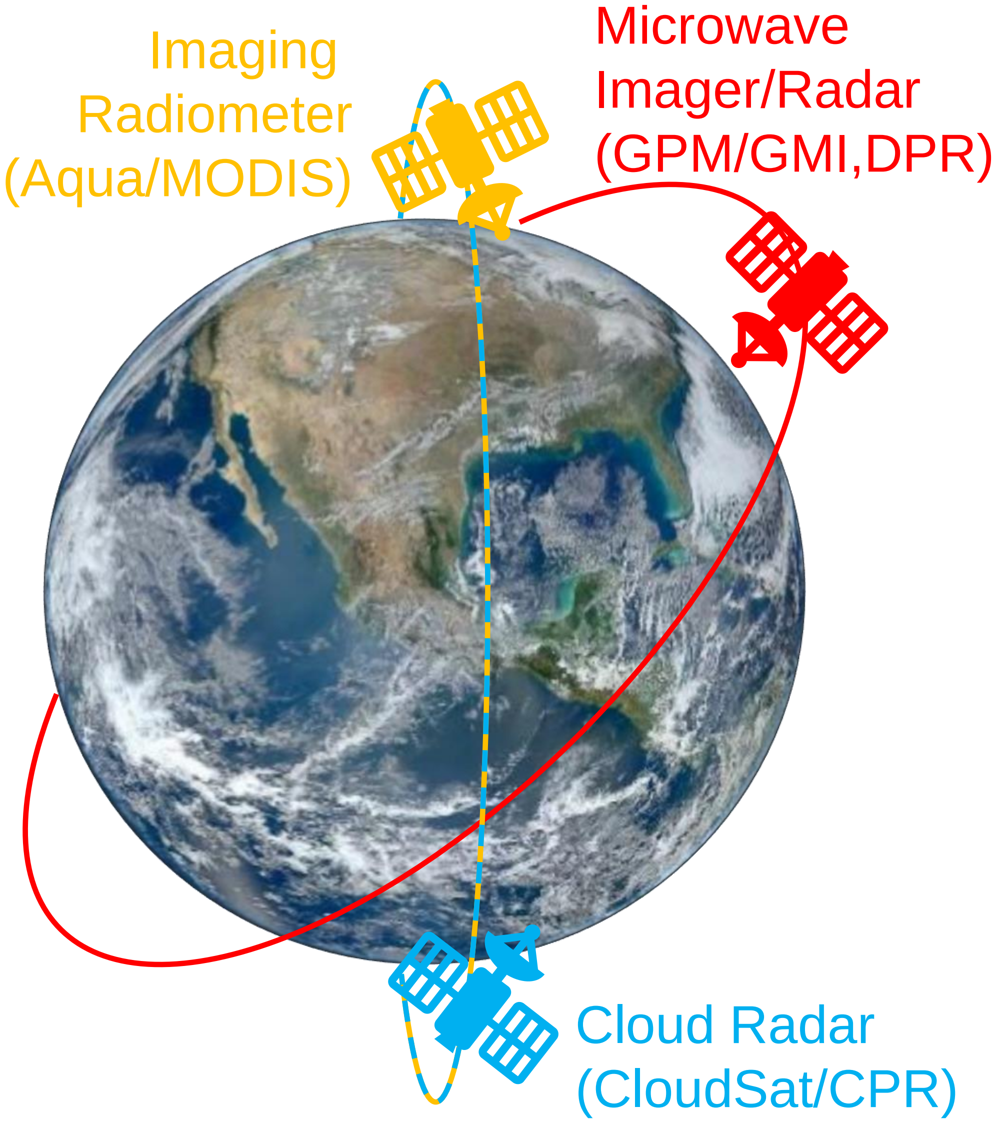
Reference Earth Science Mission Concept



How to design and evaluate an observing system with dynamic interactions among constituent nodes?

Passive: coincident measurements
- Calibration/validation
- Data assimilation

Active: responsive operations
- Cloud/precipitation screening
- Emergent event detection

Evaluate NOS technology:
- Adaptive operational processes
- Computing and networking

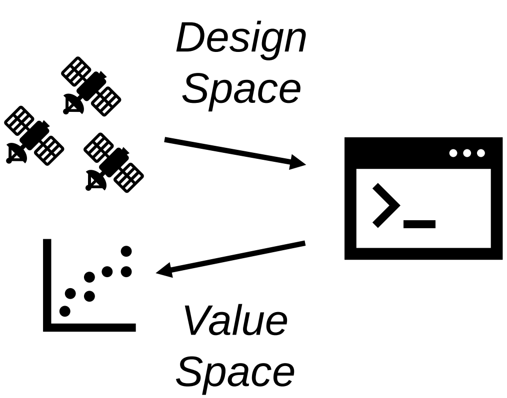
Background

Tradespace Analysis Tool for Constellations (TAT-C)

Enumerate and evaluate combinatorial design spaces for distributed space missions

- Order-of-magnitude cost
- Coverage statistics

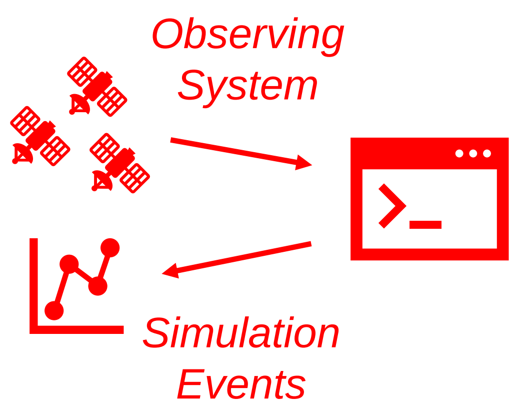
Limitations: each spacecraft evaluated independently



Simulation Toolset for Adaptive Remote Sensing (STARS)

Simulate autonomous and collaborative satellite networks

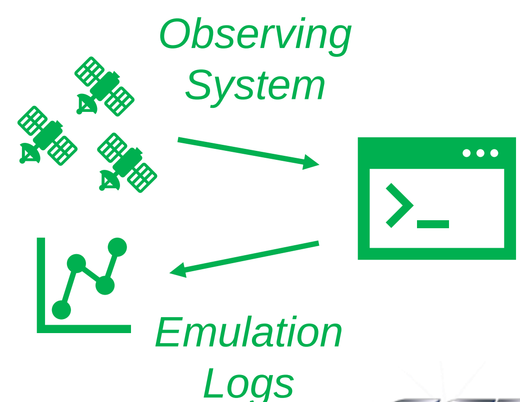
Observing system simulation experiments (OSSEs) to evaluate scientific return



Virtual Constellation Engine (VCE)

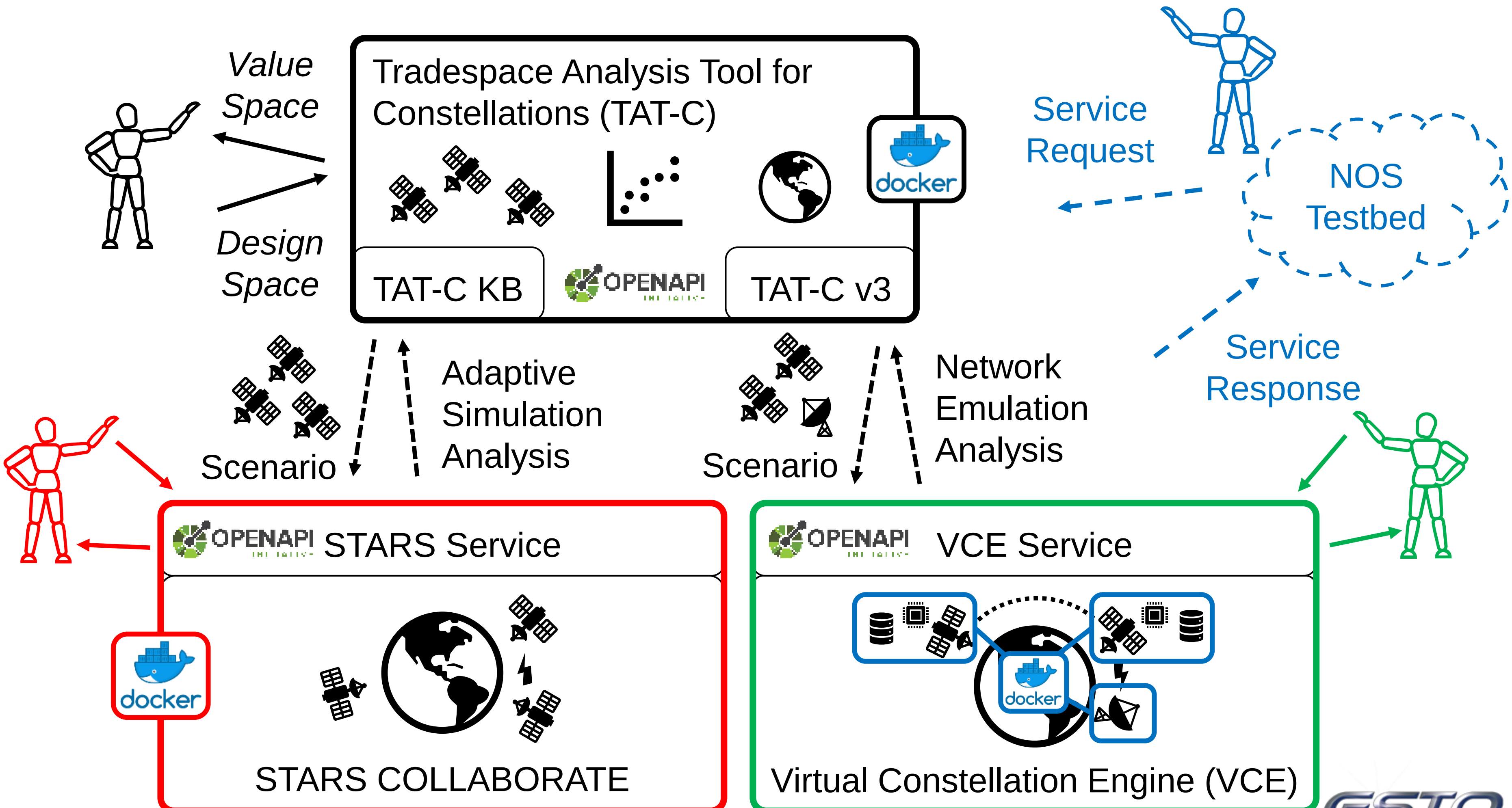
Emulate distributed, multi-satellite operations

Emulate network and instrument operation and monitor resource consumption



Project Objective

Integrate TAT-C, STARS, and VCE analysis capabilities to evaluate and mature mission concepts for New Observing Strategies (NOS).



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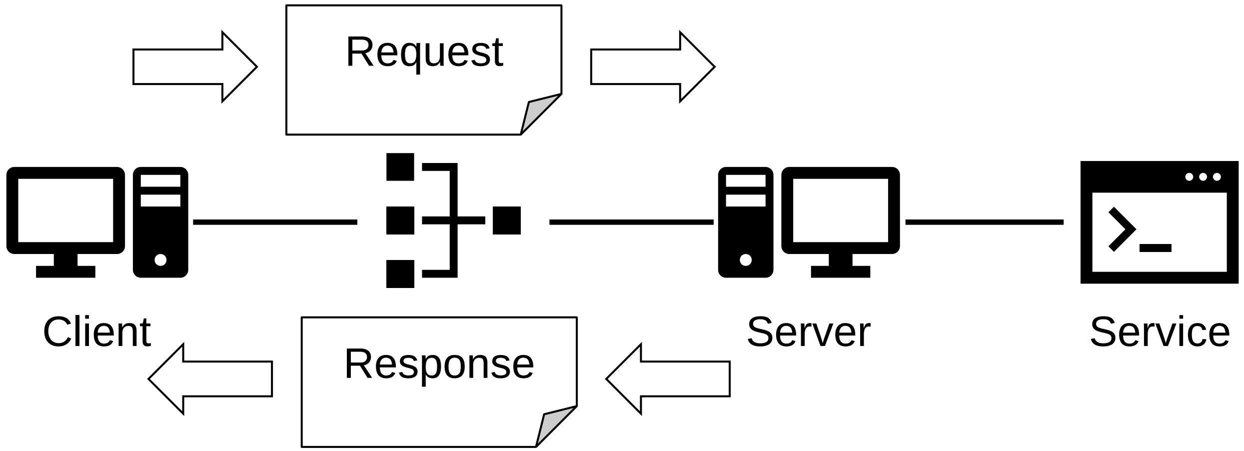
OpenAPI Standard

- Common adoption of OpenAPI (previously Swagger) standard to describe interfaces as HTTP requests
  - Documented in JSON or YAML format
  - Can be auto-generated from Python (Pydantic/FastAPI)

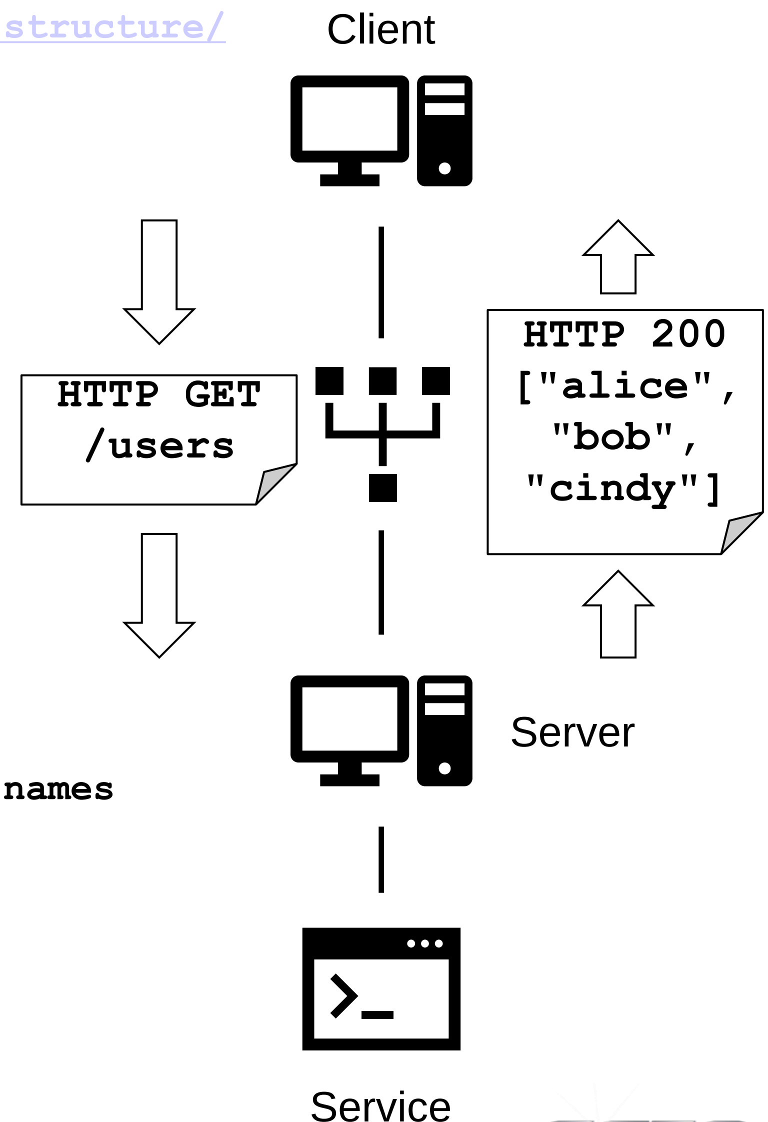


- Document *paths* as HTTP service endpoints
- Document *schemas* as request/response objects
- No software installation/configuration for clients

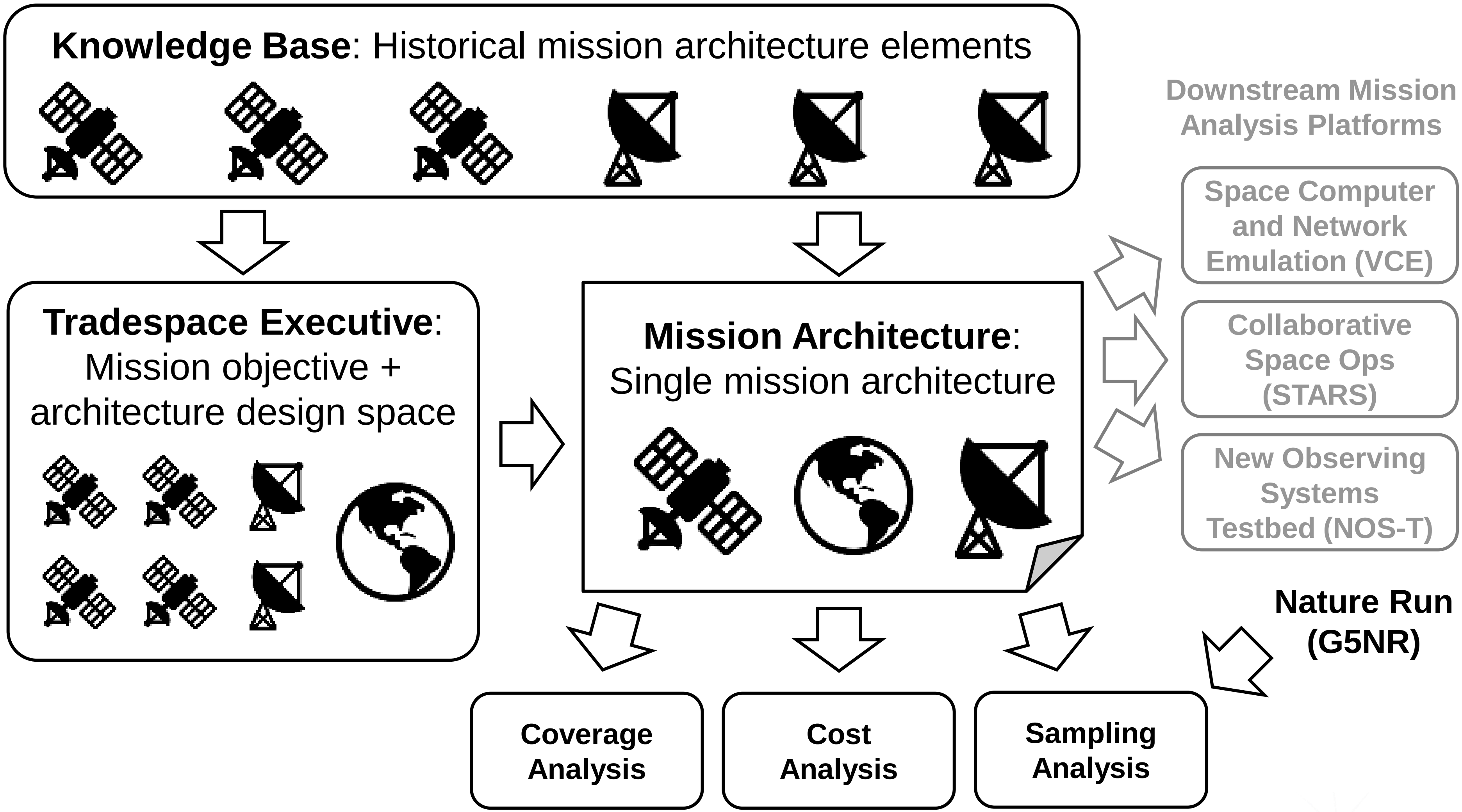
Simple OpenAPI Example

https://swagger.io/docs/specification/basic-structure/

```yaml
openapi: 3.0.0
info:
  title: Sample API
  description: Optional description.
  version: 0.1.9
servers:
  - url: http://api.example.com/v1
    description: Optional description.
paths:
  /users:
    get:
      summary: Returns a list of users.
      description: Optional description.
      responses:
        '200': # status code
          description: A JSON array of user names
          content:
            application/json:
              schema:
                type: array
                items:
                  type: string
```

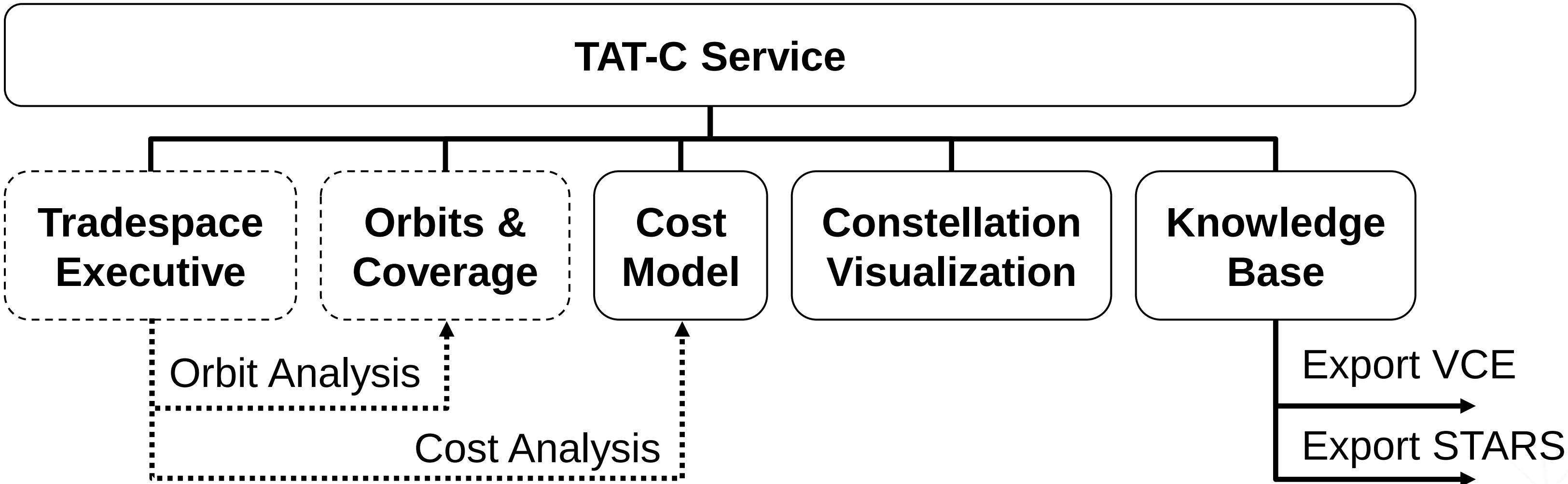


TAT-C Overview

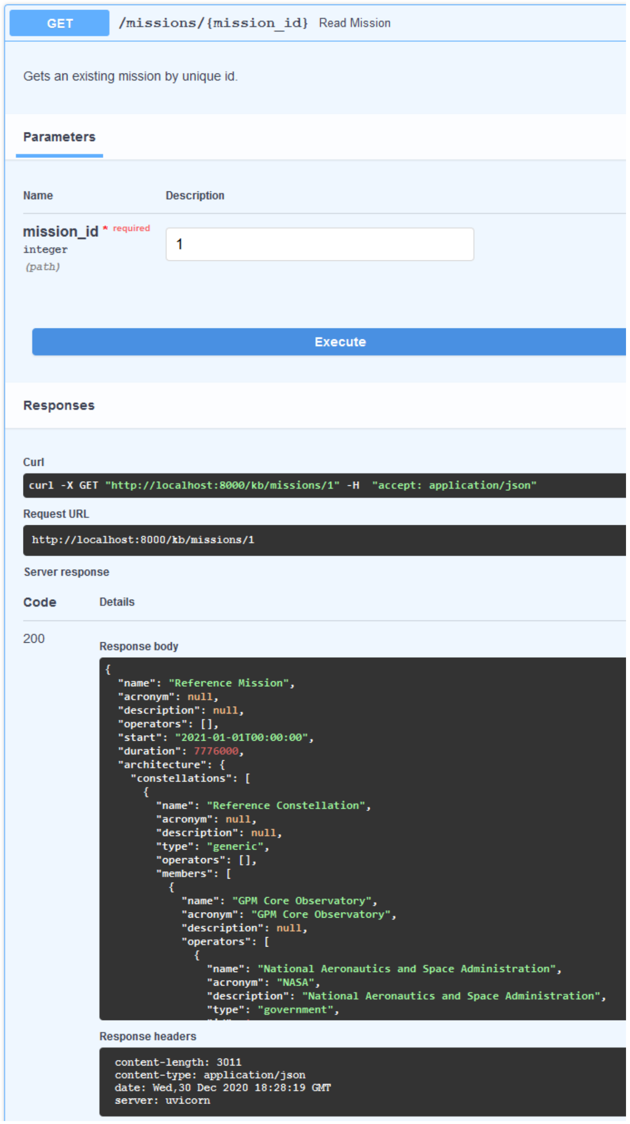


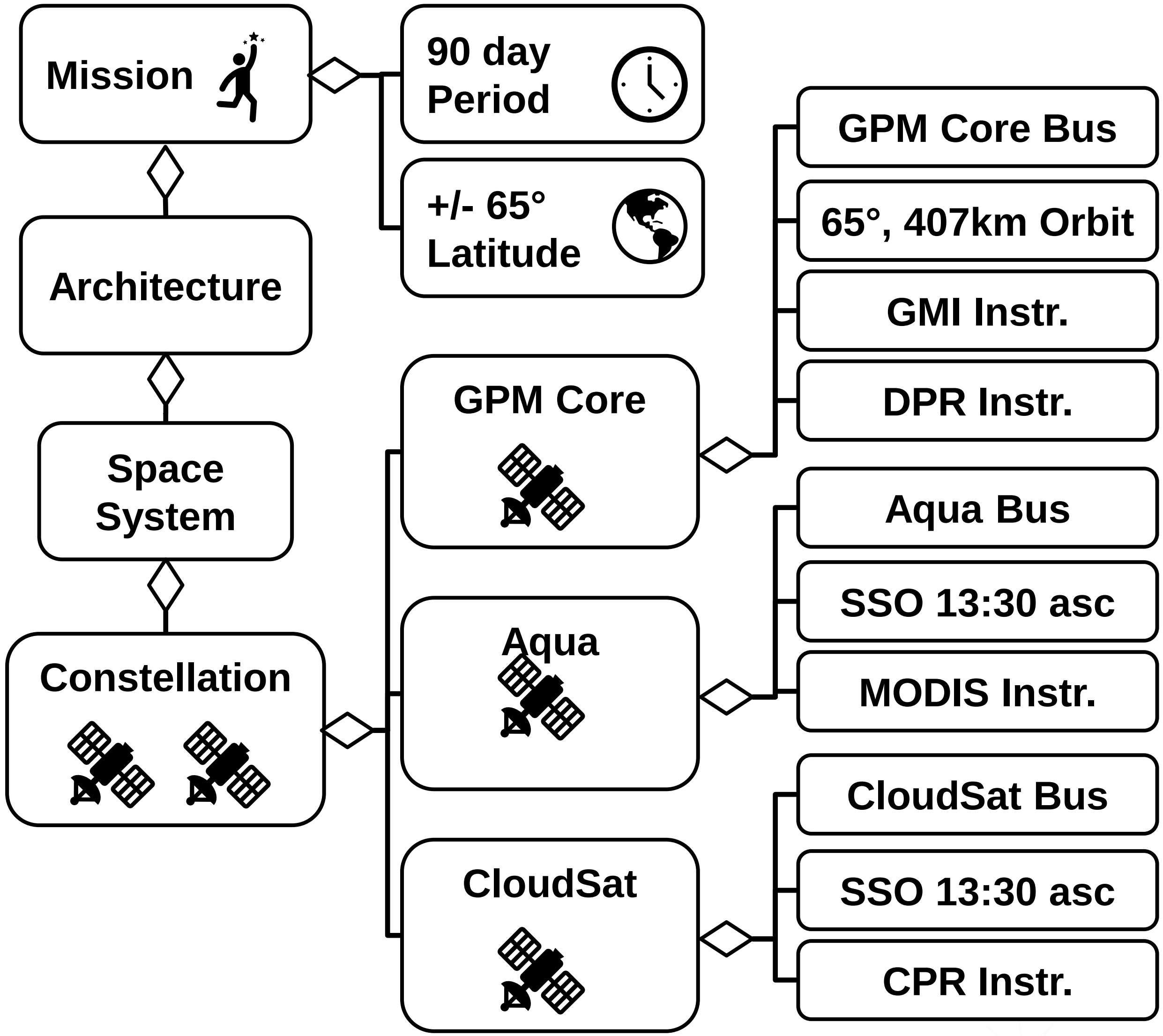
TAT-C as a Service

- Refactor TAT-C (v2) schema using OpenAPI and provide create/read/update/delete KB services
- Implement KB export services to convert from TAT-C (v3) schema to STARS/VCE schemas
  – Sequential operation: export from TAT-C to STARS/VCE
  – Integrated operation: use STARS/VCE in TAT-C workflow
- Refactor TAT-C (v2) modules to TAT-C (v3) services



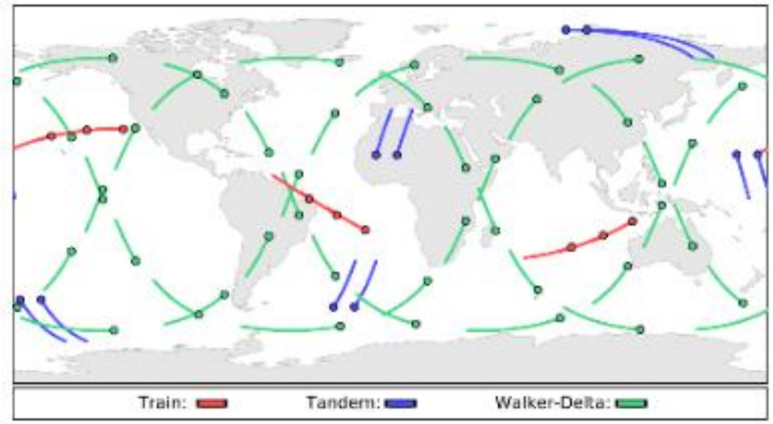
TAT-C (v3) Reference Mission Model

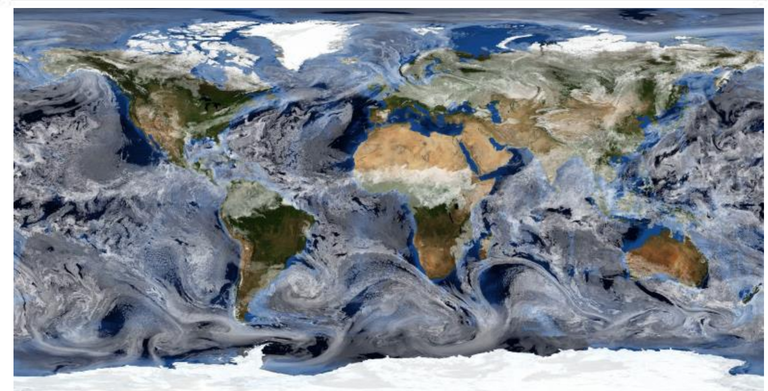


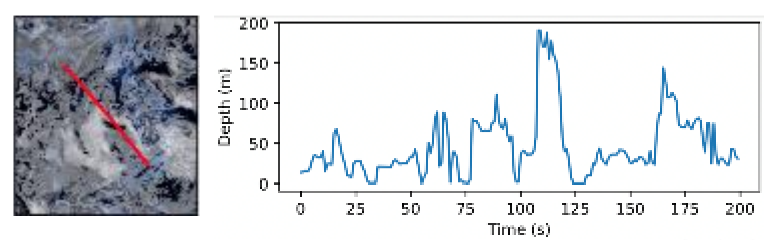


STARS - Overview

- **Simulation Toolset for Adaptive Remote Sensing (STARS)** enables simulations of heterogeneous, resource-constrained constellations for future Earth remote sensing applications
- Design constellations based on multiple instrument types in multiple orbit planes
- Model sensor performance using high-fidelity data (i.e. GEOS-5 Nature Run).
- Quantify science-value of current and predicted measurements
- Manage resources to perform collaborative observations.
- Model real communication interfaces and simulate collaboration/autonomy through network algorithms
- Complements features of TAT-C and VCE







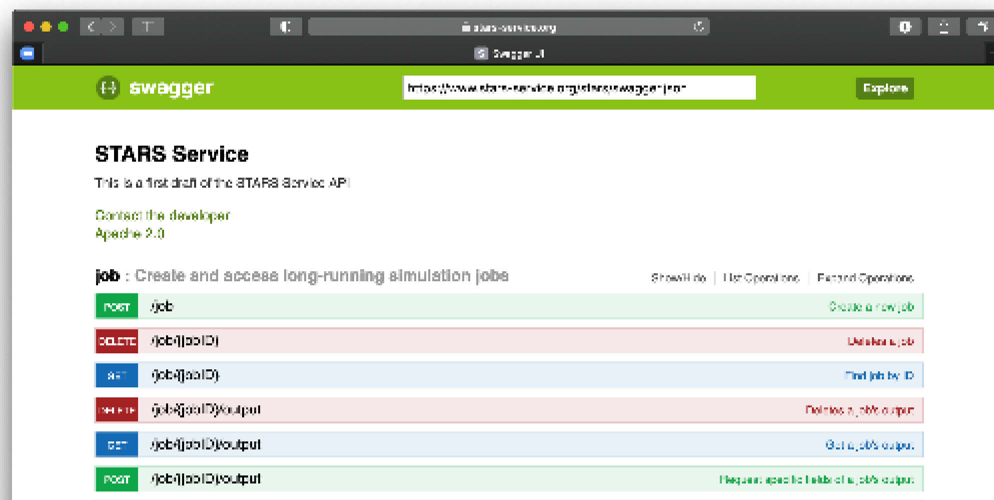
STARS as a Service

Our development effort has focused on creation of a new interface to the STARS simulation tools that allow it to be invoked as a service (by a user or by TAT-C).

- **Packaging STARS into a Container** – Our STARS C++ library was packaged into a portable Docker container that allows it to be easily distributed

- **Developing the STARS Service API** – The original STARS C++ library was intended to be used for development of new software. To create a service, we modified STARS to run as a program that can be accessed by a user. A STARS Service API (i.e. a REST API accessed using HTTP) was written and implemented.

- **Deploying STARS Service** – The STARS Service was deployed onto Amazon Web Services (AWS) for use by the TAT-C/STARS/VCE team. This provides a clear path to deployment onto NASA cloud platforms.



STARS Service Interface

- The user executes STARS simulations using simple configuration files. These files are specified in JSON format, which provides a human-readable form as well as a simple means for programs like TAT-C to access the service:

Example STARS Simulation Configuration

```
  "satellites": [
    {
      "label":"Example Constellation",

      "orbit_tle_file": { "orbit_type": "TLE_FILE", "tle_path": "input/tle/cubesat.tle", "tle_index": [0] },

      "payload": {

        "subsystem_antennas": [
            { "label": "comm_antenna", "antenna_dipole":{ "@type":"ANTENNA", "max_gain_db": 30} },
            { "label": "sensor_antenna", "antenna_helical":{ "@type":"ANTENNA", "max_gain_db": 30 } }
        ],

        "subsystem_sensing": [
            {
                "label":"sensor_cloud_radar",
                "sensor_cloud_radar": {"@type":"SENSOR", "path": "input/nc4/","duration_s": 10,"antenna_name": "sensor_antenna"}
            }
        ],

        "subsystem_comm": [  { "label":"UHF modem",  "comm_modem_rf": { "antenna_name": "comm_antenna"} } ],

        "subsystem_power": {
            "idle_power_w": 6.2425,
            "battery": { "cell_amp_hr": 0.9333, "num_cells": 6,  "voltage_v": 12.9,   "charging_efficiency_percent": 85},
            "solar_panels": [
```

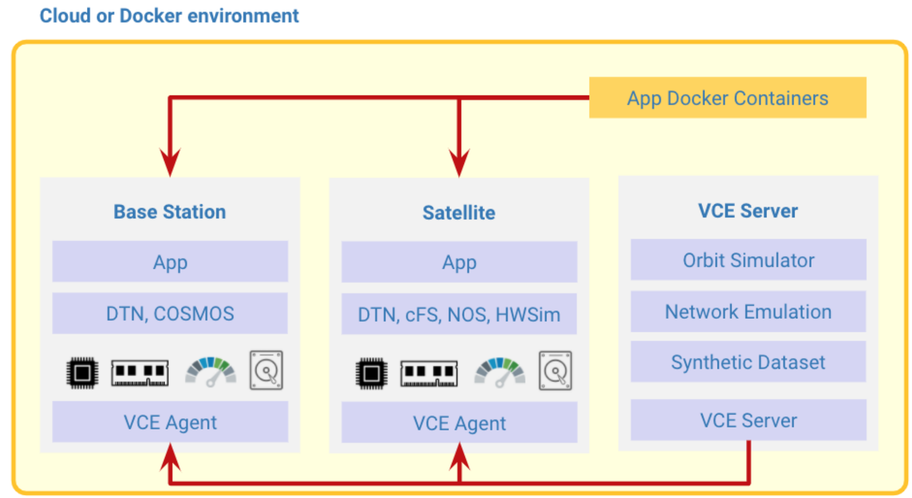
VCE - Overview

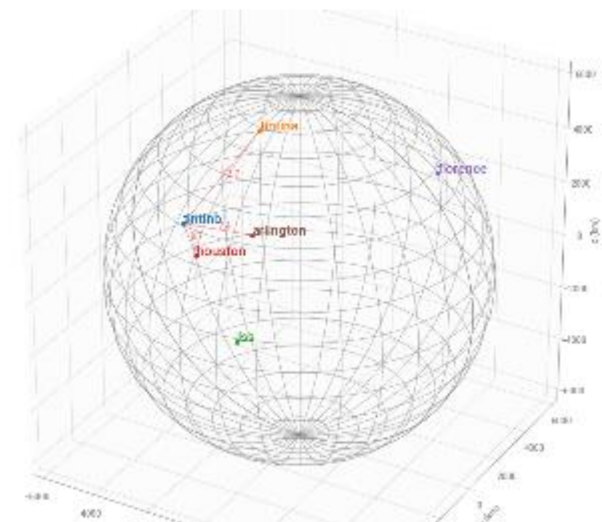
Virtual Constellation Engine (VCE) enables the emulation of distributed, multi-satellite applications.

VCE provides support for:

- Orbits propagation (from TLEs)
- Network latency/bandwidth emulation between nodes (satellites, stations)
- Emulation of instrument outputs (from user-provided time series)
- Monitoring of resource usage (CPU/memory/disk/network)
- Log collection from all nodes
- Use of cloud resource (GPU/FPGA) or local Docker containers

VCE runs a real distributed application in a controlled environment, gathers metrics/logs useful to evaluate correctness/performance





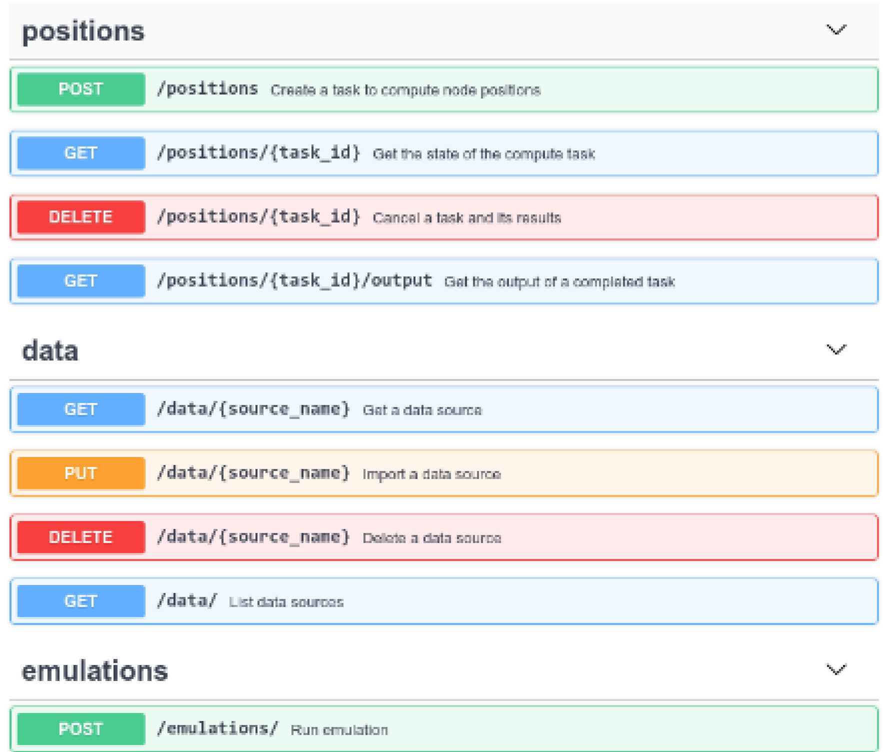
VCE as a Service

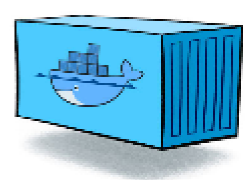
We developed a **REST API** to VCE

- Available to the user, allows full control of VCE
- Allows the integration of VCE with other tools such as TAT-C
- Every API endpoint documented through **OpenAPI**

Transition to Docker orchestration

- Goal: Allowing local emulations to facilitate use/integration of VCE
- Constellations can be run in multiple Docker containers on a single node
- In progress (required an extensive refactoring of VCE)





VCE Service Interface

Users or other tools can start VCE emulations through HTTP requests

- Inputs specified using JSON format (documented in OpenAPI)
- Input/output data (emulated sensor data or output metrics) provided as binary JSON (msgpack)


```
{
  "start_delay": 0,
  "duration": "50.0",
  "backend": "docker",
  "positions": {
    "start": "2020-01-21 16:40:00",
    "duration": "50.0",
    "step": "0.1",
    "orbits": [{
        "hostname": "iss",
        "tle1": "1 25544U 98067A   20019.89419477  .00000526  00000-0  17435-4 0  9998",
        "tle2": "2 25544  51.6459   7.1546 0004970 148.0163 296.3061 15.49574014208870"
    }],
    "stationary": [{
        "hostname": "wallops",
        "lat": "37.9239",
        "lon": "-75.4761",
        "alt": "10.0"
    }]
  },
  "nodes": [{
      "hostname": "iss",
      "cmd": "python app.py --sat",
      "image": "vce-stub:latest"
    }, {
      "hostname": "wallops",
      "cmd": "python app.py --ground",
      "image": "vce-stub:latest"
    }]
}
```


Example Configuration of VCE Emulation

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Current Accomplishments

- Adopted common web-based interface standard:
  - OpenAPI (formerly Swagger): standard, language-agnostic interface to RESTful APIs
  - Human- and machine-readable format
  - Supported by Python libraries for easy development
- Incrementally developed API services:
  - TAT-C KB endpoints (create, read, update, delete)
  - STARS service wrapper to build and execute simulations
  - VCE service to propagate orbits and configure emulations
- Development servers operational:
  - https://www.stars-service.org/
  - https://vce-framework.github.io/
  - https://tatc.code-lab.org/

Remaining Work

- Refine object schemas from integrated testing
- Refactor tool functionality to fully implement services
  - TAT-C: tradespace executive and orbit analysis
  - STARS: automatic compilation of simulation scenarios
  - VCE: full support for emulation using Docker backend
- Implement integrated operations to use STARS/VCE analysis in TAT-C architecture evaluation workflow
  - Trigger STARS/VCE analysis for selected architectures in a tradespace; store results and outputs as data appendices
  - Orchestration by TAT-C tradespace executive
- Improve service deployment and documentation
  - Docker containers to easily share services
  - Development servers to prototype and test services

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List of Acronyms

API	Application Programming Interface
HTTP	Hypertext Transfer Protocol
KB	Knowledge Base
NOS	New Observing Strategies
OSSE	Observing System Simulation Experiment
REST	Representational State Transfer
STARS	Simulation Toolset for Adaptive Remote Sensing
TAT-C	Tradespace Analysis Tool for Constellations
VCE	Virtual Constellation Engine

New Observing Strategies Testbed (NOS-T) Design and Development

Paul T. Grogan (PI, Systems Engineering Research Center)

ART-015 Group Technical Review

Contract No. W15QKN-18-D-0040, Task Order W15QKN20F0551

January 4, 2021

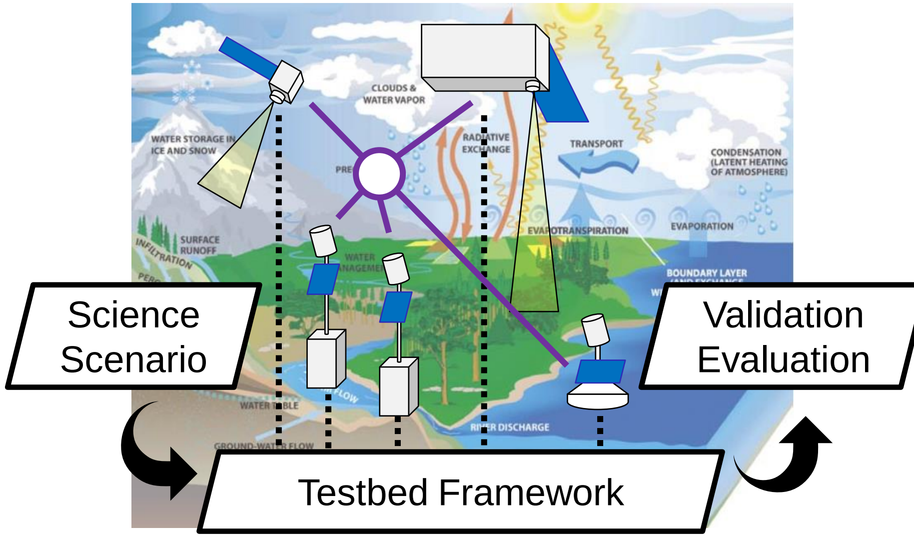
Jerry Sellers, Hayden Daly, Matthew Brand
(Systems Engineering Research Center)

New Observing Strategies Testbed (NOS-T) Design and Development

PI: Paul Grogan, Systems Engineering Research Center

Objective

- Design and develop the NOS-T framework for disparate organizations to propose and participate in developing NOS software and information systems technology capabilities and services
  - Individually validate new NOS technologies
  - Debug and demonstrate novel NOS concepts
  - Compare competing technologies
  - Socialize NOS technologies and concepts
- Identify appropriate NOS-T governance model
- Identify appropriate NOS-T concept of operations



Approach

- Enterprise system architecting processes
  - Identify and trace value streams for program objectives
  - Model-based systems engineering methods for traceability
- Loosely-coupled information system architecture
  - Achieve nonfunctional requirements such as modularity, extensibility, security, and scalability
  - Provide technical functions such as data distribution, time synchronization, and interoperability
- Engage with Earth Science community to support emerging NOS technologies and scenarios of interest
  - Adopt representative Earth Science use case
  - Demonstrate proposed NOS-T technology for community

Key Milestones

- Framework Design v1.0: Dec. '20
  - Initial architecture/governance/operations
  - Development plan
- Framework Architecture v1.0: May '21
  - Refine requirements
  - Propose architecture
- Framework Development v1.0: Feb. '22
  - Define representative use case
  - Perform framework demonstration
  - Develop Interface Control Document
- Framework Design v2.0: Nov. '22
- Framework Development v2.0: Aug. '23

Entry TRL: 2, Current TRL: 3

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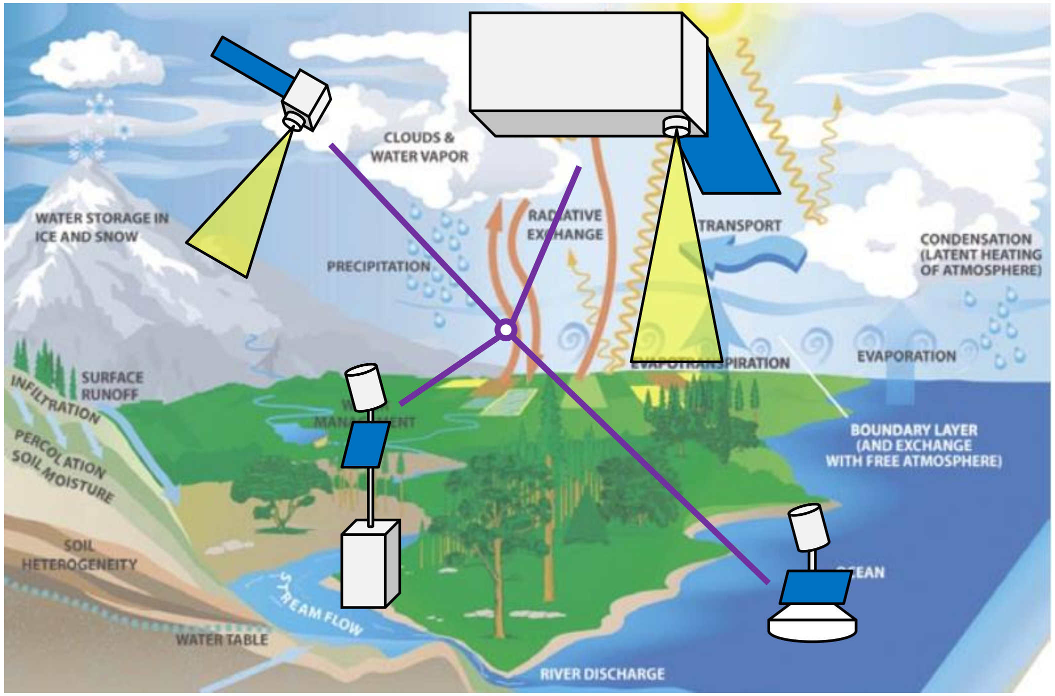
Background: New Observing Strategies Testbed (NOS-T)



- Validate NOS technologies, independently and as a system
- Demonstrate novel distributed operational concepts
- Enable meaningful comparisons of competing technologies
- Socialize new technologies and concepts with the science community by significantly retiring the risk of integration

NOS-T Framework Objectives

- **Enable disparate organizations to propose and participate in developing NOS software and information technology using the Testbed**
- Propose the NOS-T Framework Architecture:
  - Concept of Operations
  - Governance Model
  - Technical Protocols and Interfaces
- Iteratively develop system prototypes and demonstrate NOS-T operation for a representative Earth science mission with at least three nodes
  - Version 1.0 (18 months ending February 2022)
  - Version 2.0 (18 months ending August 2023)

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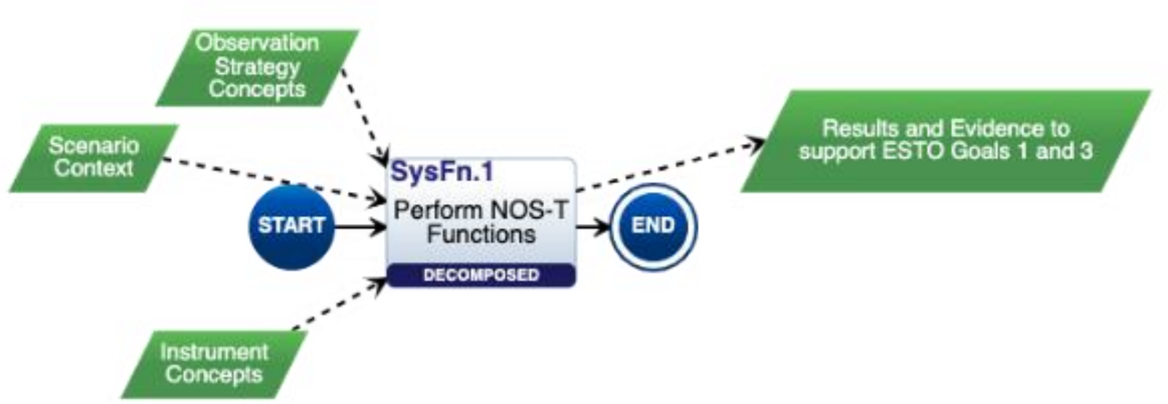
NOS-T Value Stream



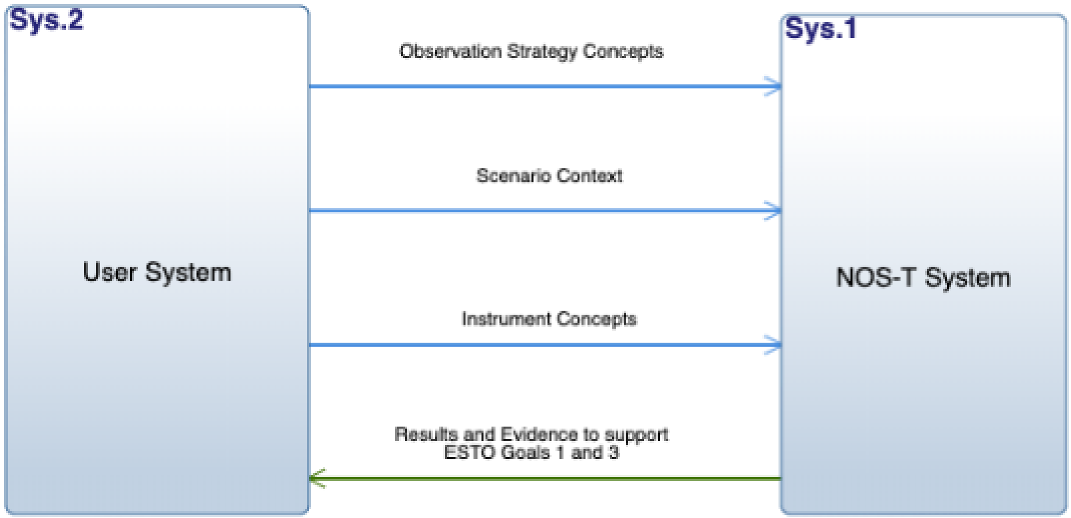
NOS-T Inputs:

- *Observing Strategy Concept*: system-of-systems definition
- *Instrument Concepts*: participating systems (nodes)
- *Scenario Context*: spatial and temporal configuration

NOS-T Outputs:

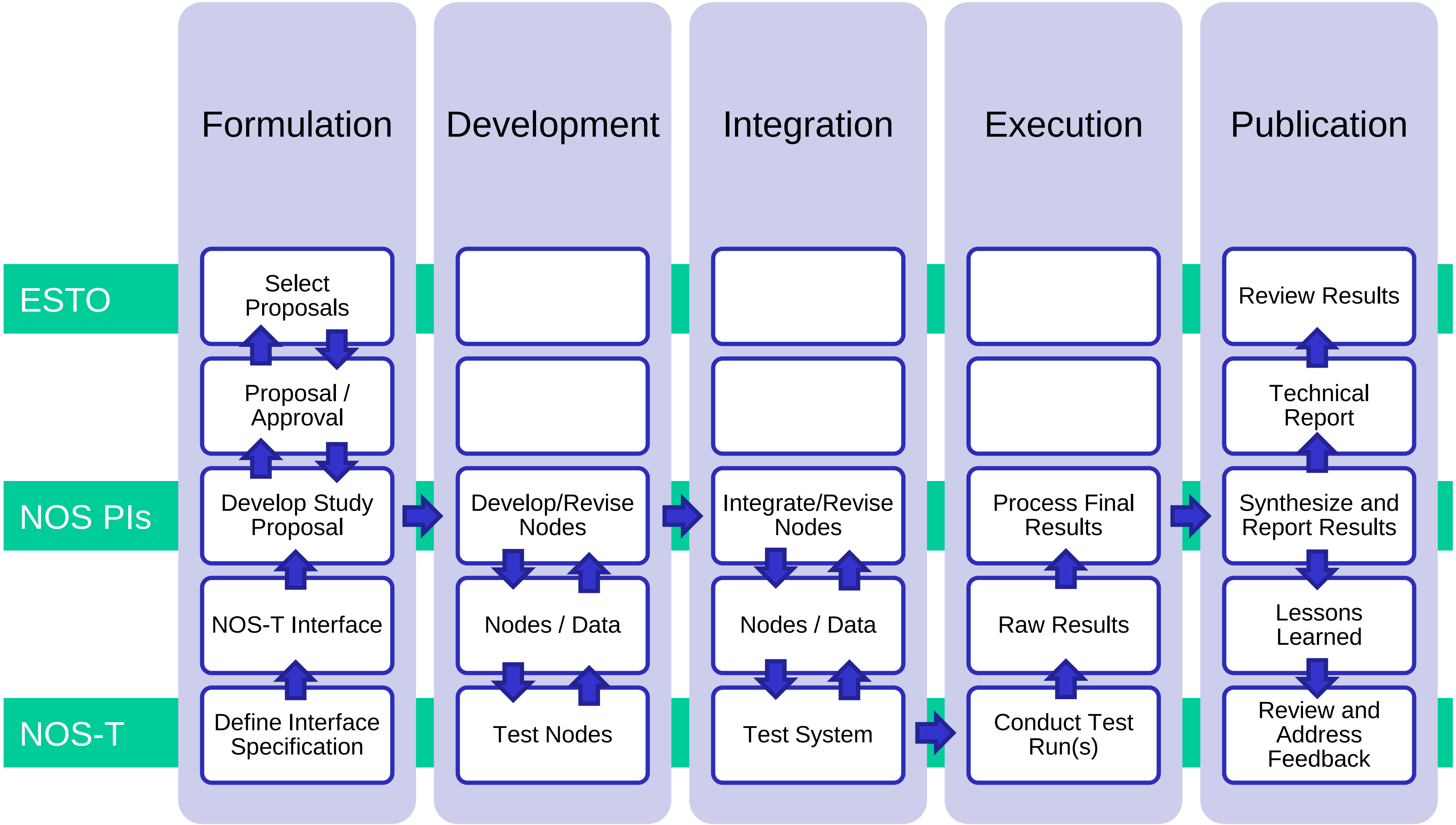
- Results and evidence to support ESTO goals:
  - Advance TRL of new technology
  - Improve or innovate measurement techniques

NOS-T Project System



- User System: managed by NOS-T user(s)
  - Provides inputs to NOS-T system
  - Post-processes outputs (data) from NOS-T system
- NOS-T System: managed by a NOS-T operator
  - Infrastructure to integrate inputs from user systems
  - Orchestrates execution of test runs to produce outputs

NOS-T Concept of Operations



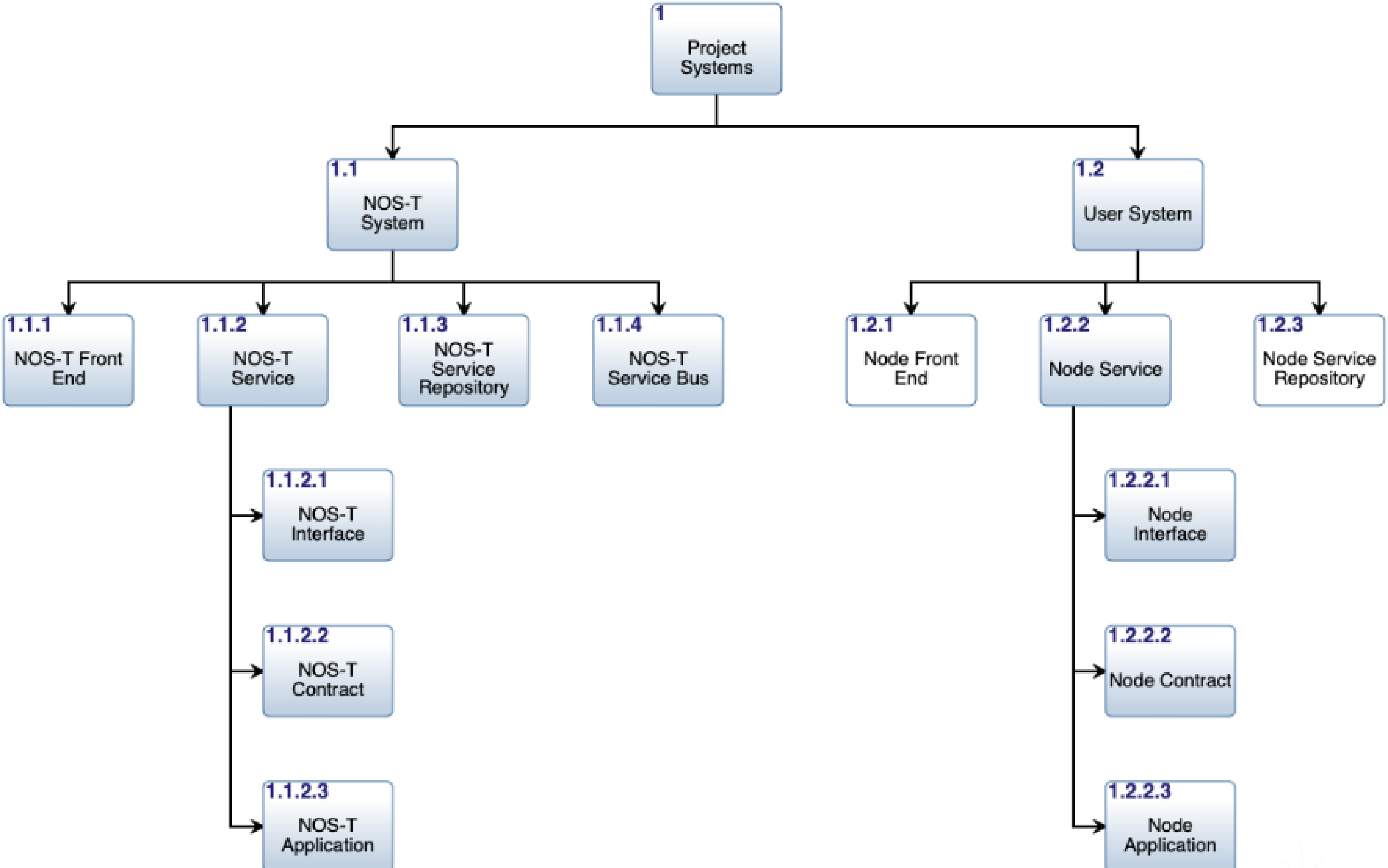
NOS-T Governance Functions

Budget

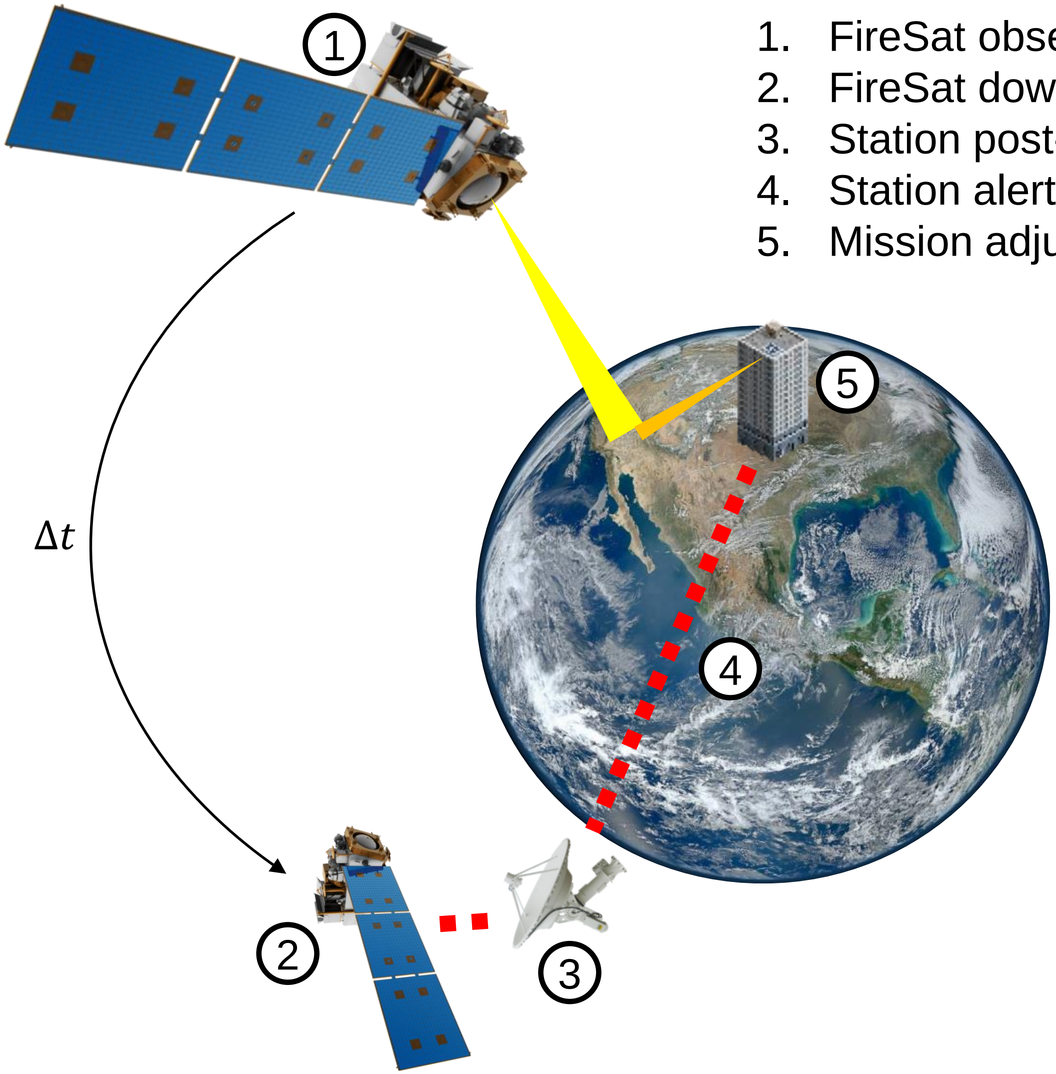
Fund and Review	Guidance, Administration Funding			Call for Proposals, Project Funding	
General Reporting	Administrate NOS-T	Personnel			Administration Requirements
	Internal Reporting	Operate NOS-T	NOS-T Access, Procedures, Personnel	NOS-T Interface	Operation Requirements
		Study SMEs	Execute Study	Raw Results	Execution Requirements
Proposals, Synthesized Results		Project Staff	System Nodes and Scenario Context	Propose and Analyze Study	Lessons Learned
		NOS-T Infrastructure, New Releases			Sustain NOS-T

Achieved Goals

NOS-T System Architecture

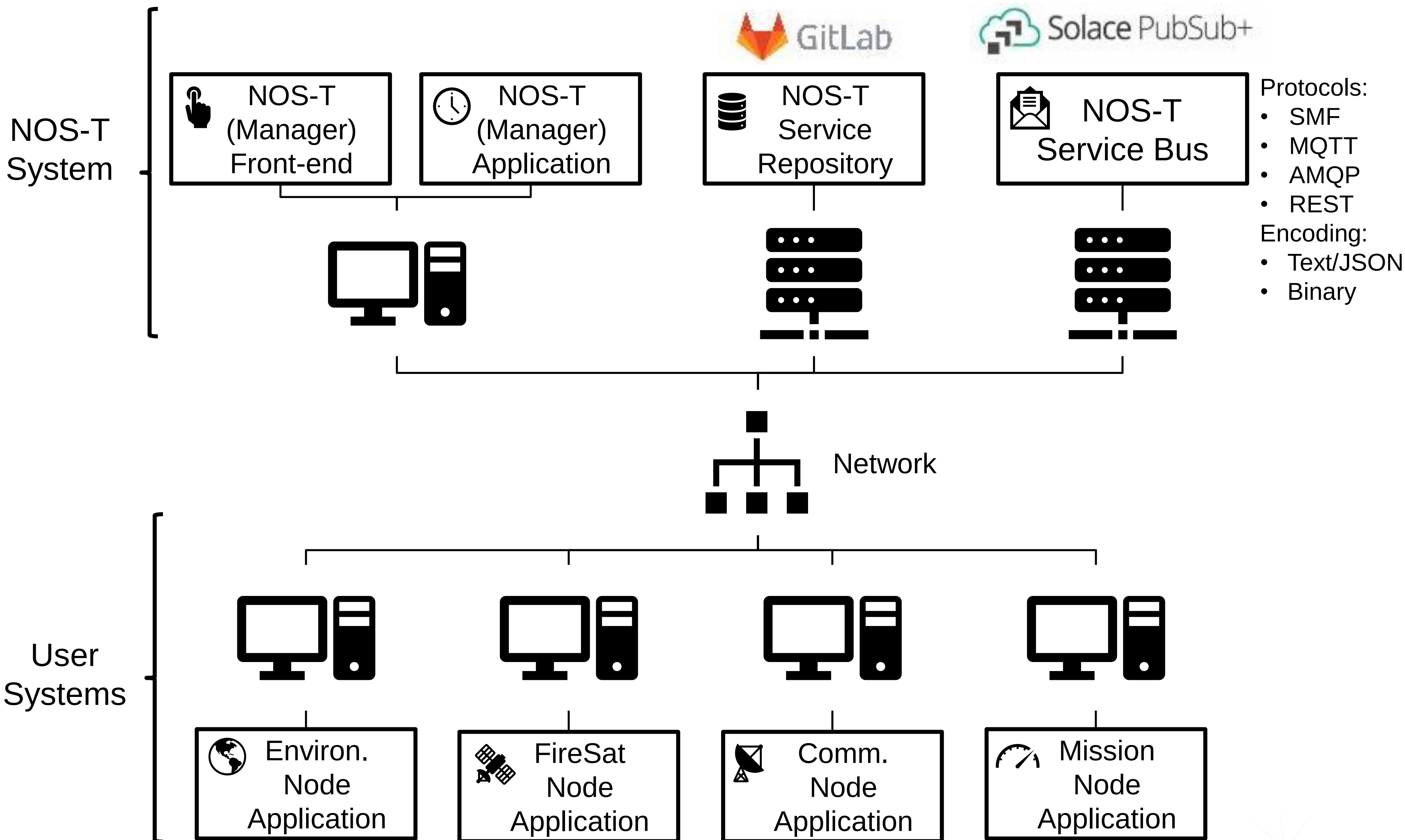


Reference Mission: FireSat

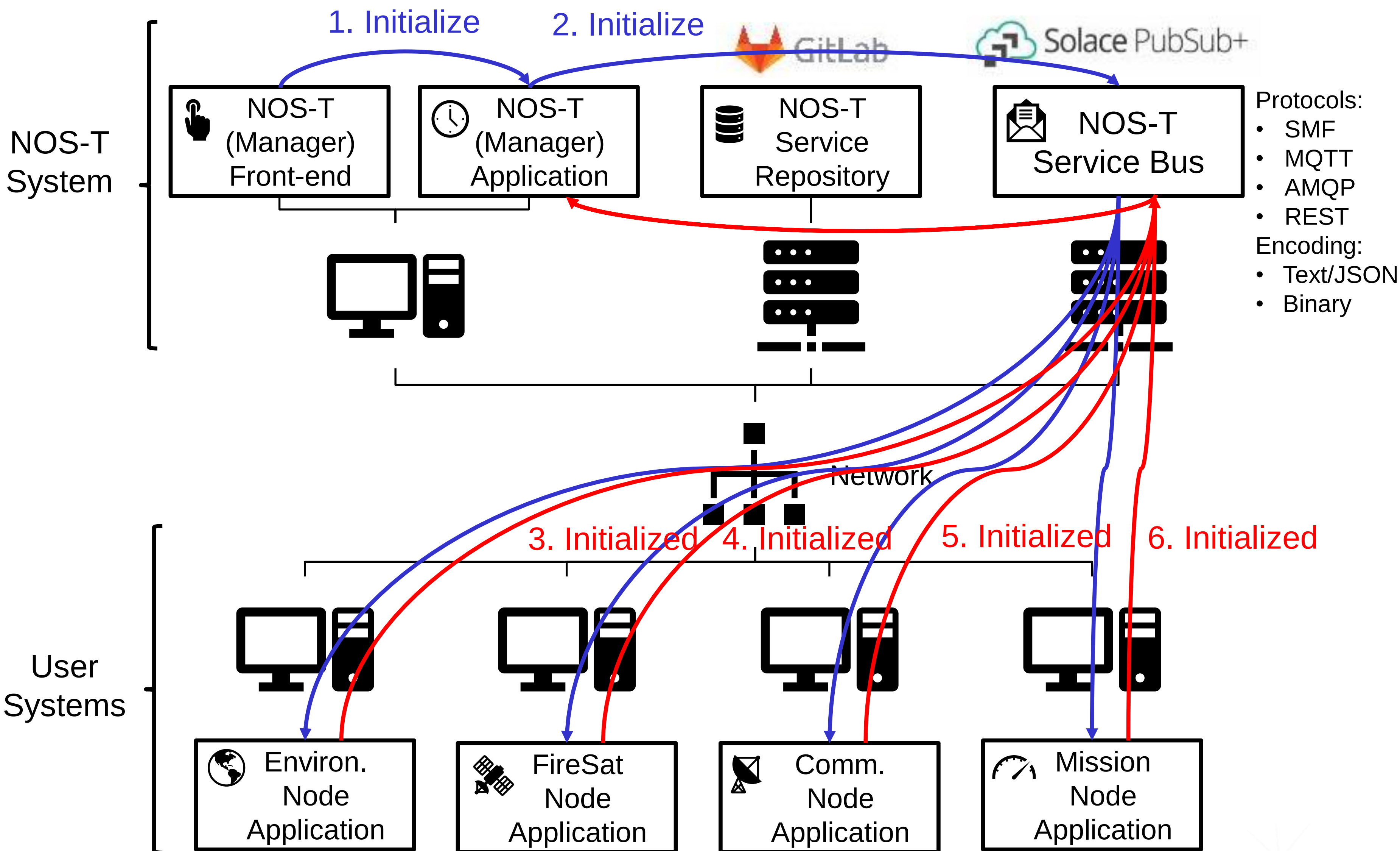


1. FireSat observes thermal signature
2. FireSat downlinks observation to station
3. Station post-processes data, identifies signature
4. Station alerts mission adjudicator
5. Mission adjudicator verifies and scores run

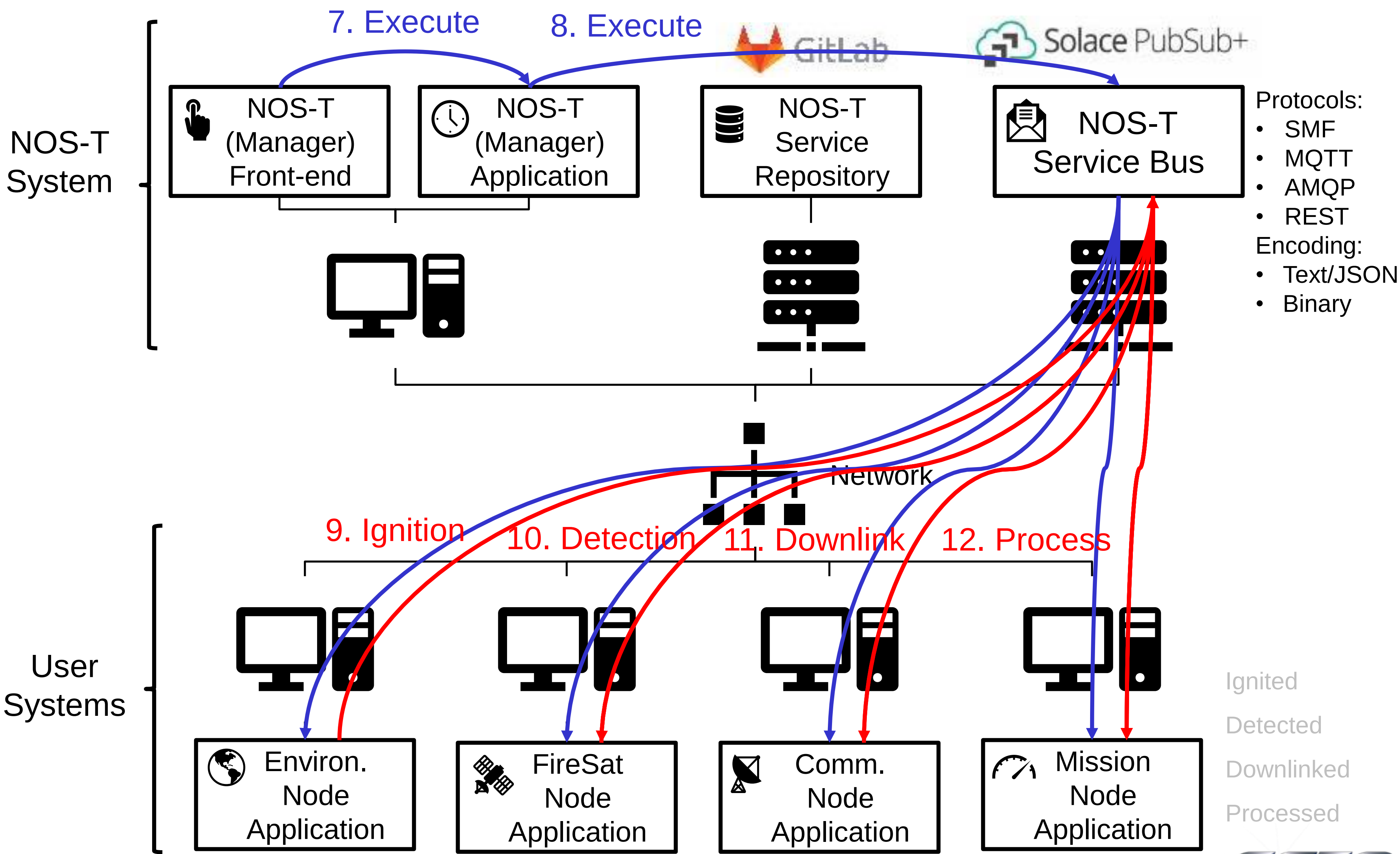
Preliminary Technical Architecture



Preliminary Technical Architecture



Preliminary Technical Architecture



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Current Accomplishments

- Defined NOS-T framework architecture components:
  - Value Stream and Project System
  - Concept of Operations
  - Governance Functions
- Defined preliminary technical architecture:
  - *NOS-T Front-end*: browser-based user interface dashboard
  - *NOS-T Service*: manager (Python implementation)
  - *NOS-T Service Repository*: GitLab source code repository
  - *NOS-T Service Bus*: Solace PubSub+ Message Broker
- Conceived of prototype user nodes:
  - Environment node
  - FireSat observation node
  - Communication node
  - Mission adjudication node

Remaining Work

- Incrementally develop core capabilities:
  - Execution time management
  - Message quality-of-service
  - Authentication/authorization
  - Execution environment (hybrid versus virtual)
  - Example applications and documentation
- NOS-T Framework Architecture Design (May '21)
  - Design document to formalize framework architecture
  - System architecture, concept of operations, governance model, technical implementation of common infrastructure, and key interfaces between NOS-T and user systems
- Demonstration of Initial Framework (Feb. '22)
  - Develops, integrates, and tests user-contributed nodes connected by common infrastructure
  - Release of NOS-T interface control document (v1.0)

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Publications

Presentations:

- P.T. Grogan and J.J. Sellers, "New Observing Strategies Testbed (NOS-T) Design and Development," 12th Annual SERC Sponsor Research Review, Virtual, Nov. 18, 2020.

Abstracts/Presentations:

- P.T. Grogan, "Co-Design and Co-Simulation Infrastructure for a New Observing Strategies Testbed," eLightning Talk, *2020 AGU Fall Meeting*, Virtual, Dec. 10, 2020.

List of Acronyms

AMQP	Advanced Message Queuing Protocol
API	Application Programming Interface
HTTP	Hypertext Transfer Protocol
JSON	JavaScript Object Notation
MQTT	Message Queuing Telemetry Transport
NOS	New Observing Strategies
REST	Representational State Transfer
SMF	Solace Message Format
SSL	Secure Sockets Layer
TLS	Transport Layer Security
TRL	Technology Readiness Level

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)

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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

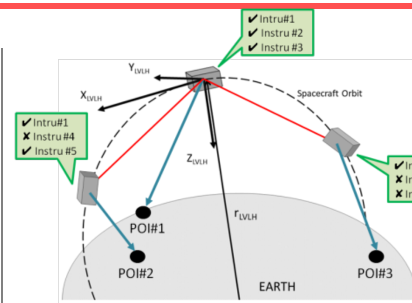
PI: Sreeja Nag, ARC and Bay Area Environmental Research Institute

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

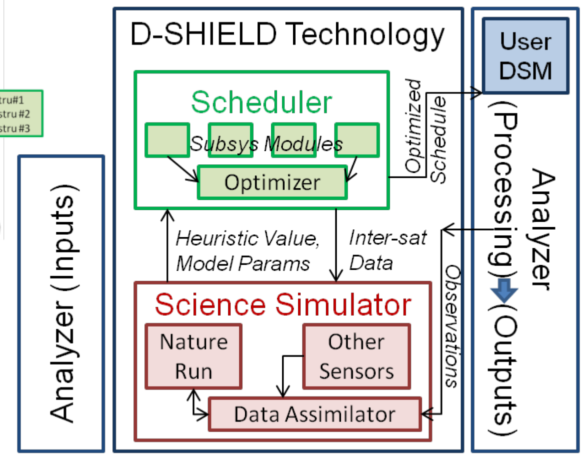
This project contributes to the New Observing Strategy (NOS) thrust area by developing an AI-based planning and scheduling-based DSM operations tool



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

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

Modular Technology and Assessment:



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

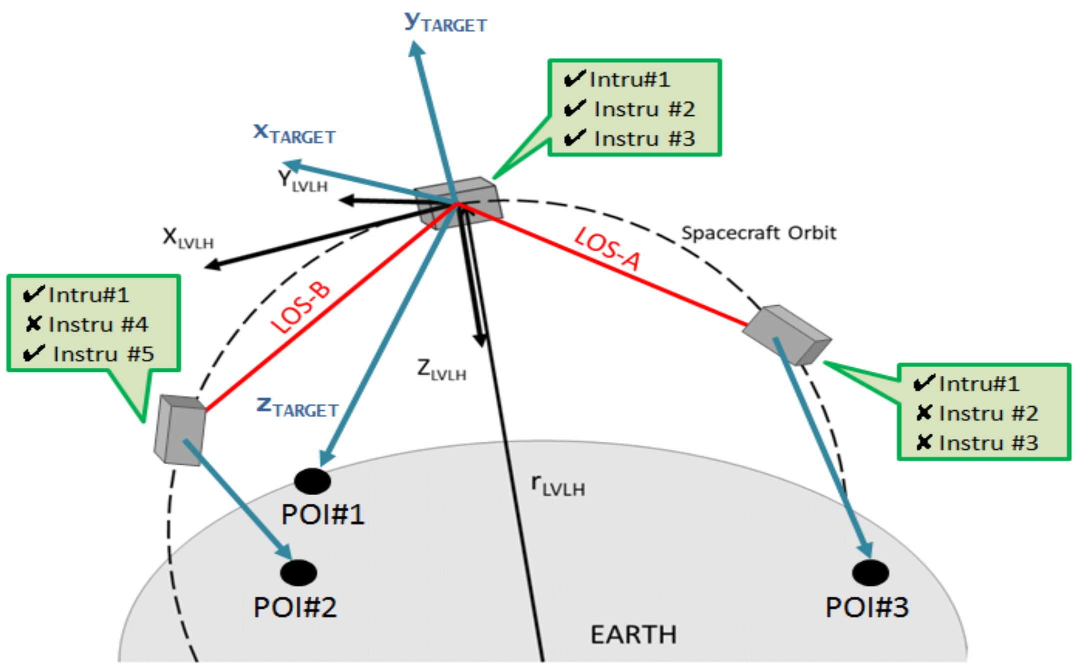
Presentation Contents

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

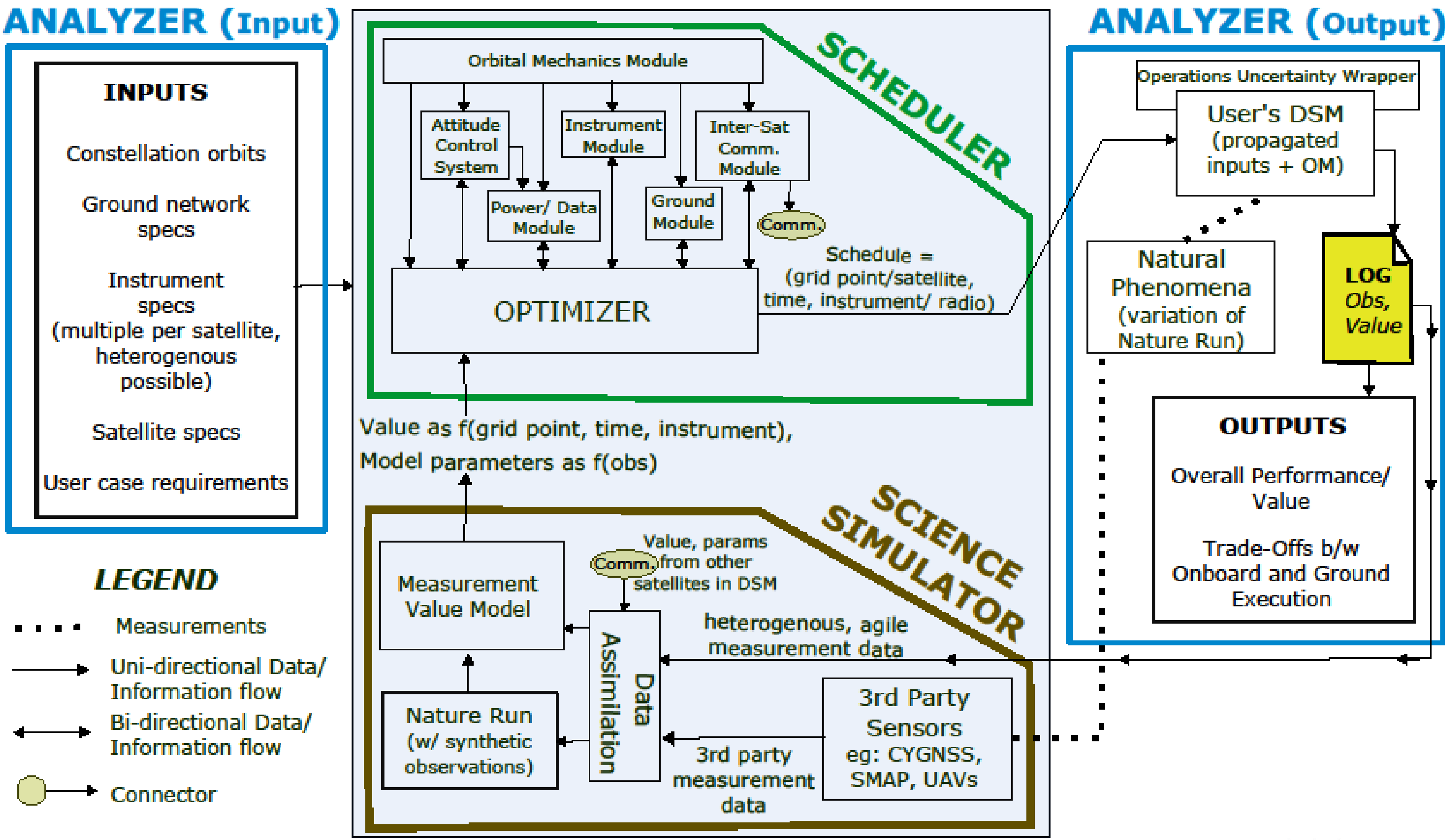
Background: Motivation

- 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



Presentation Contents

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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 (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

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

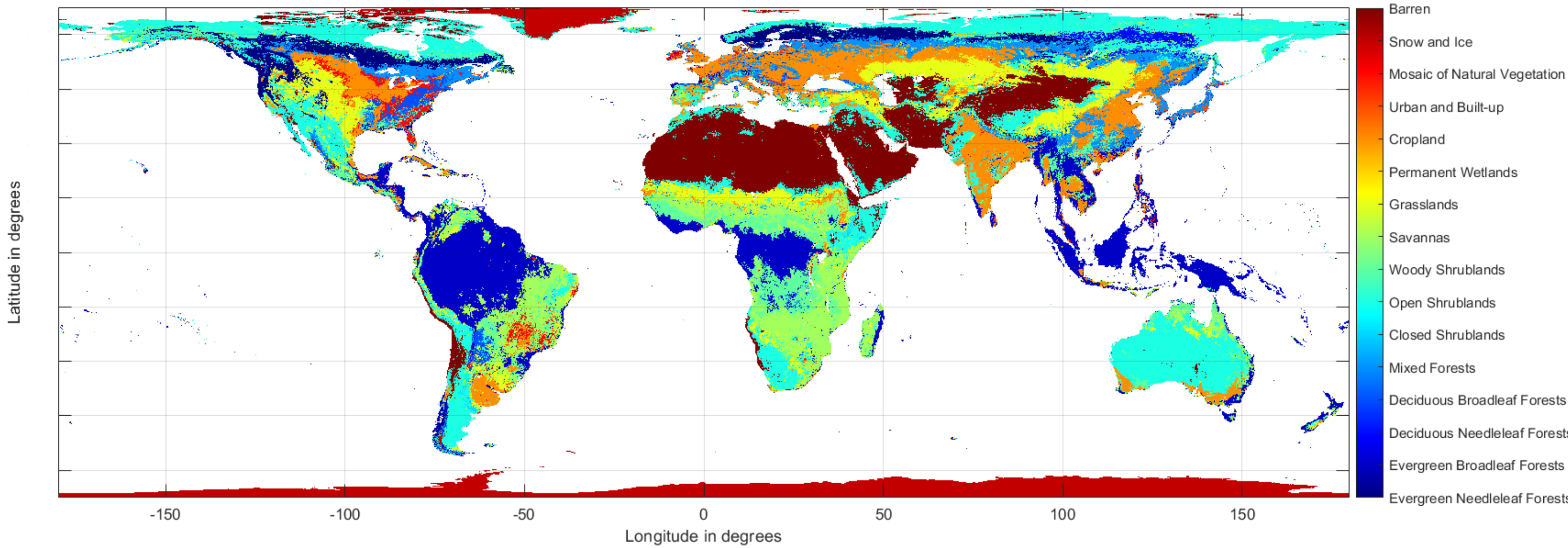
* ~7m AT and >250m CT resolution

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

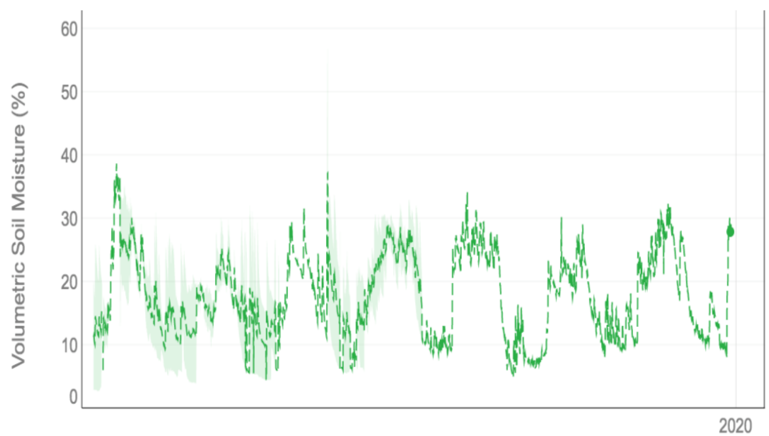
Soil Moisture Uncertainties

Sources of variation over the global 9km tile grid:

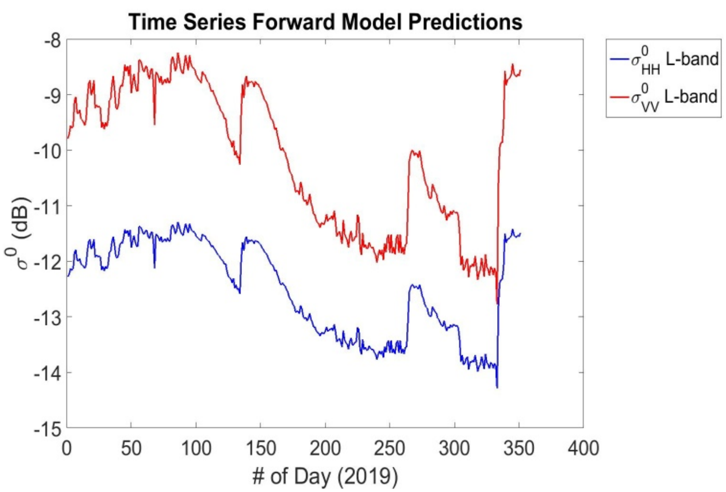
1. Soil type and vegetation
2. Season and solar conditions
3. Precipitation
4. Saturation of Soil

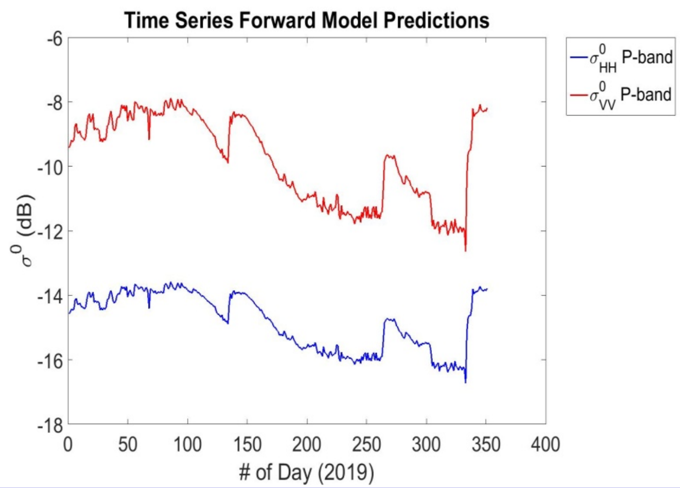
Will be accounted for in the speckle noise model of the science simulator

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*





Soil Moisture Uncertainties

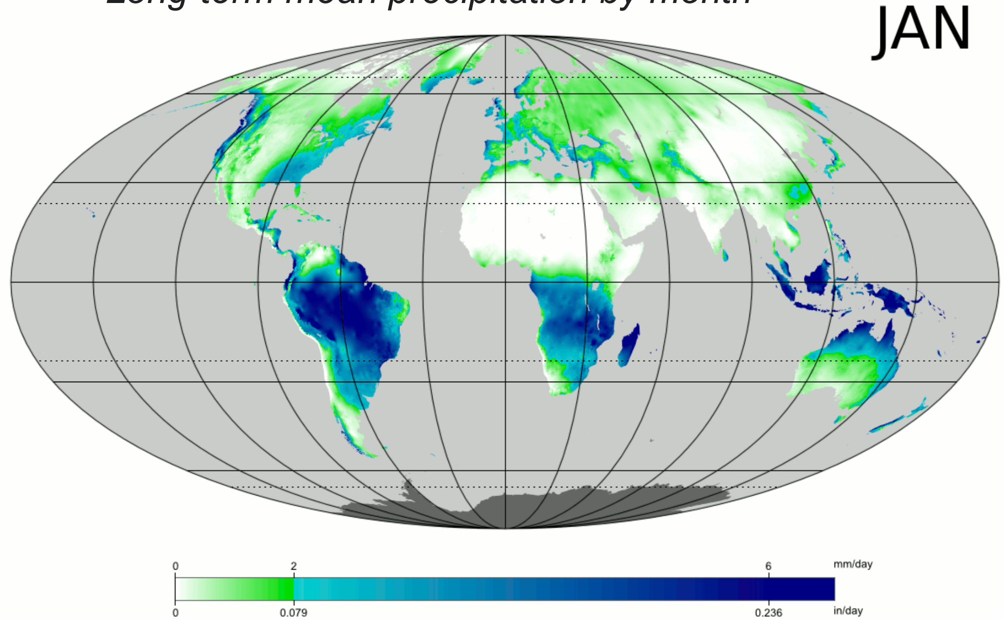
Sources of variation over the global 9km tile grid:

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

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…

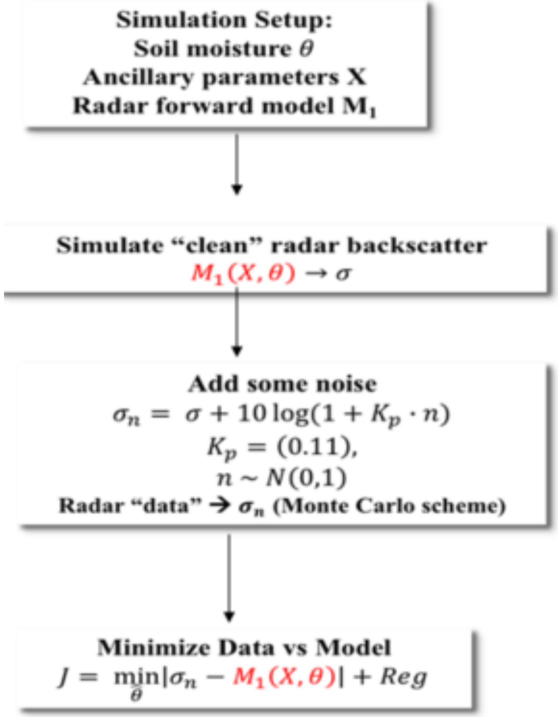
Long-term mean precipitation by month



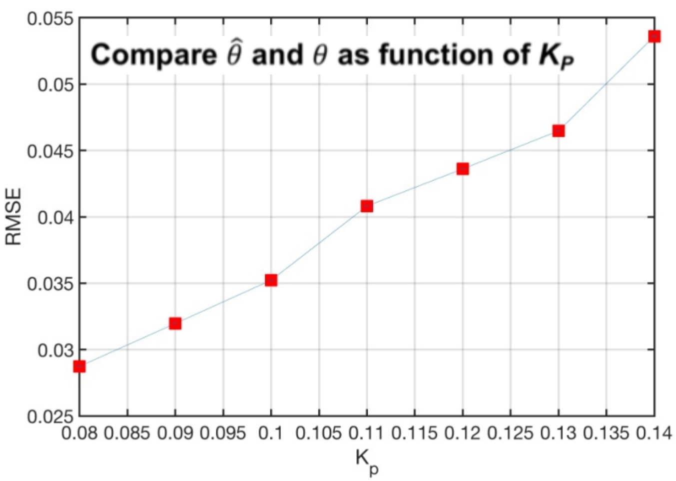
Website: https://gmao.gsfc.nasa.gov/GMAO_products/NRT_products.php
Forecast data: https://fluid.nccs.nasa.gov/weather/

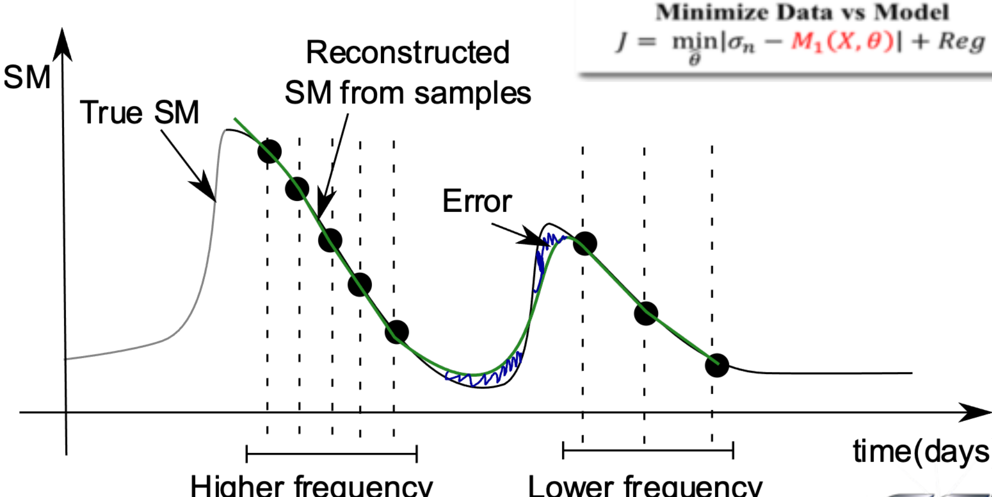
Addressing Temporal Resolution / Science Needs

- 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



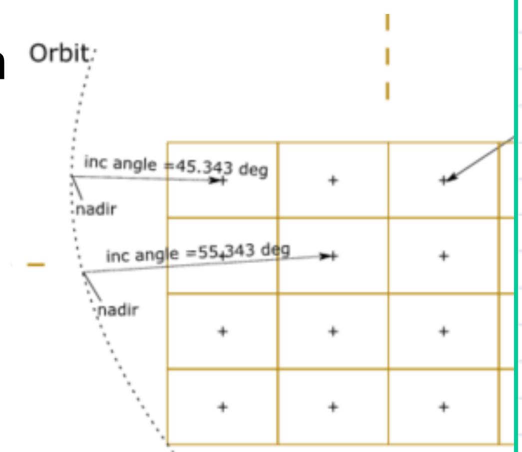
ΔT=2hours





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

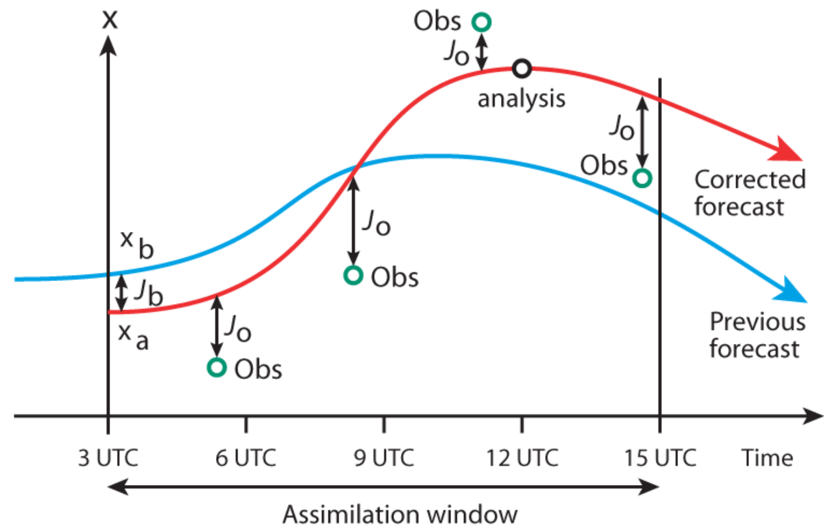
Alt: 500km	Instrument metrics, specs: *Instru #1* *L-band Quad-Pol SAR*	*Instru #2* *P-band Quad-Pol SAR*
Metric@35deg inc	*Value*	
NESZ [dB]	-40.69	-41.45
AT res [m]	6.67	4.54
CT res [m]	364.66	52.28
N looks/ km2	411.136504	4213.16598
Swath [km]	25	50
PRF [Hz]	2666	2406
Metric@45deg inc		
NESZ [dB]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

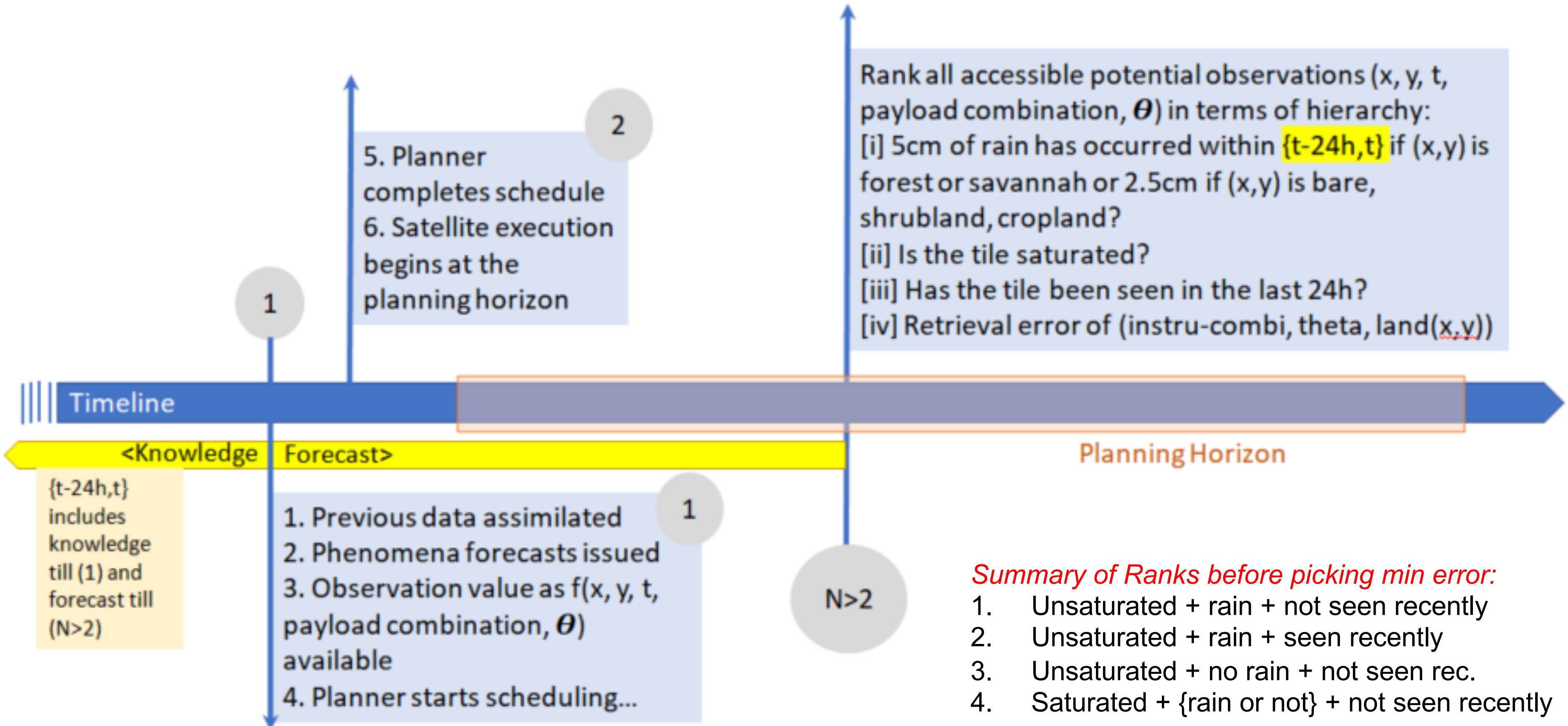
Shrubland, wet period

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:



Summary of Ranks before picking min error:

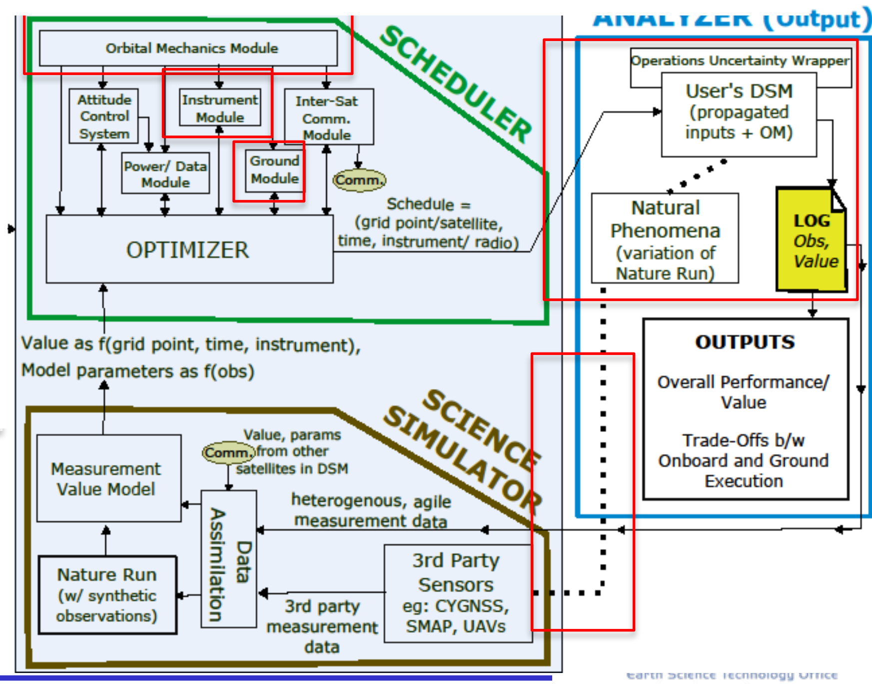
1. Unsaturated + rain + not seen recently
2. Unsaturated + rain + seen recently
3. Unsaturated + no rain + not seen rec.
4. Saturated + {rain or not} + not seen recently
5. Unsaturated + no rain + seen recently
6. Saturated + {rain or not} + seen recently

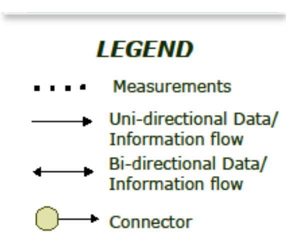
Observing System Model and Simulation

- 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:

*https://github.com/EarthObservationSimulator

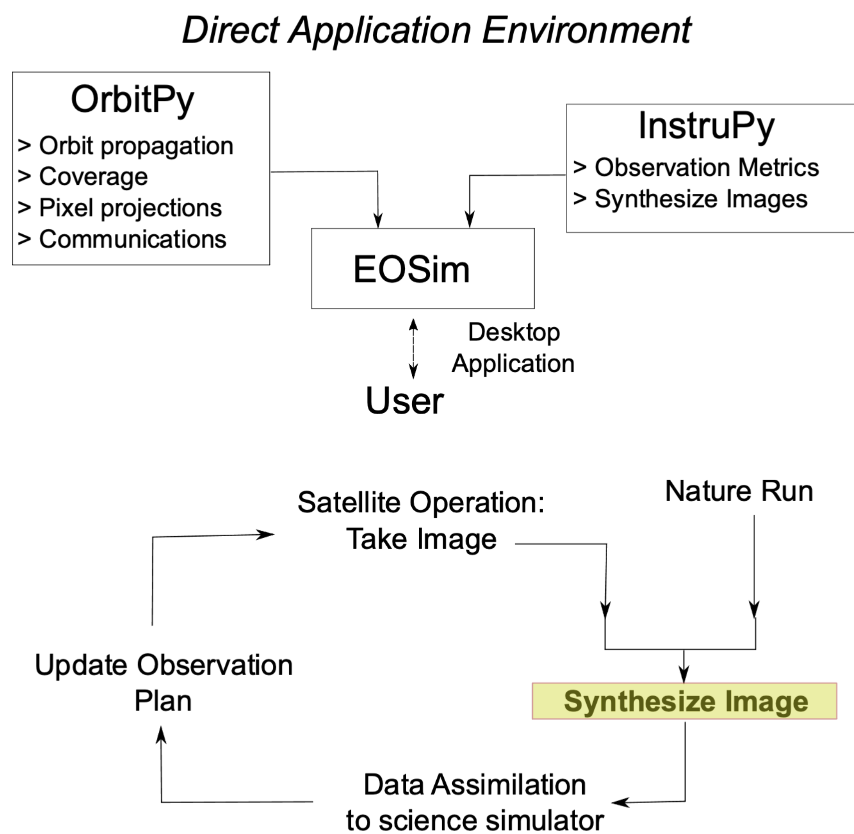
  - Desktop app w/ GUI and visualization options; modular w/ Python
  - Simulation of constellation missions (orbit and coverage) with multiple satellites, multiple and heterogenous distribution of instruments per satellite and across the constellation.
  - Simulation of inter-satellite and ground-station comm links.
  - Synthetization of artificial satellite imagery from DBs



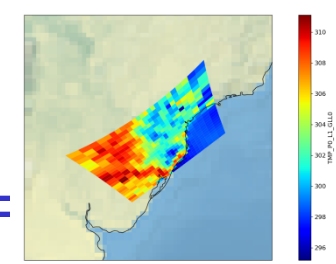


Observing System Feedback to Science Value

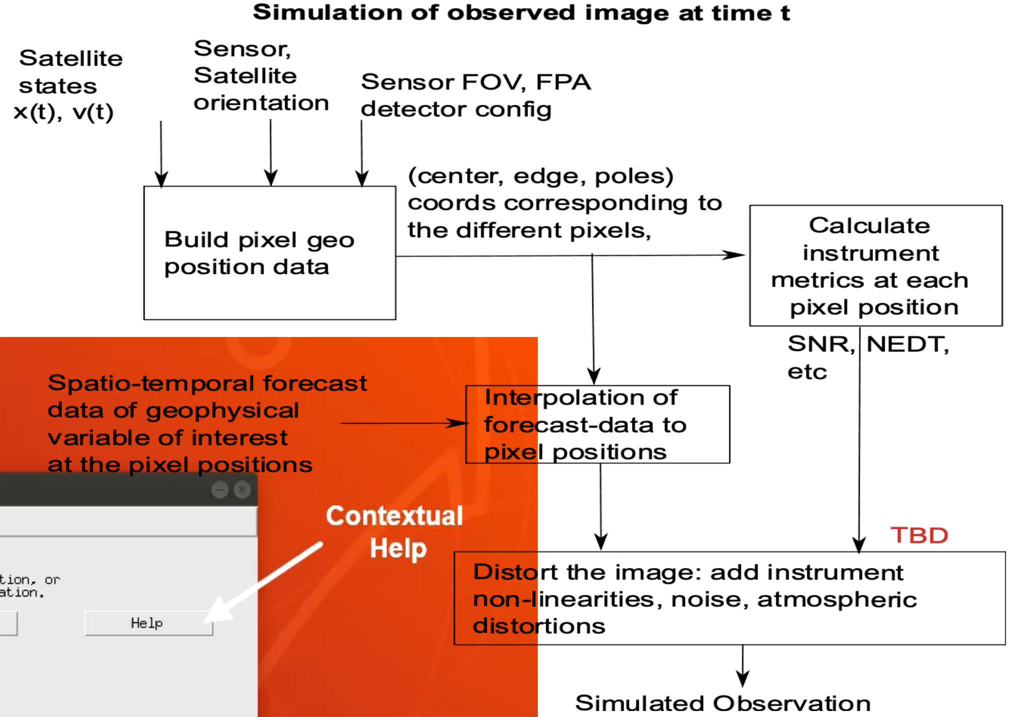
- OrbitPy module* is a significant improvement to our AIST 2014 work for TAT-C (GMAT open source)
- InstruPy* module is a significant add-on to our AIST 2016 work
- EOsim module with ability to couple the two with nature run sub-sampling for science value
- Built with Python, C++, JS with the support 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….

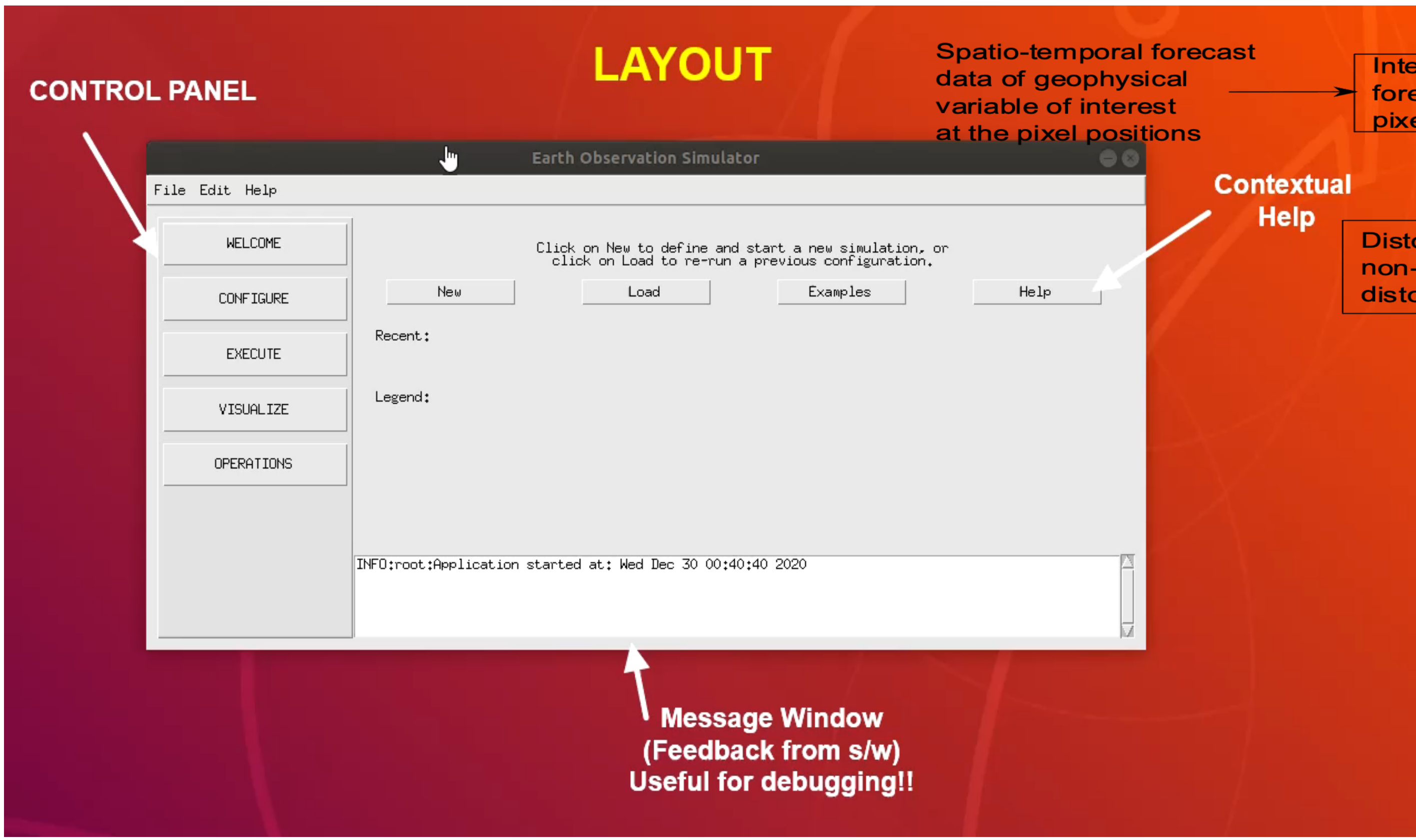


* https://orbitpy.readthedocs.io/
https://instrupy.readthedocs.io/



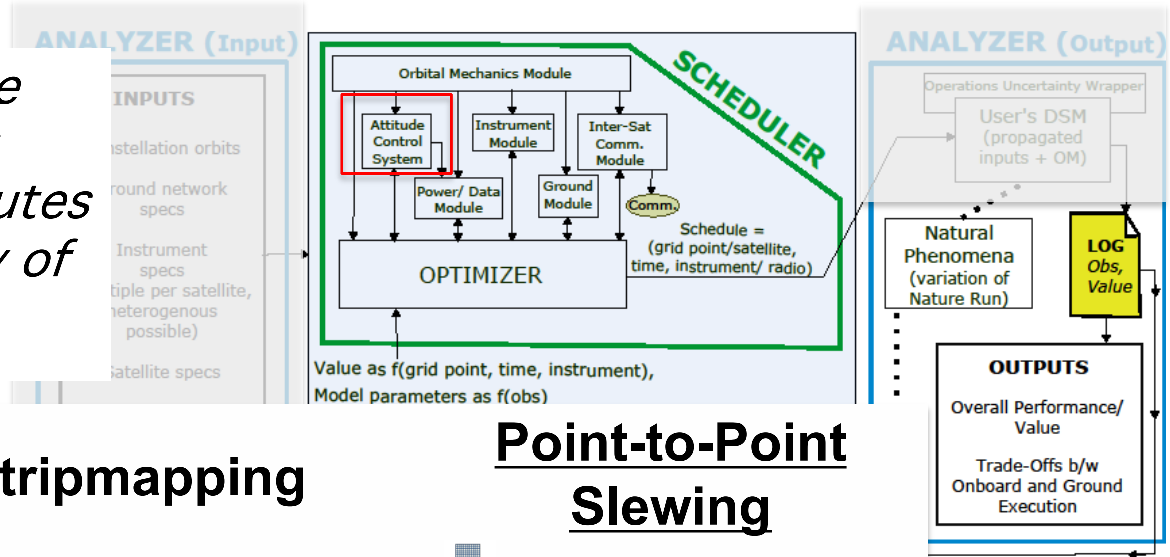
Observing System Feedback to Science Value (Demo)

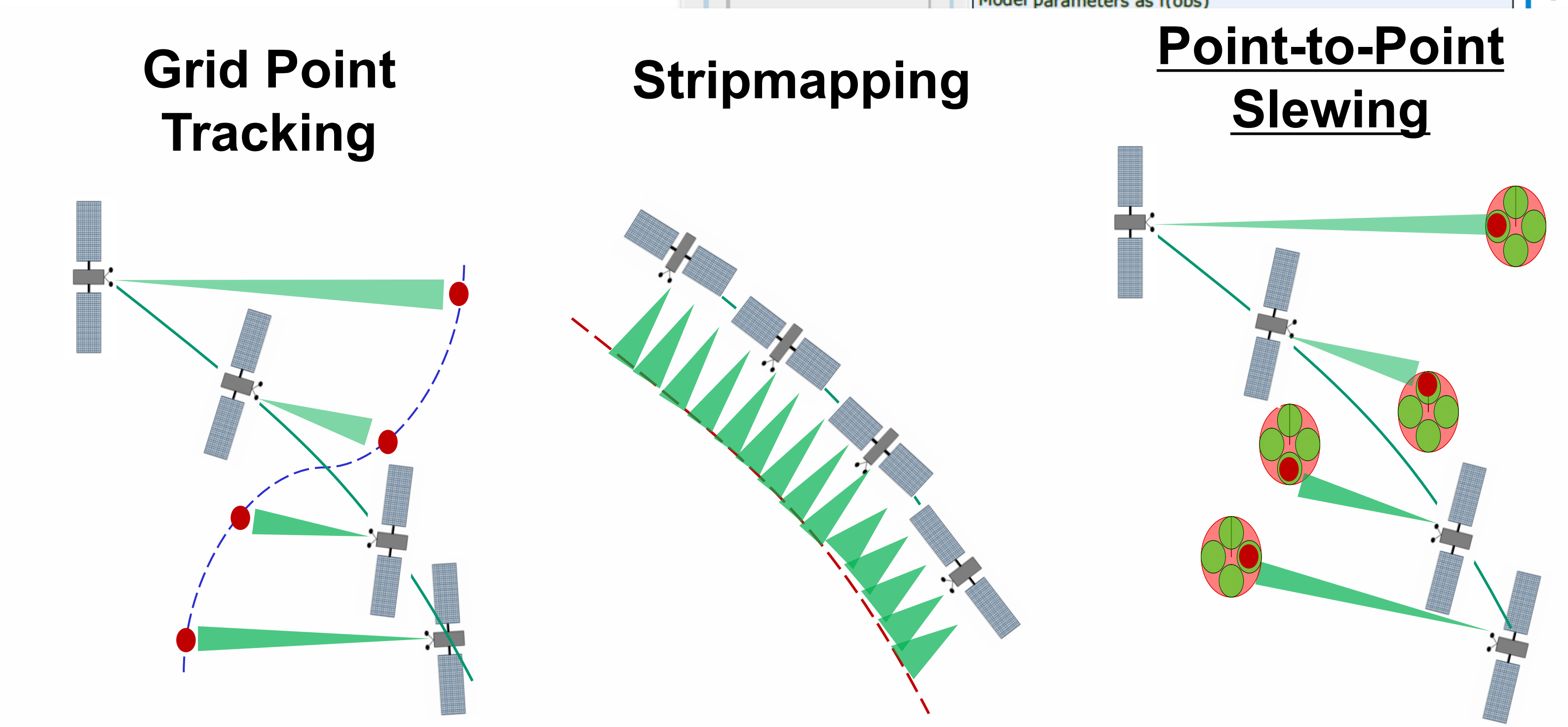




Attitude Control Systems for Agile Slewing

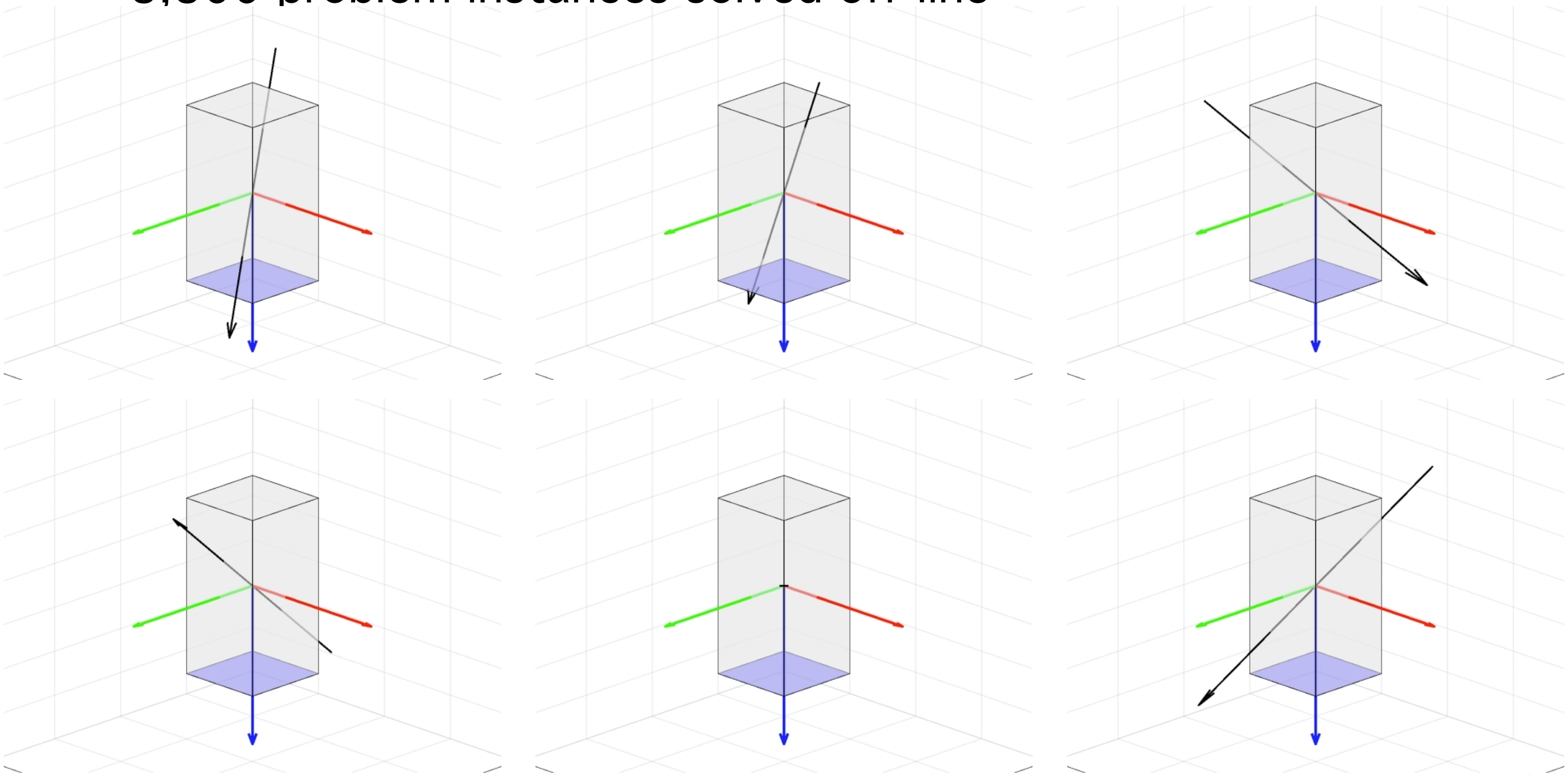
*ACS module informs the planner of time/energy constraints *and* executes commanded plan in any of 3 modes:*





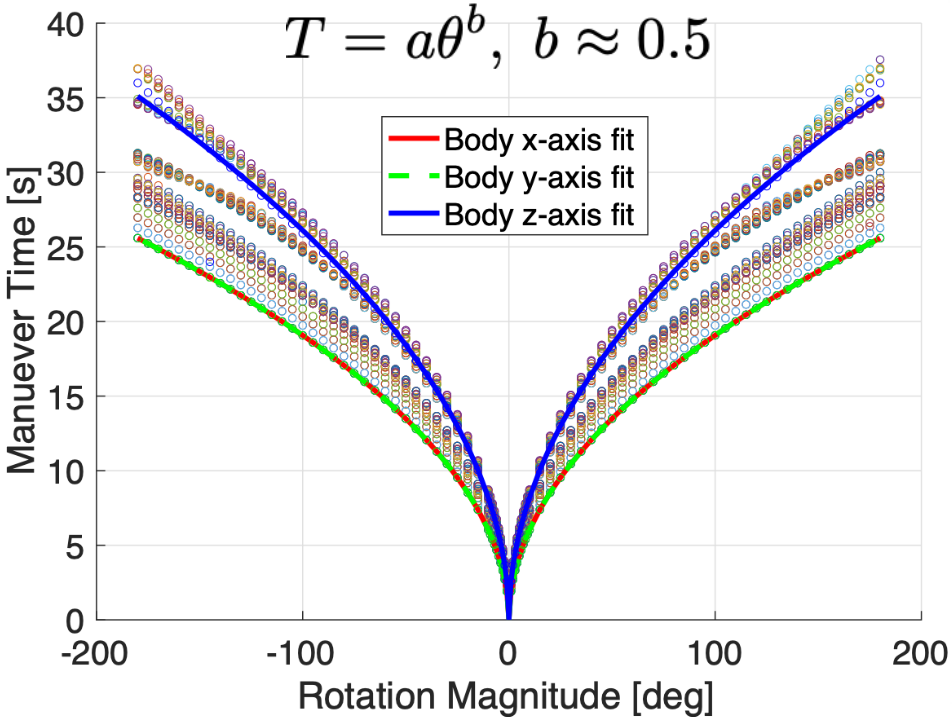
Attitude Control Systems for Agile Slewing

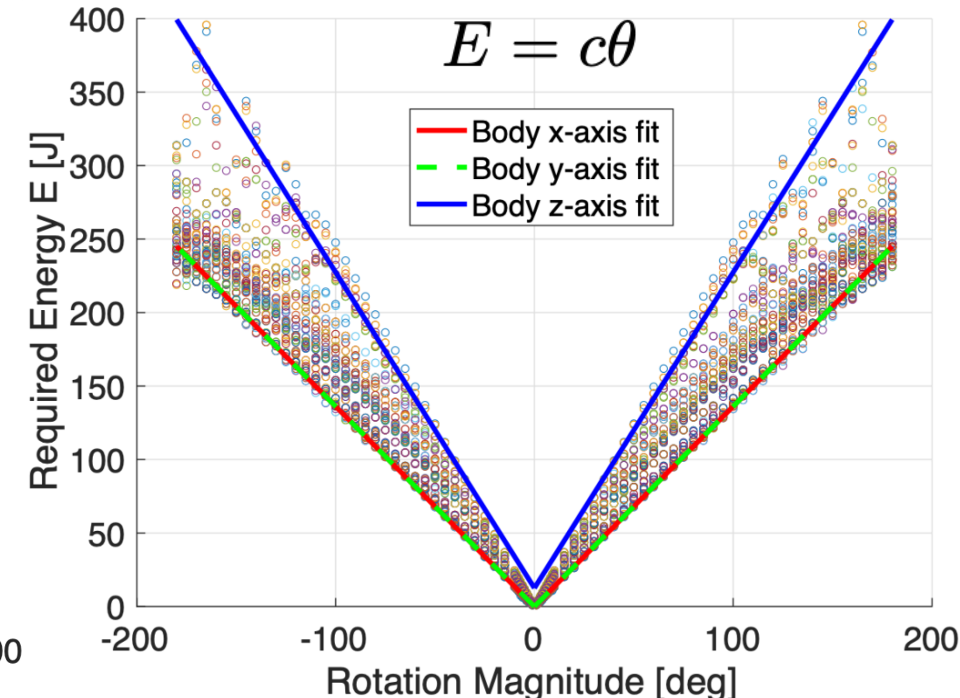
- Module validated on reference Planet Skysat of 110kg mass
- 100 rotation axes, 88 rotation magnitudes {-180,-175, ..., +175,+180}
- 8,800 problem instances solved off-line



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

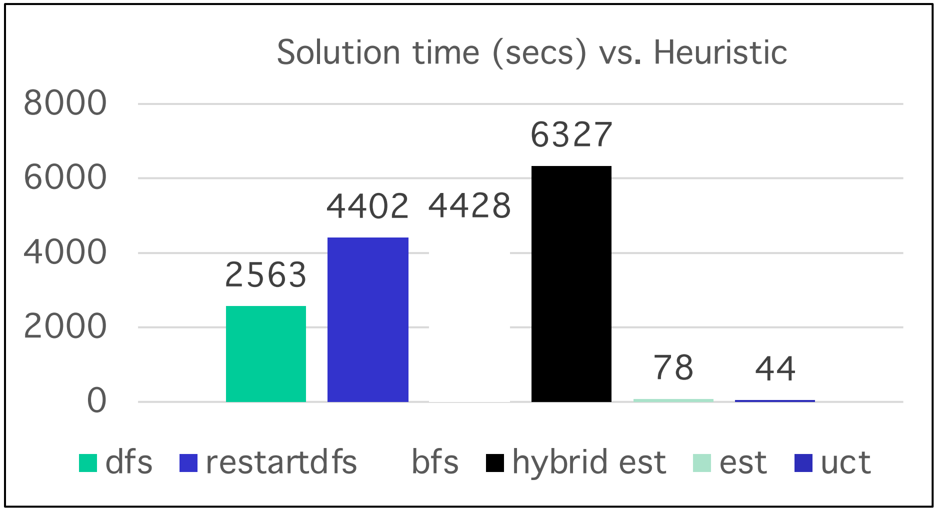


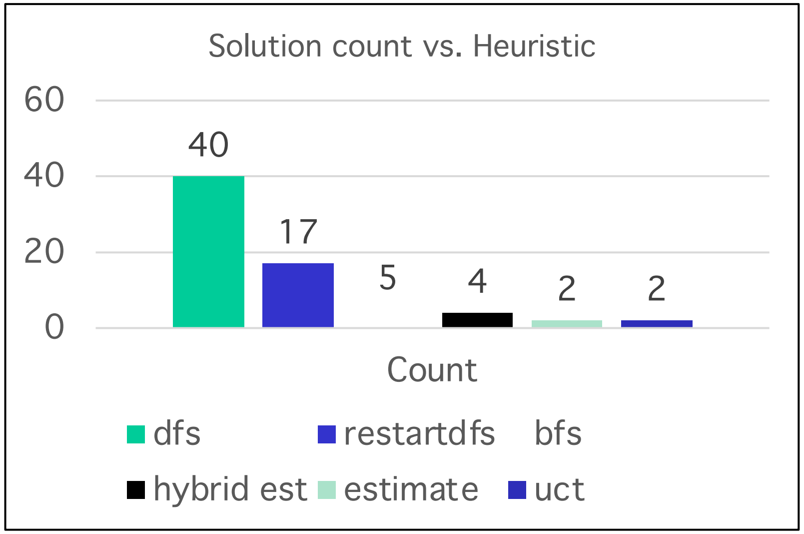


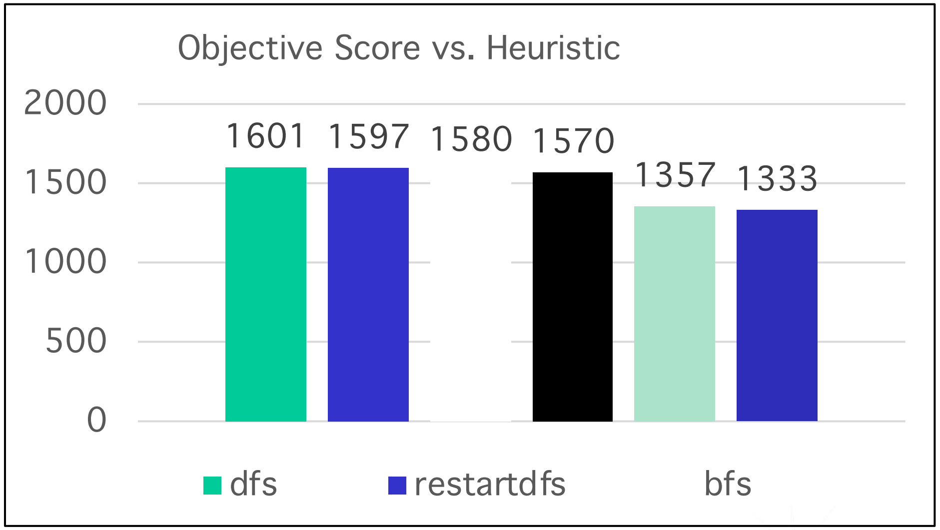
ESTO
Earth Science Technology Office

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*

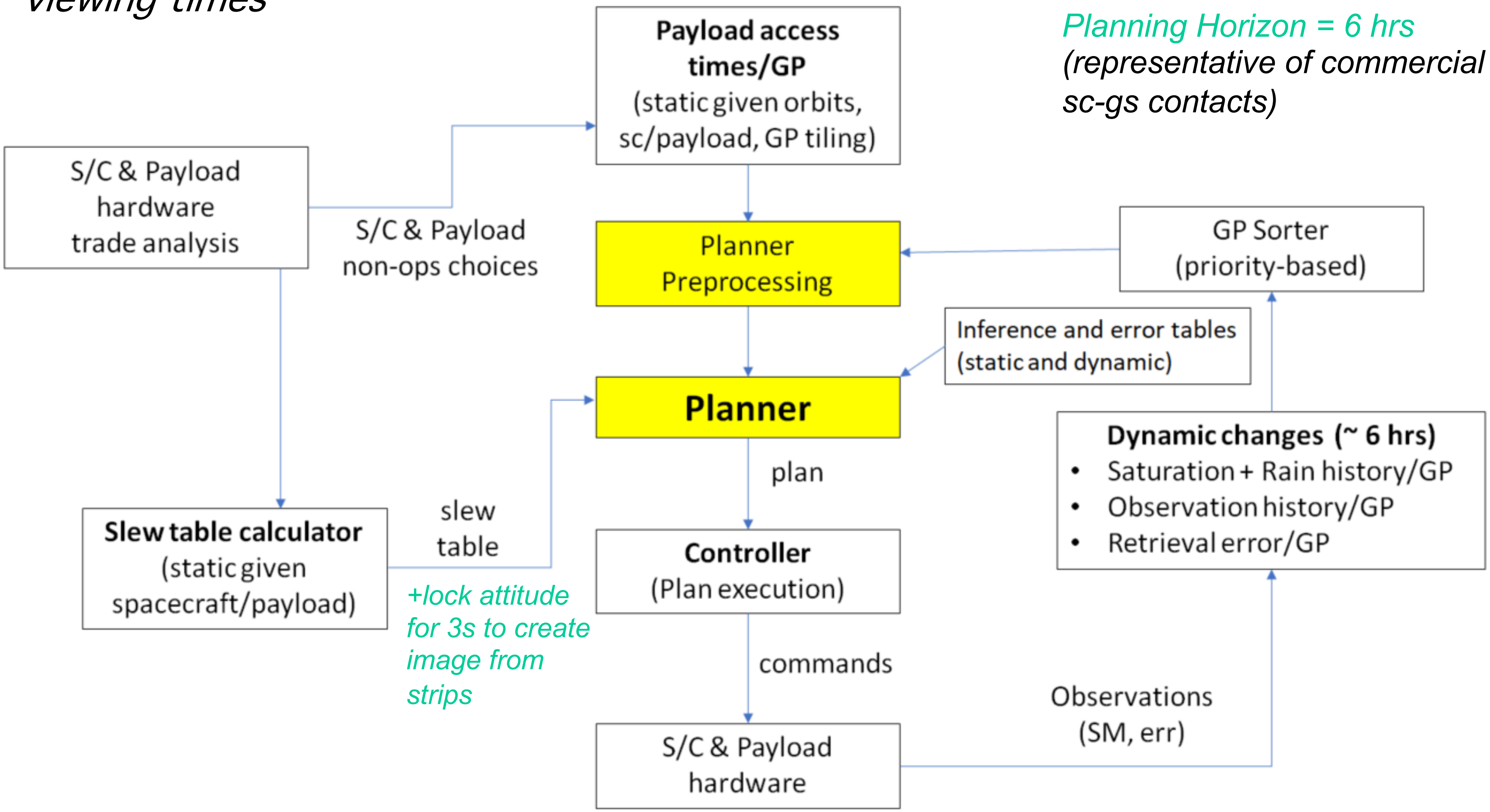






Observation Planner: Optimizing the Schedule

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

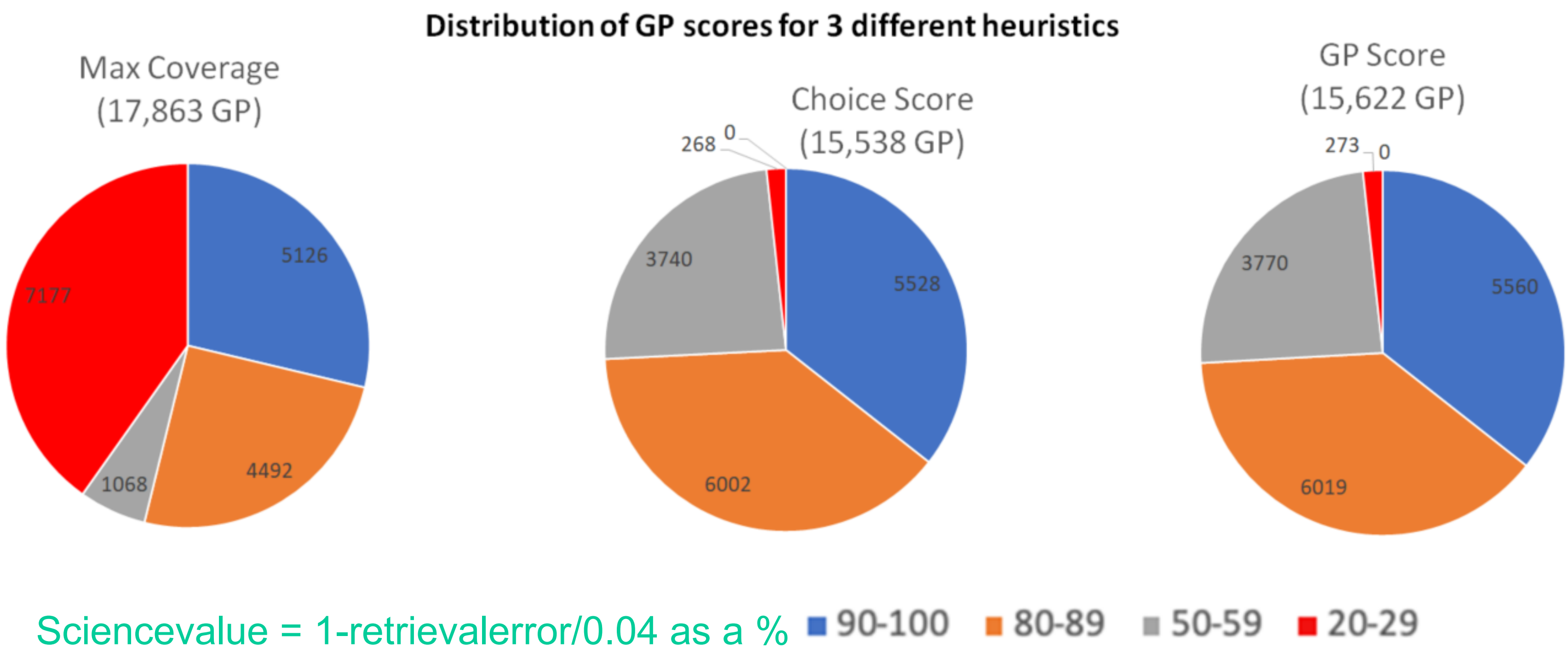
sciencevalue= 1-retrievalerror/0.04 (after ranking for seen, rain, saturation)

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

Please contact the PI for a copy of the demo

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%)

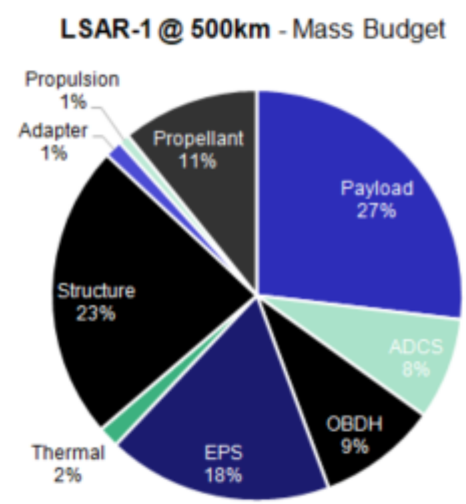
For 1 horizon of 6h:
Interesting land cover GPs = 637k
9.8k variables, 3.8mins to solve
Adding all constraints and heuristics
~16k GP, 3.2k variables, 43s to solve

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

Addressing Temporal Resolution / Constellation

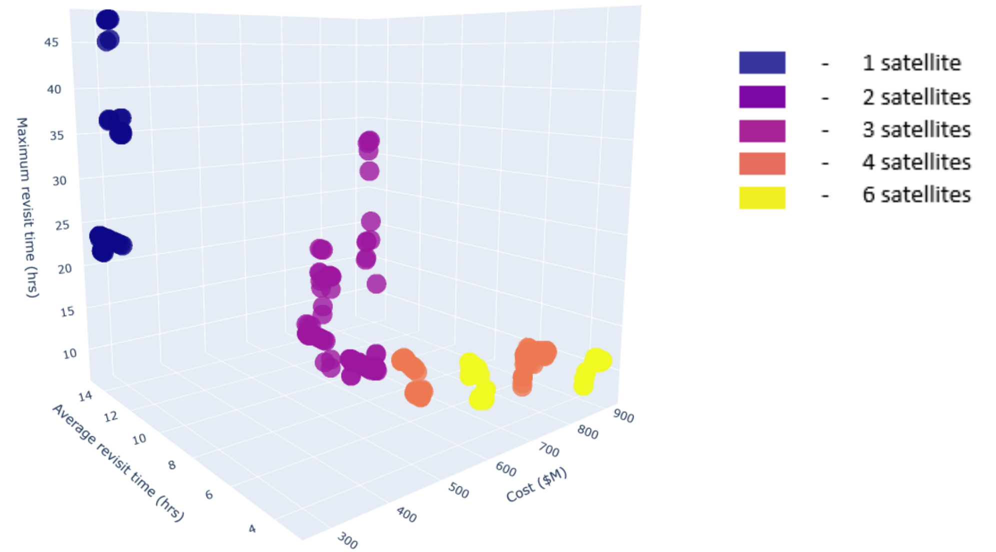
- Payload input => spacecraft sizing => Constellation sizing
- Options: Prior knowledge e.g. IceEye, Capella, Tradespace tool e.g. TAT-C, self-evaluation to account for P/L band radars + multi-instrument spacecraft + heterogeneous constellation + loose coupling with spatio-temporal resolution of agility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

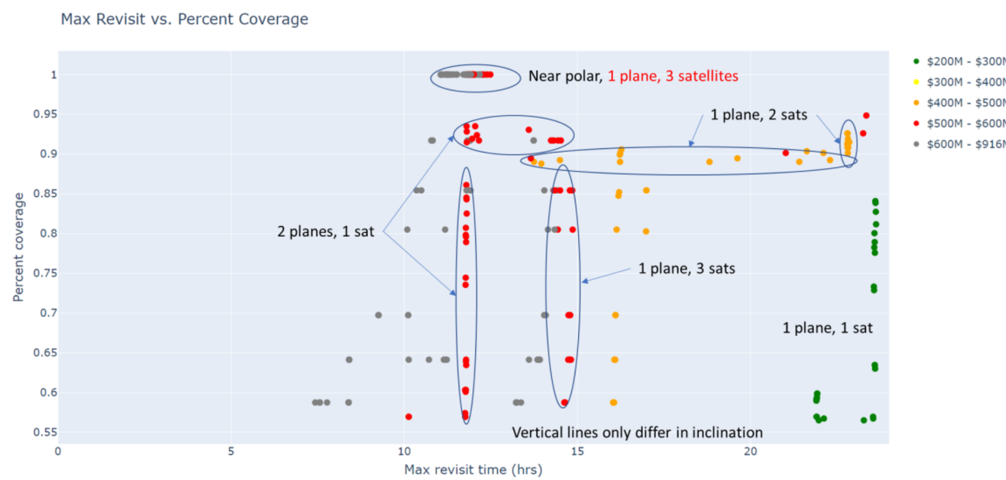
- Used JESS-based tool to size the s/c at 10% duty cycle, 500 km orbit, pending better estimates of electronics mass (old tech) for radars<100kg and extension to radiometers and reflectometers
- Used VASSAR to find baseline constellations that minimizes lifecycle cost and maximizes ability to point to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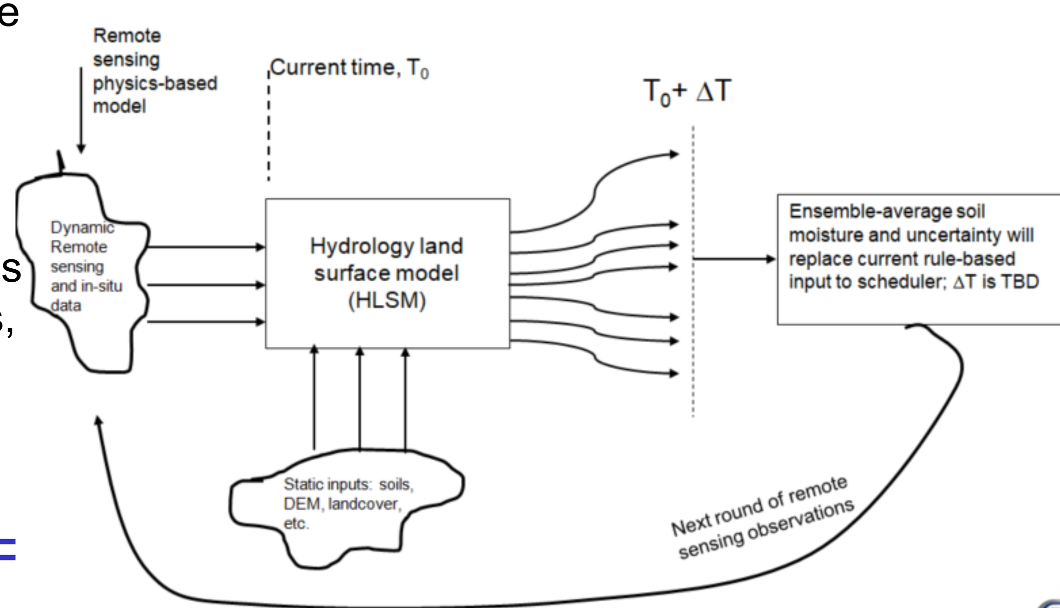
Summary of Accomplishments and Future Plans

- 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

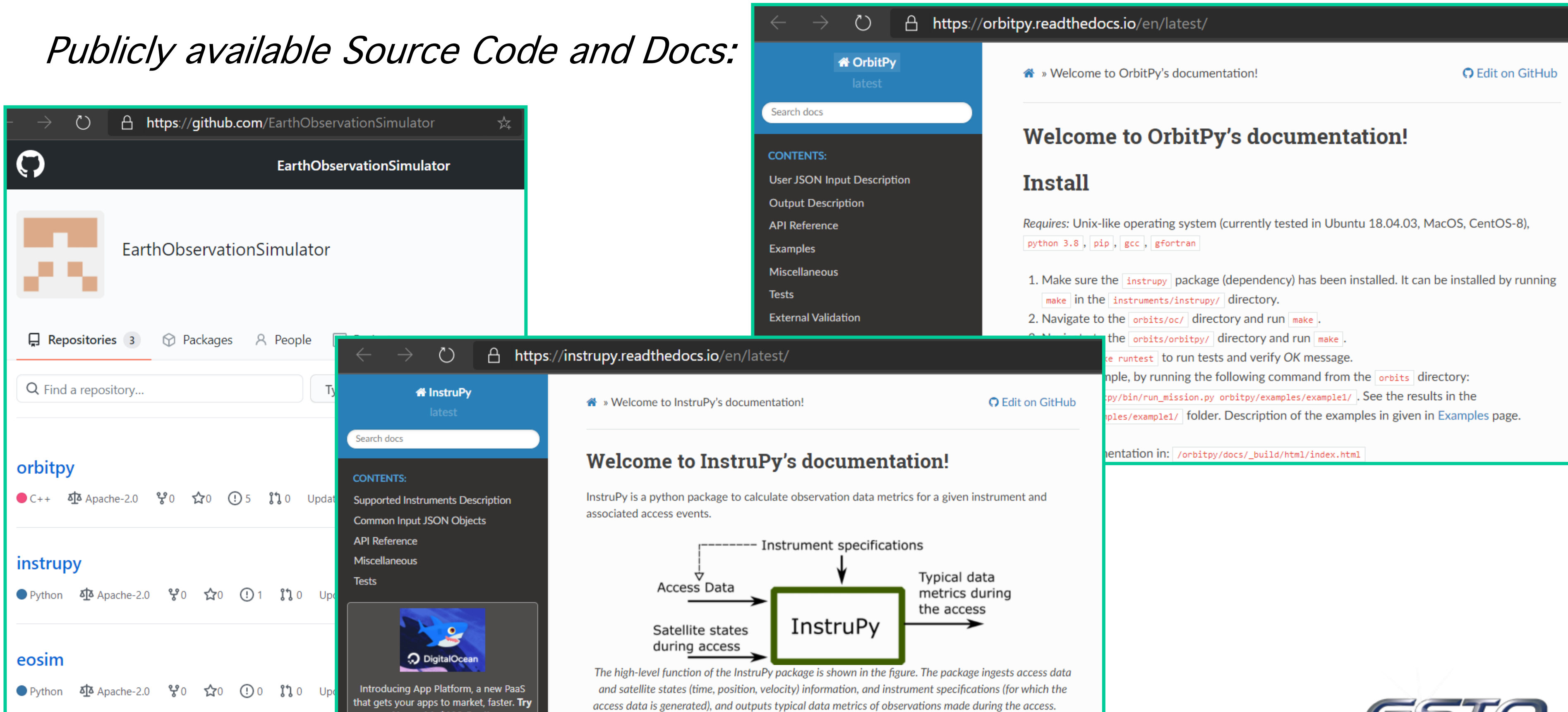
Conference Talks

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

Thank you!

Questions?
Sreeja.Nag@nasa.gov

Publicly available Source Code and Docs:



StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science

James Carr (PI, Carr Astronautics)

Chris Wilson (Institutional PI, NASA/GSFC)

Dong Wu (Co-I, NASA/GSFC)

Matt French (Co-I, USC/ISI)

Marco Paolieri (USC/ISI)

Mike Kelly (Collaborator, JHU/APL)

AIST-18-0082 Annual Technical Review

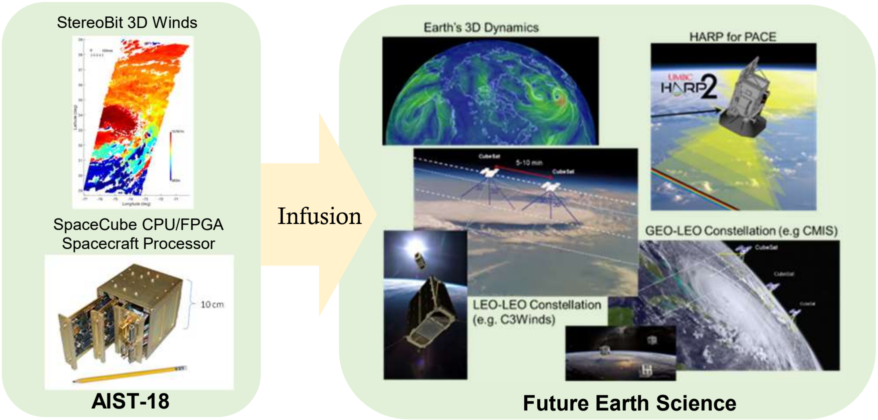
4 January 2021

StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science

PI: James Carr, Carr Astronautics Corporation

Objective

- Demonstrate on-board processing to vertically resolve winds in support of high-priority Decadal Survey science
- Enable future CubeSat/SmallSat constellation missions by:
  - Demonstrating onboard Science Data Processing on a CubeSat-type flight processor, e.g., by developing StereoBit 3D Winds application on the SpaceCube hardware
  - Demonstrating integrated operations between platforms
  - Removing downlink bottleneck on CubeSats



StereoBit technology (left) can be infused into future Earth Science missions (right)

Approach

- Build upon ESTO investments in SpaceCube, Compact Mid-wave IR System (CMIS), and Virtual Constellation Engine (VCE)
- Prototype Structure from Motion (SfM) 3D Winds science algorithms on the SpaceCube hardware, including stereo tracking of clouds to vertically resolve winds
- Demonstrate StereoBit with flight-like datasets in the Application Development Testbed
- Simulate integrated operations using VCE
- Perform early risk reduction with a flight demonstration of reprogramming the Robotic Refueling Mission 3 (RRM3) payload on the International Space Station, under IRAD funding

Co-Is/Partners: Dong Wu and Christopher Wilson, GSFC; Matthew French, USC-ISI; Michael Kelly, JHU APL

Key Milestones

• IGARSS	07/20
• Science Peer Reviews	07/20
• Testbed Available	08/20
• Science Algorithms Deployed	09/20
• Deliver Final Flight Code	05/21
• Complete Flight Code Verification	08/21
• Perform Final Demonstration	10/21

TRL_{in} = 4 **$TRL_{current}$ = 4 (5 very soon)**

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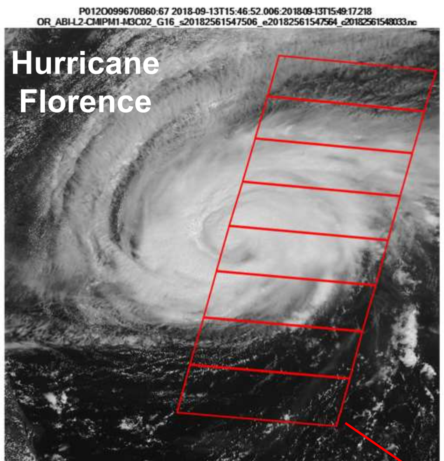
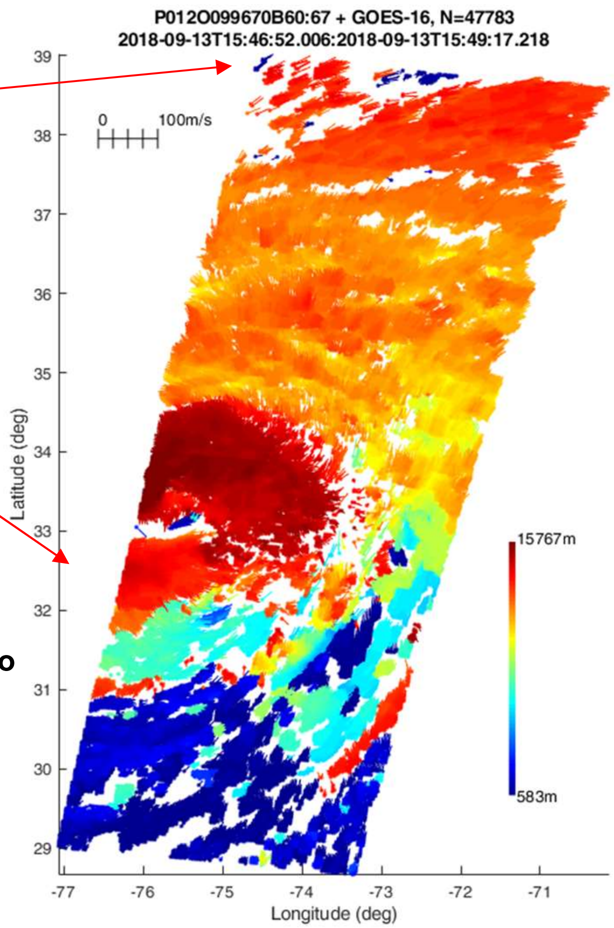
Background and Objectives

High Priority Decadal Survey Science

Applications: Weather & Planetary Boundary Layer (PBL)





Multi-Platform, Multi-Angle constellation architecture

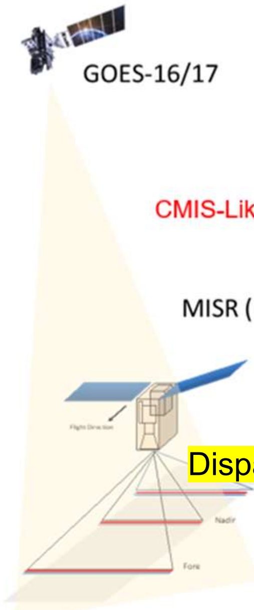
Vertically resolve winds using **Structure from Motion (SfM) stereo tracking** of clouds

Integrate operations between platforms

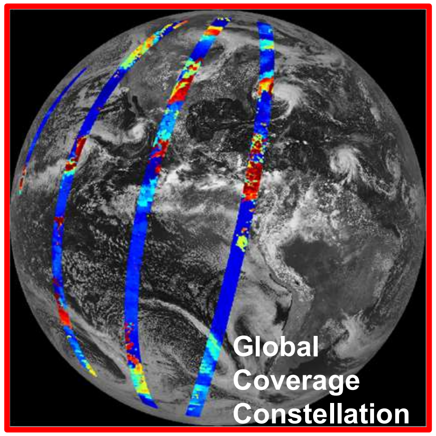
Disaggregate science processing to **alleviate downlink bottleneck** of constellation architectures

- Objectives that are both Specific & General
  - Decadal Survey Science
  - Advance Community Capabilities to Develop for SpaceCube Hardware
- Leverage ESTO Investments
  - Compact Midwave IR Sensor (CMIS)
  - SpaceCube
  - Virtual Constellation Engine (VCE)
- Target Project End State
  - TRL=6 Code for an SfM Science Application
  - Constellation Concepts
  - Global Networks in VCE
  - Lessons to Share

Stereo Winds Methods



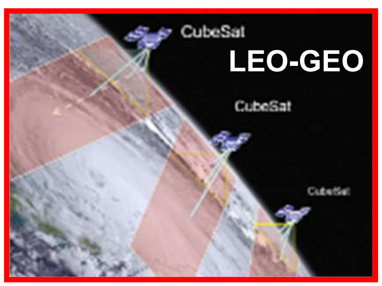
StereoBit Vision

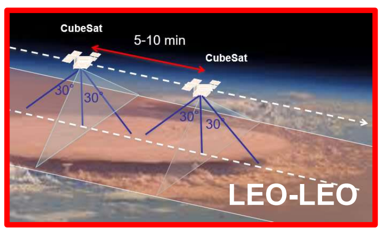


Disparities = Parallax + Motion

Carr, J.L., D.L. Wu, M.A. Kelly, and J. Gong, "MISR-GOES 3D Winds: Implications for Future LEO-GEO and LEO-LEO Winds," *Remote Sensing*, 2018, MISR Special Issue. https://www.mdpi.com/2072-4292/10/12/1885

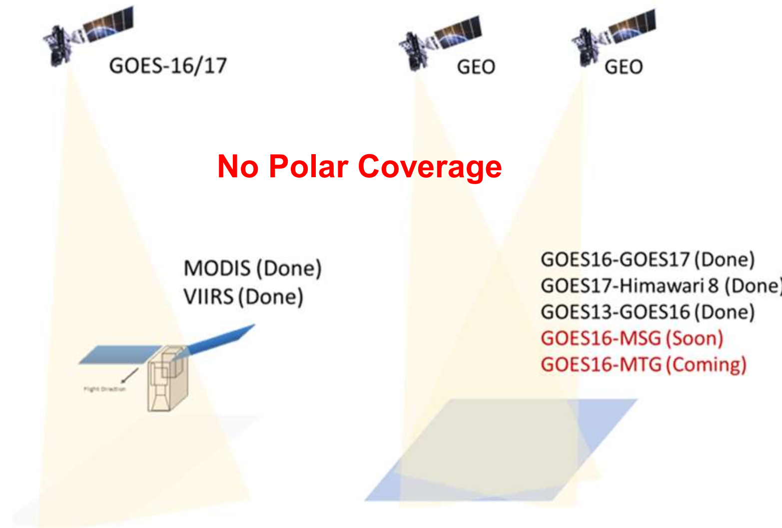
Multi-Platform: Resolves Height + In-Track Wind Ambiguity Existing with Single-Platform (e.g., MISR) Approach





LEO-LEO Enables Polar Coverage

LEO=Low-Earth Orbit GEO=Geostationary Orbit



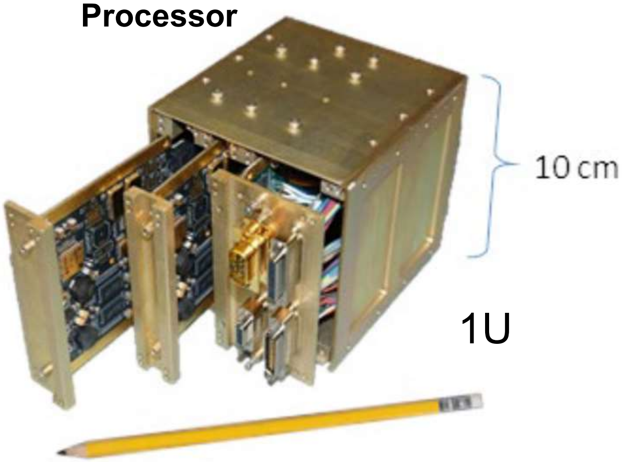
Carr, J.L., D.L. Wu, R.E. Wolfe, H. Madani, G. Lin, B. Tan, "Joint 3D-Wind Retrievals with Stereoscopic Views from MODIS and GOES," *Remote Sensing*, 2019, Satellite Winds Special Issue. https://doi.org/10.3390/rs11182100

Carr, J.L.; Wu, D.L.; Daniels, J.; Friberg, M.D.; Bresky, W.; Madani, H. "GEO-GEO Stereo-Tracking of Atmospheric Motion Vectors (AMVs) from the Geostationary Ring," *Remote Sensing*, 2020. https://doi.org/10.3390/rs12223779

ESTO Earth Science Technology Office

ESTO Technologies

SpaceCube Processor



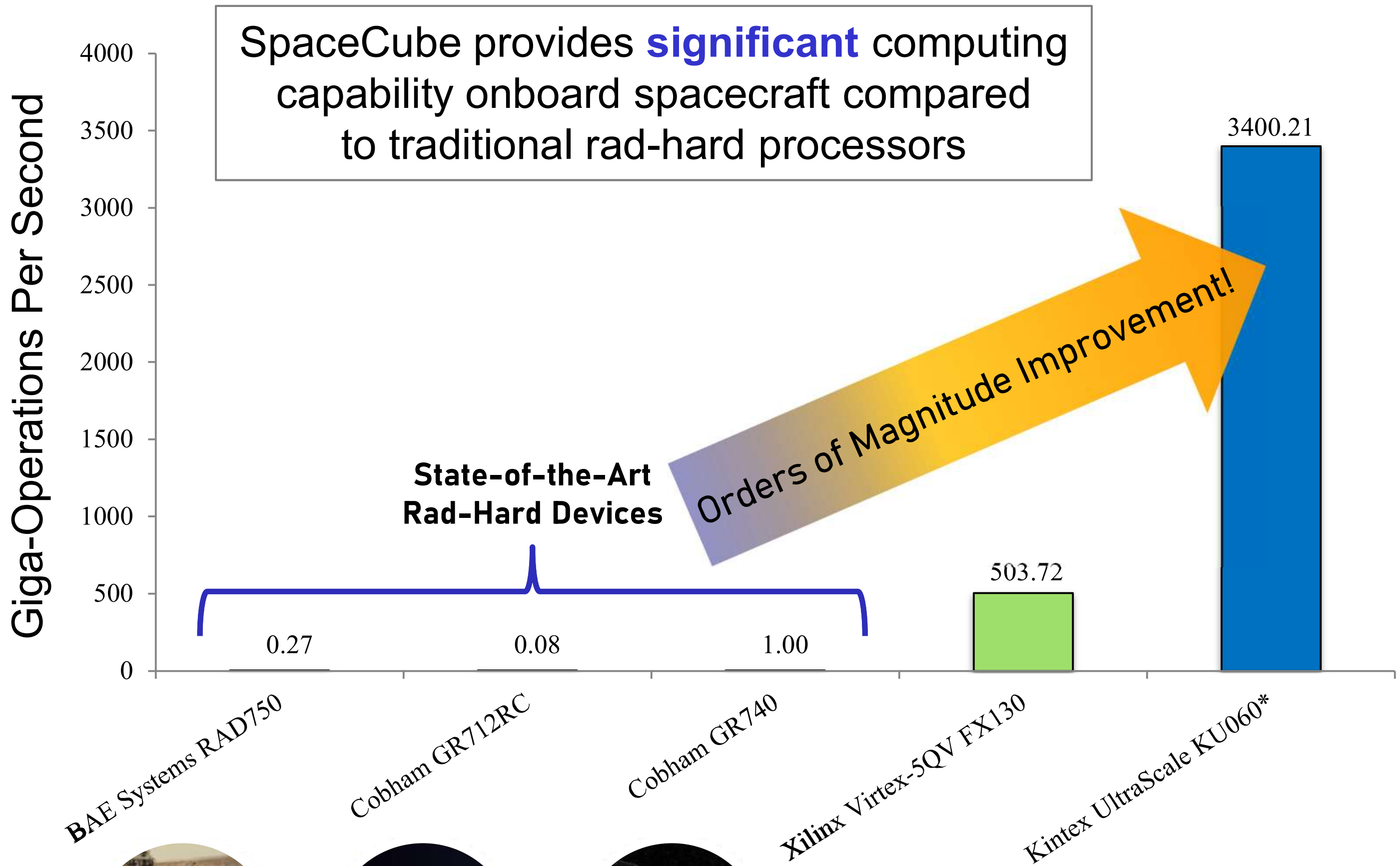
- CPU and Reconfigurable Field Programmable Gate Arrays (FPGAs)
- Mini/Mini-Z: fits within CubeSat Resource Limits
- ESTO Funded

Compact Midwave IR Sensor (CMIS)*

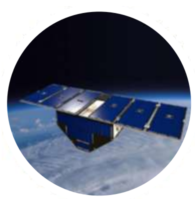
- Target for our science application
- Multi-angle push-broom with fore, nadir, aft views like MISR but Day/Night
- Type-2 Super Lattice (T2SL) detector
- ESTO Instrument Incubator Program

*PI: Dr. Michael Kelly, JHU/APL

SpaceCube High-End Spacecraft Computing



MSL



CYGNSS

WFIRST

Device used in SpaceCube v2.0

Device used in SpaceCube v3.0 Mini

Lovelly, T. M. and George, A D., "Comparative Analysis of Present and Future Space-Grade Processors with Device Metrics,"AIAA Journal of Aerospace Information Systems, Vol. 14, No. 3, Mar. 2017, pp. 184-197. doi: 10.2514/ 1.I010472

8-Bit Integer Operations
*UltraScale results are an estimate based off of existing data, new metrics are in progress but not currently available

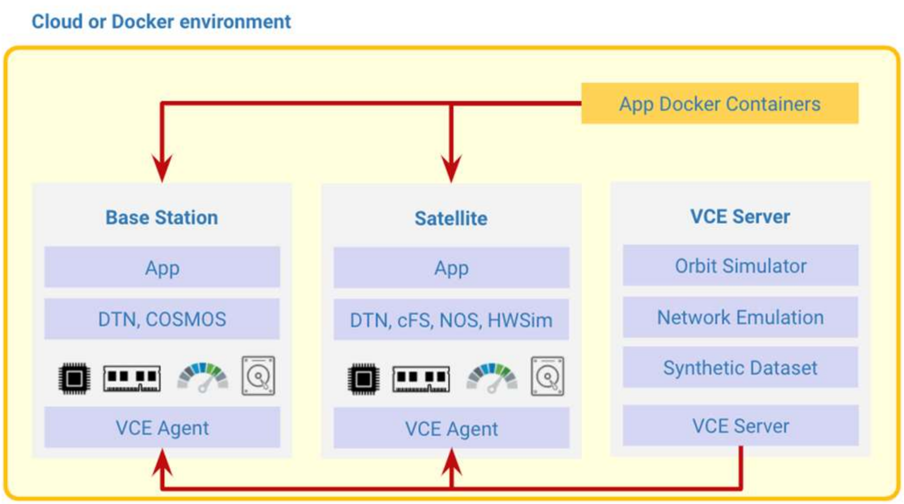
VCE - Overview

Virtual Constellation Engine (VCE) enables the emulation of distributed, multi-satellite applications.

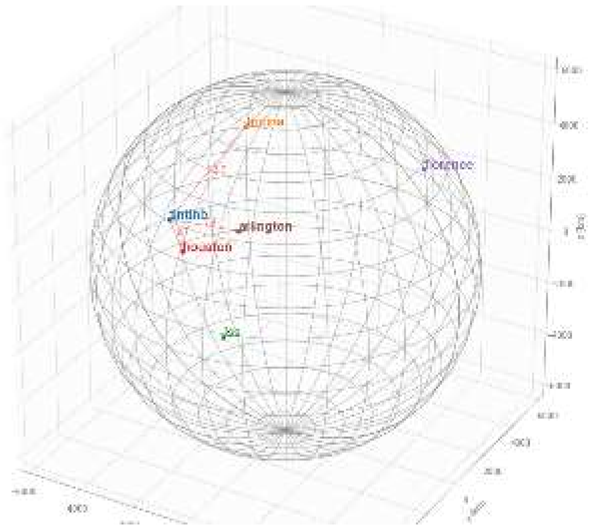
VCE provides support for:

- Orbits propagation (from TLEs)
- Network latency/bandwidth emulation between nodes (satellites, stations)
- Emulation of instrument outputs (from user-provided time series)
- Monitoring of resource utilization (CPU/memory/disk/network)
- Log collection from all nodes
- Use of cloud resource (GPU/FPGA) or local Docker containers

VCE runs a real distributed application in a controlled environment, gathers metrics/logs useful to evaluate correctness/performance



AIST Project!



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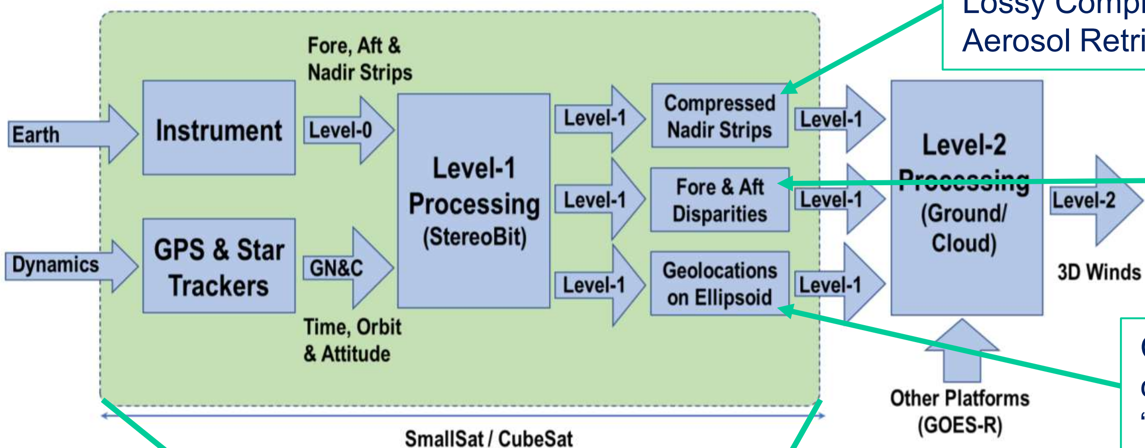
StereoBit Application, Development & Testing

StereoBit SpaceCube Application



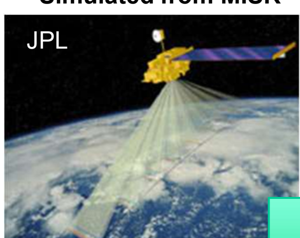
JPEG-LS Implemented in FPGA; Lossy Compression Tolerated by Aerosol Retrieval Algorithms

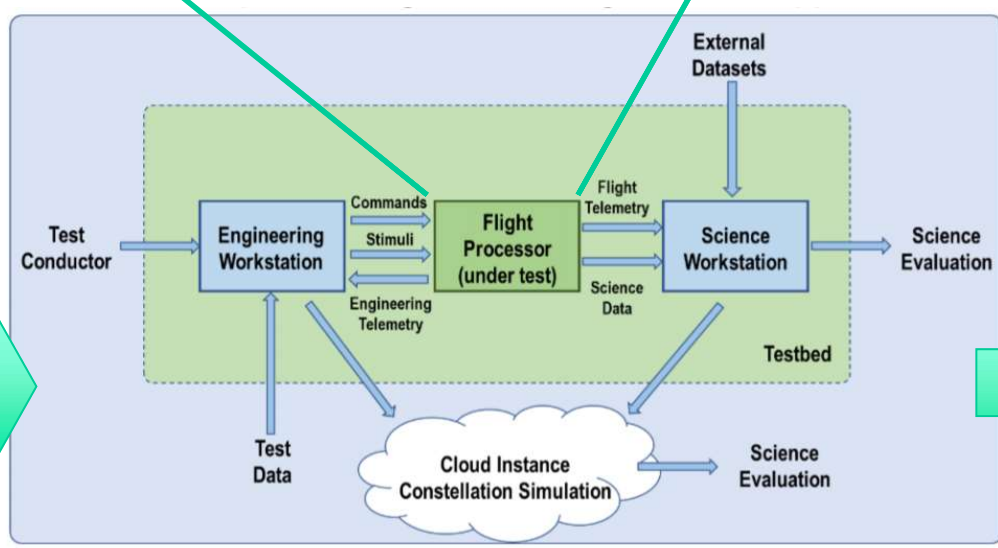
SfM Implemented in FPGA; Data Reduction >20:1 Equivalent- Compression without any Science Loss

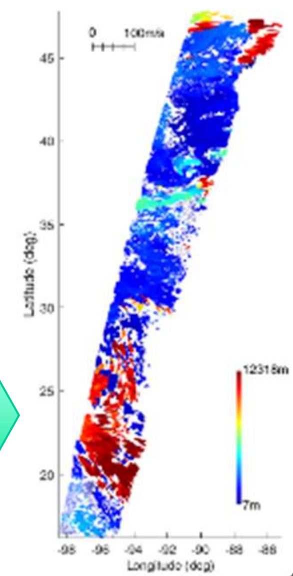
Complicated Procedural Code can be Implemented in FPGA "Soft Core" and/or HW

Application Development Testbed

CMIS Proxy Data Simulated from MISR

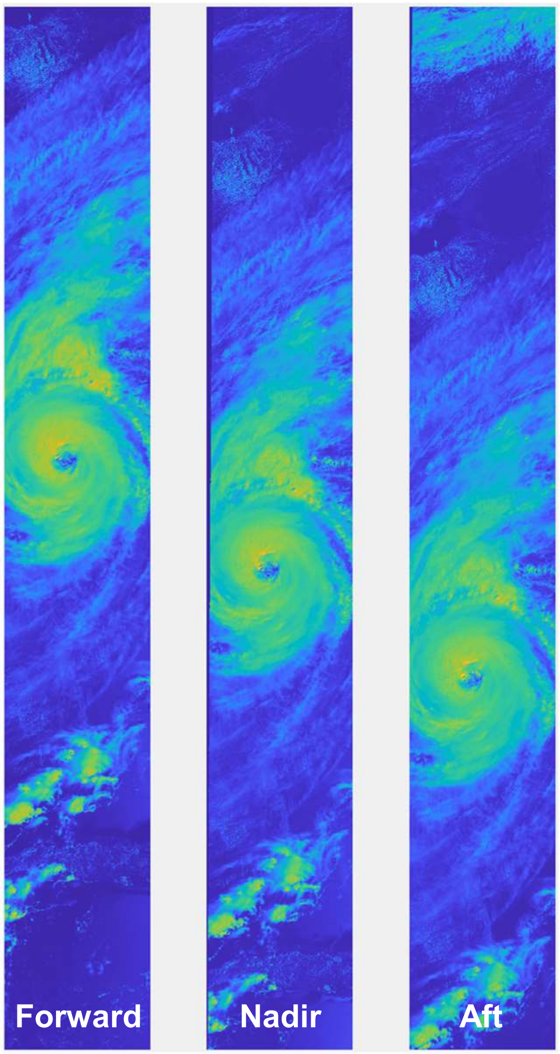






End-to-End Pipeline

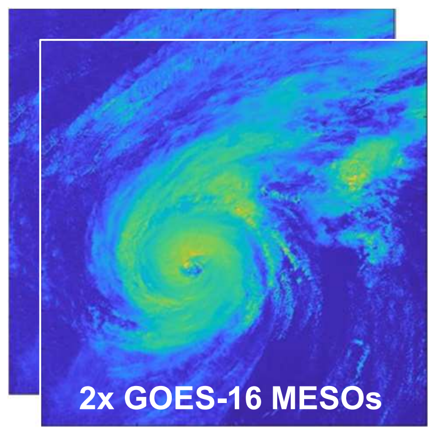
N
W E



S

MISR-Derived Proxy

+



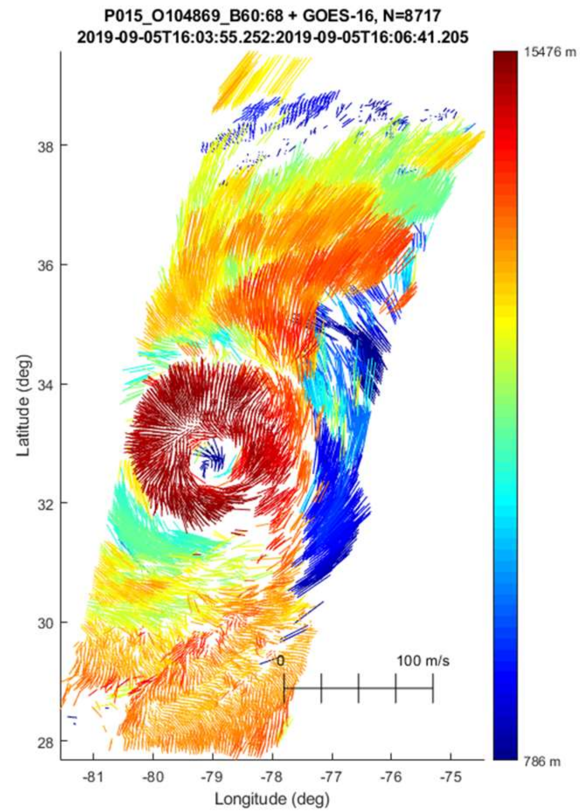
Real GOES Imagery

=

Development Process

Code in C → Validate → HLS* → Test

*HLS = High-Level Synthesis C-to-FPGA Logic



Hurricane Dorian

Science Product

High-Level Synthesis for Rapid FPGA Development in StereoBit

- Field Programmable Gate Array (**FPGA**)
  - Large amount of logic resources and specialized design units connected with complex and configurable routing network in single integrated chip
  - Custom architectures can be designed to **rapidly accelerate applications**
- However, compared to conventional programming, FPGA-based systems frequently incur ***longer*** development cycles
  - Designs describe low-level digital hardware architectures compared to high-level software instructions
  - Slow "build" compilation on order of hours/days, compared to software's sec/minutes
- Recent state-of-the-art FPGA tools have introduced high-level synthesis (**HLS**) to alleviate productivity challenges
  - Generates FPGA designs from high-level languages (e.g., C/C++), providing **high-level design abstractions** of hardware logic
  - Grants faster design iterations through **fast algorithmic validation** in high-level languages (sec/min), instead of typical slow FPGA design simulation (min/hrs)
- HLS is used to rapidly develop hardware-accelerated FPGA designs for StereoBit applications
  - Execute **Structure from Motion (SfM) matching** algorithm to measure disparities between fore/aft looks with nadir look
  - Calculate **geolocations** (lat, lon) coordinates for pixels using GPS, quaternions, and optical calibration parameters

C Function

```
float sum =
  input1 + input2;
float sum2 =
  input3 + input4;
```

High-Level Synthesis

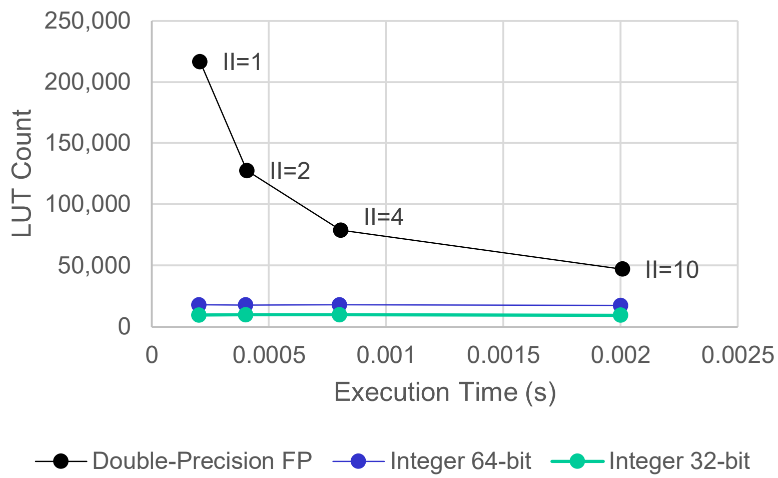
```
U_FLOAT_SUM1 :
altfp_add_sub_speed
port map(
 aclr      => rst_n,
clock      => clk,
 dataa     => input1,
 datab     => input2,
 result    => sum1_result,
 nan       => sum1_nan,
 overflow  => sum1_o);

U_FLOAT_SUM2 :
altfp_add_sub_speed
port map(
 aclr      => rst_n,
clock      => clk,
 dataa     => input3,
 datab     => input4,
 result    => sum2_result,
 nan       => sum2_nan,
 overflow  => sum2_o);
```

VHDL Instantiation
(FPGA Code)

Results and Challenges of HLS explored for StereoBit

- Vivado[1] HLS has enabled rapid development of FPGA-accelerated StereoBit apps
  - Enabled **rapid development** of geolocation algorithm and several different SfM implementations
  - Enabled rapid **design space exploration** of different architectural designs through high-level parameters
- However, Vivado HLS development has revealed a number of limitations
  - Vivado HLS commonly needs algorithm code rewritten in an HLS-amenable fashion
  - Vivado HLS users need both FPGA and SW expertise to develop/debug efficient HLS designs
  - Certain FPGA structures are not easily described in Vivado HLS
- Even with Vivado HLS, it important to still **closely collaborate** with algorithm developers
  - Identify problematic code for FPGA implementation (e.g., FPGA area-expensive trigonometric functions) and explore alternatives implementations (e.g., lookup tables)
  - Determine feasibility of potential algorithm optimizations (e.g., lower precision data types for smaller FPGA area/power designs)

Rapid design space exploration in geolocation HLS design by "tweaking" HLS initiation interval (II) parameter



Lower-precision data types significantly decreased FPGA area cost in SfM HLS designs

[1]Vivado HLS is design tool by Xilinx FPGA Company

[2]LUT is used as measurement for available FPGA Resources

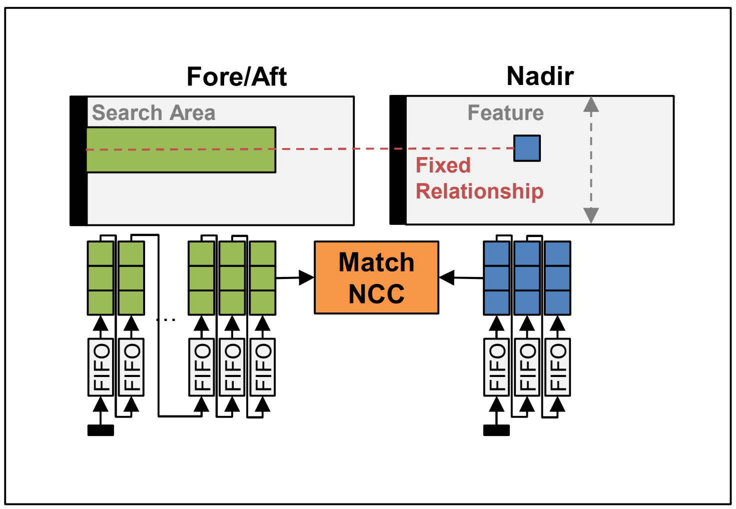
Development Iteration Example: How Software Changes Affects FPGA Design

- Minor changes in software can have dramatic changes to FPGA architecture design
- However, HLS allows for more rapid architecture restructuring and **design trade-off exploration for StereoBit** that would **otherwise be infeasible** within time constraints if FPGA were designed with traditional manual hand-coding VHDL techniques

C-Code Function

```
for(int i=0; i<FEATURE_COUNT; ++i){
  Vector2f result = MatchNCC(
    searchArea(s[i]), feature(f[i]);
```

Corresponding FPGA Design



Simple sliding window design

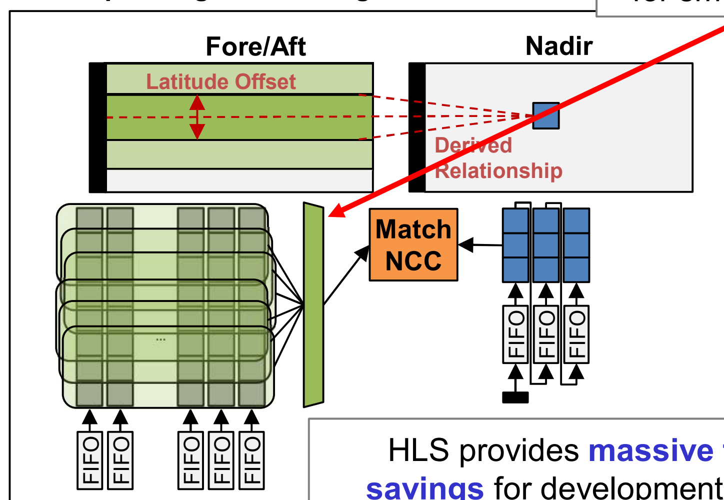
Small software change

C-Code Function

```
for(int i=0; i<FEATURE_COUNT; ++i){
  Vector2f result = MatchNCC(
    searchArea(s[i + offset]), feature(f[i]);
```

Extensive FPGA redesign required for small change

Corresponding FPGA Design



HLS provides **massive time-savings** for development efforts

Simple latitude offset change drastically changes sliding window design to require large LUT-expensive muxes

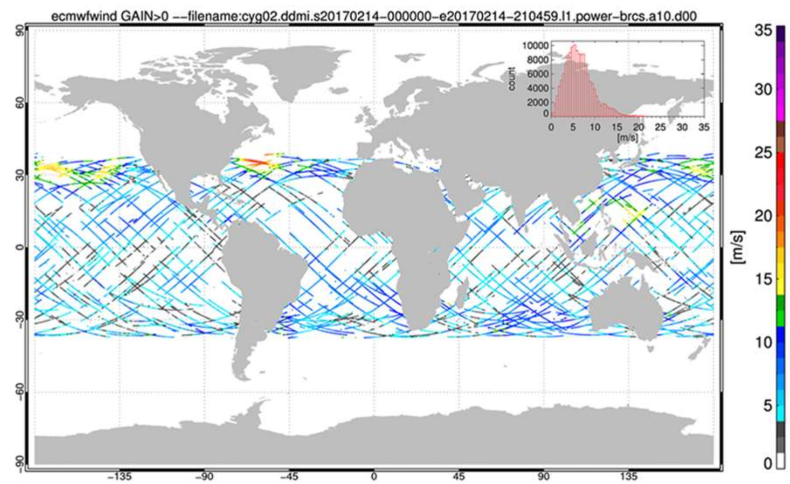
StereoBit Mission Prototype in VCE

Goal: To evaluate performance metrics for different mission architectures / parameters

Reference Constellation

- CYGNSS: 8 satellites
- Altitude of 510 km, period of 95'
- Ground stations: Hawaii, Chile, Australia
- 6-7 passes/day, ~8 minutes of visibility

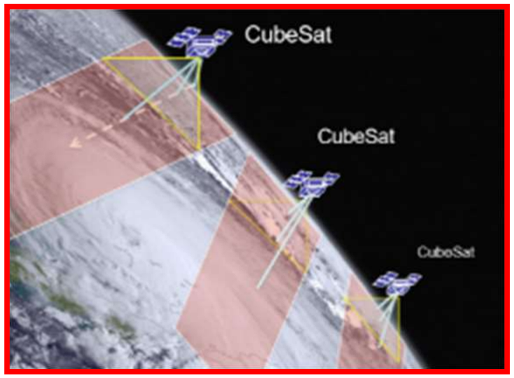
(We are using a different instrument model)



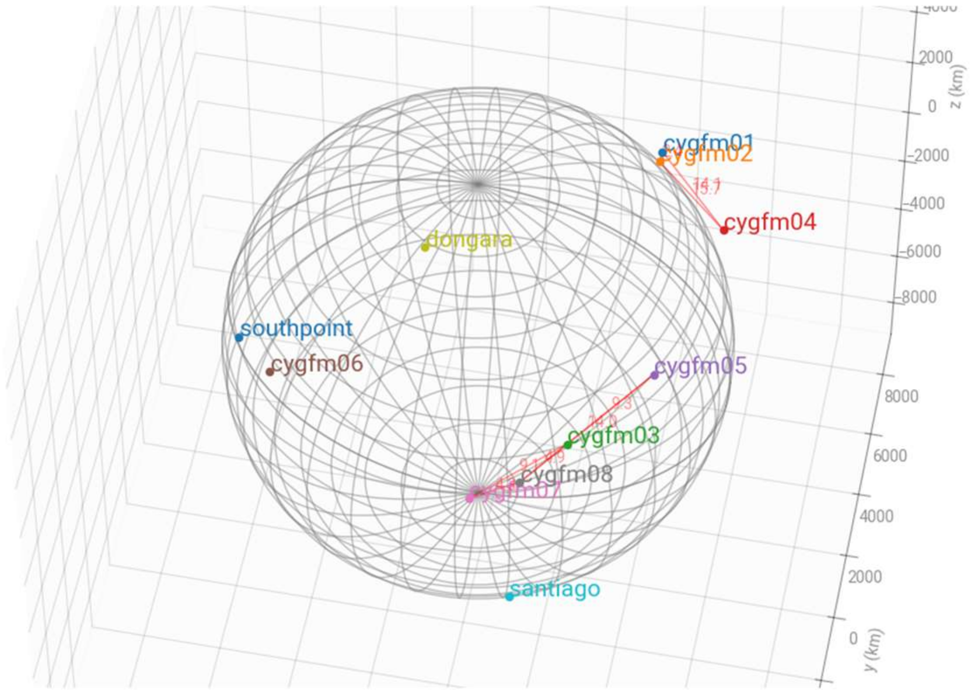
https://www.nasa.gov/feature/nasa-s-cygnss-satellite-constellation-enters-science-operations-phase

Tasks

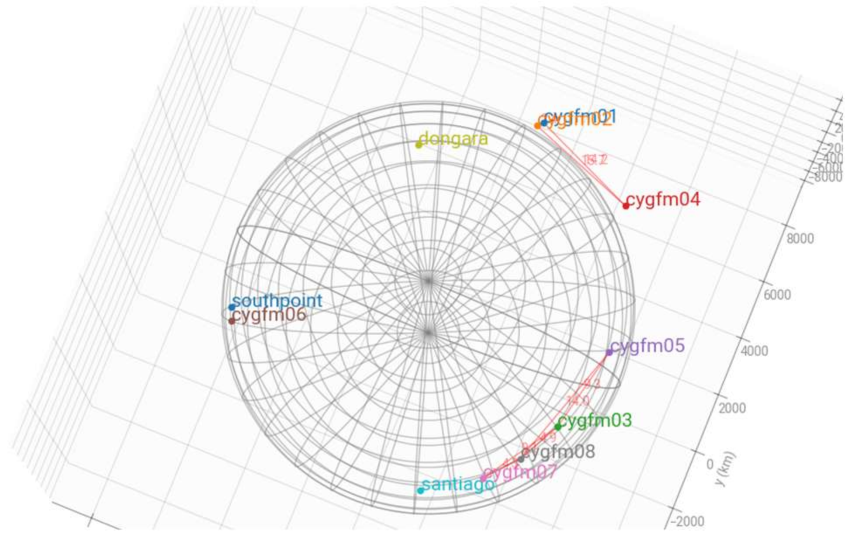
- Analyze/emulate orbits using VCE
- Model instrument, cooperative data acquisition strategy, downlink schedule
- *Implement application stubs (in progress)*
- *Evaluate performance metrics in different scenarios (in progress)*



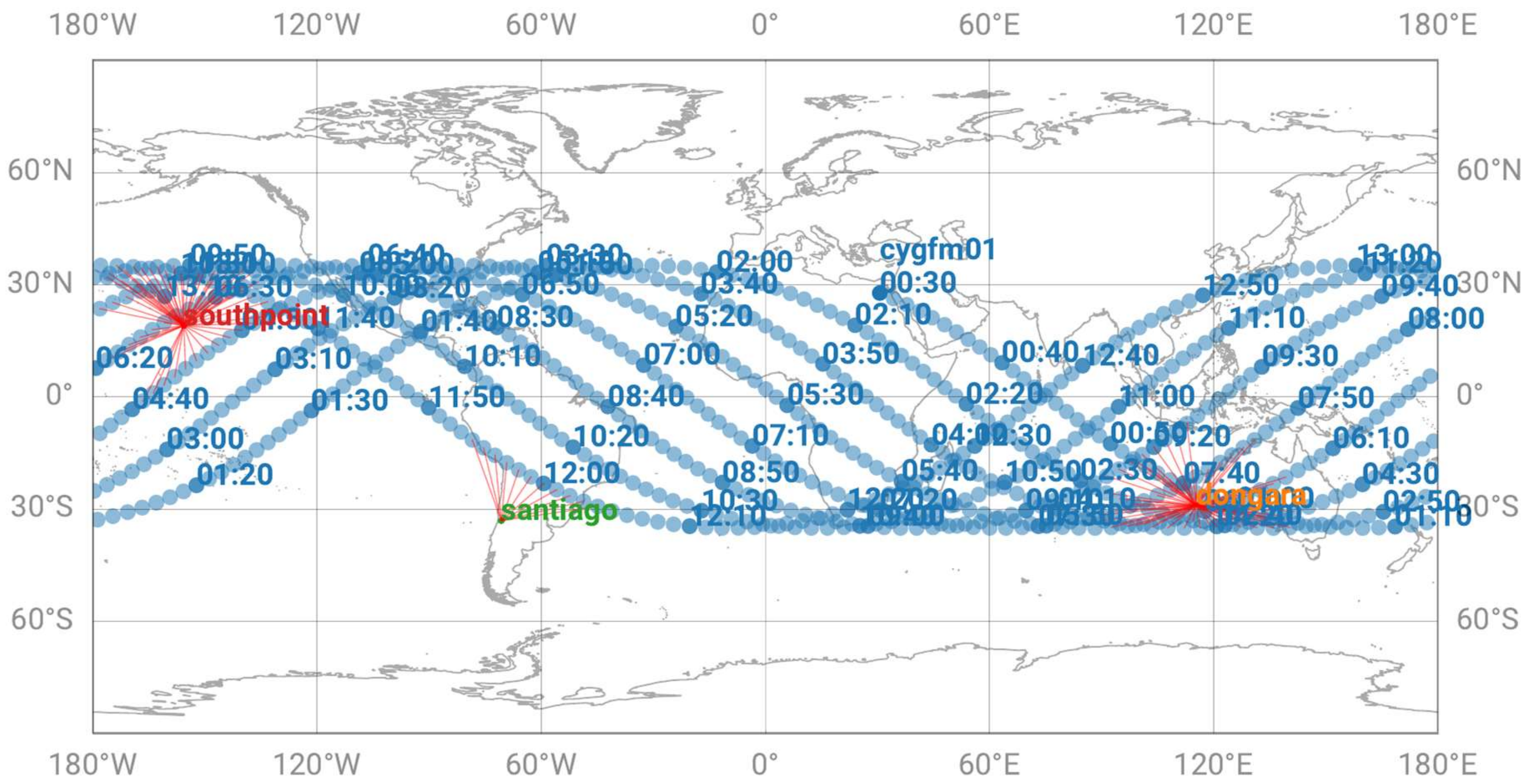
Orbits Propagation in VCE



Three groups of satellites
- 1 and 2, with 4 following
- Train of 5, 3, 8, 7
- 6 is 30 minutes apart

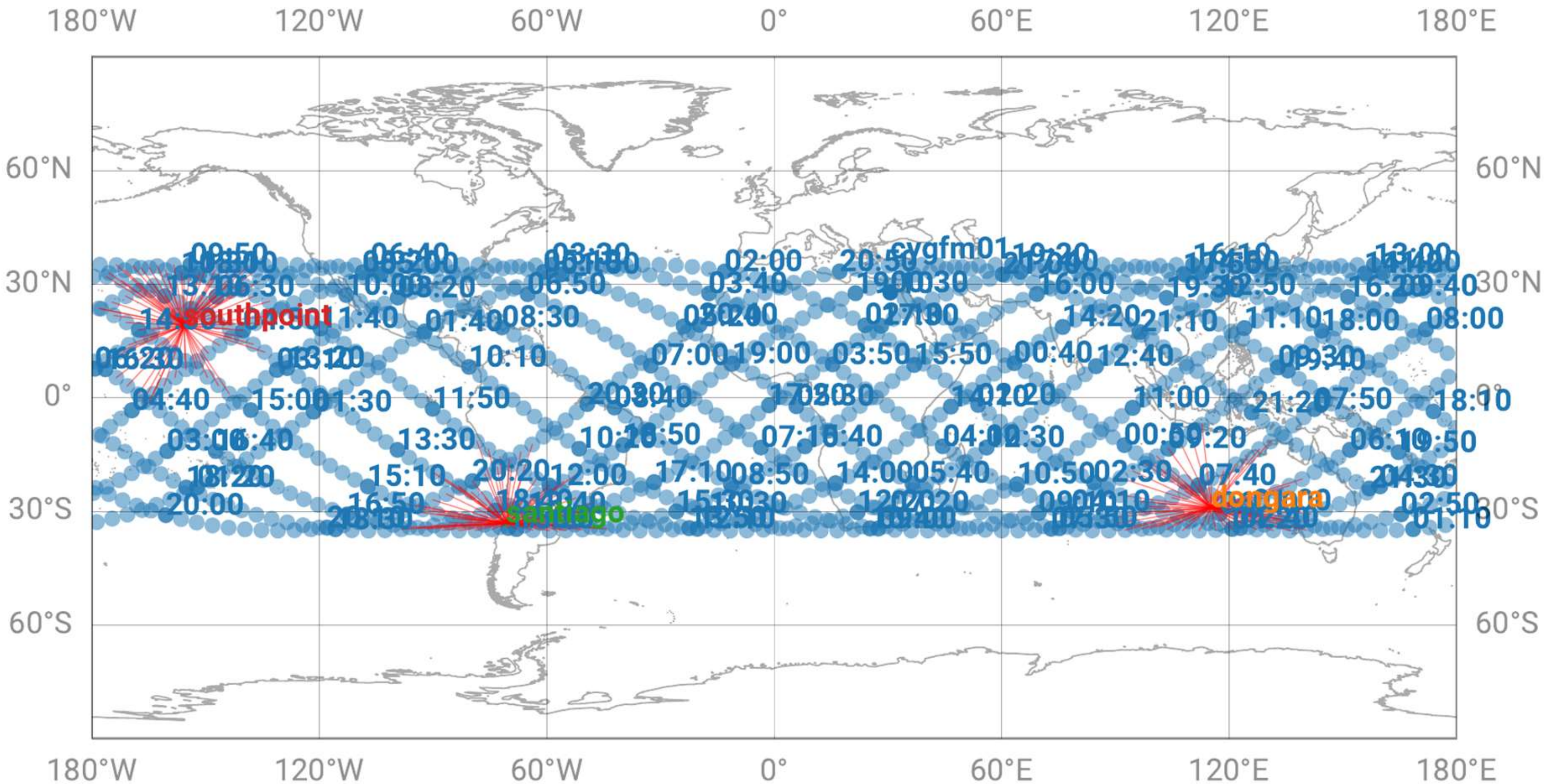


Coverage and Downlinks Opportunities



CYGFM 01, 760 minutes (8 orbits)

Coverage and Downlinks Opportunities

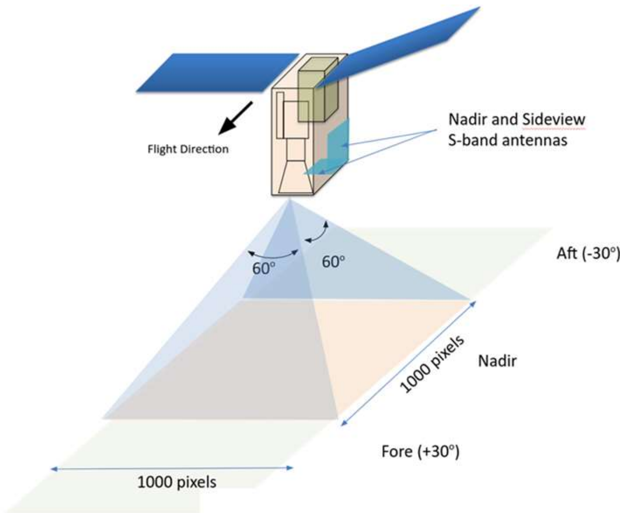


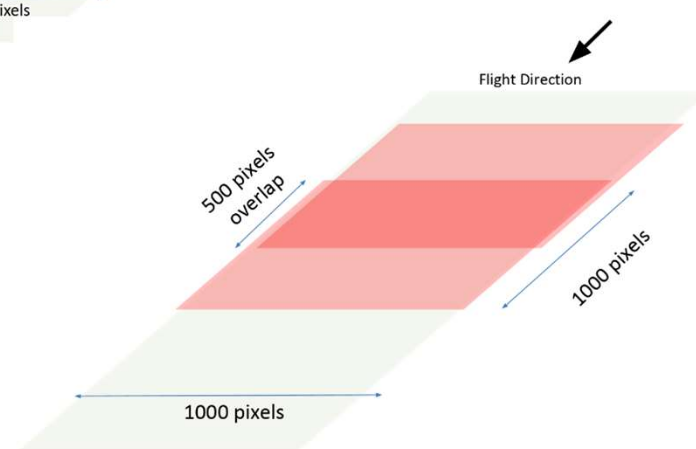
CYGFM 01, 1260 minutes (~13 orbits, 21 hours)

Instrument model implemented in VCE

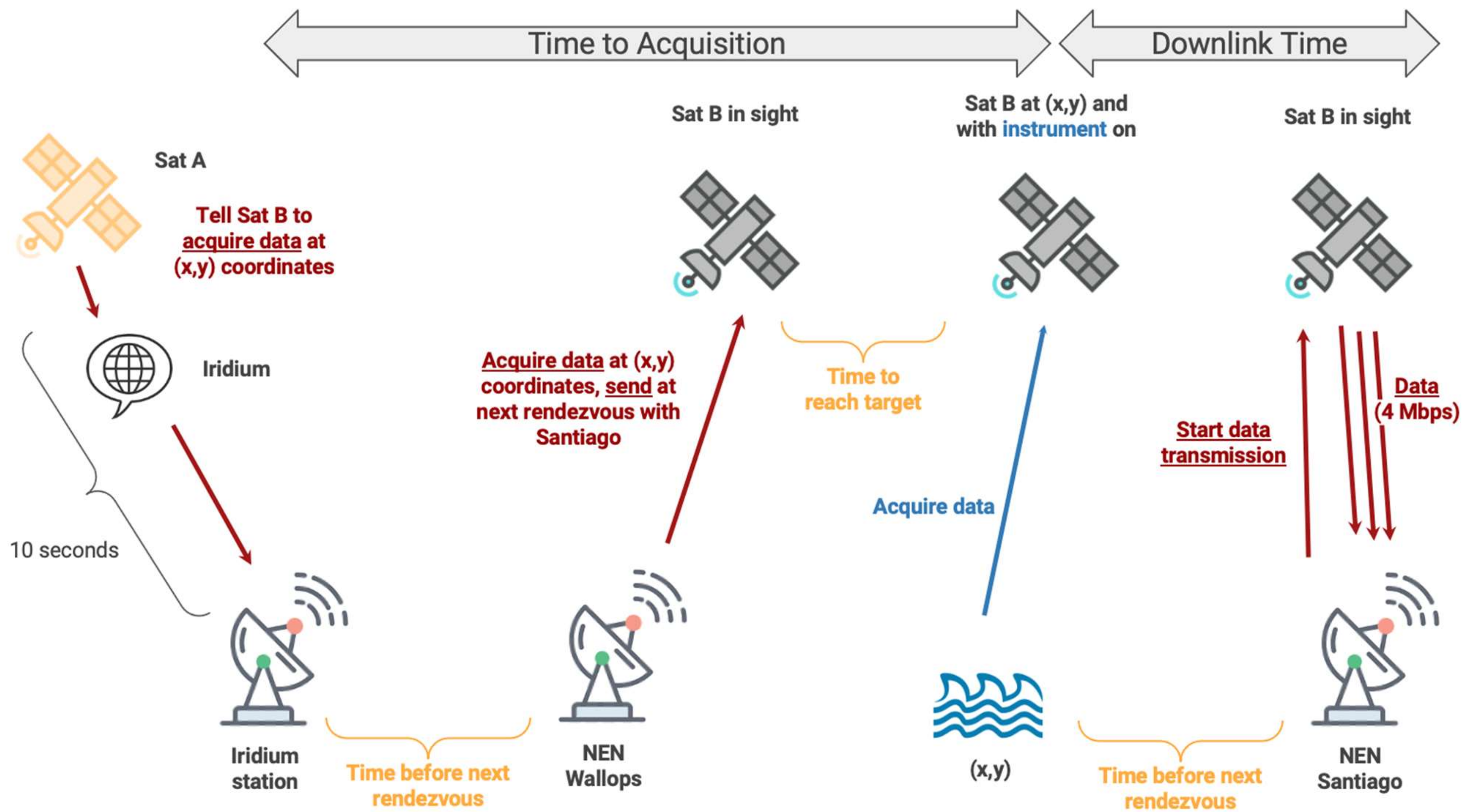
Camera

- 1 frame every 41 seconds
  16-bit x 1024 x 1024 images
- Data rate of 0.39 Mbps
  - 0.1 Mbps after compression
- Altitude of 550 km
  GIFOV = 635 km (620 m/pixel)
- Intended to be representative of the StereoBit concept in terms of coverage and data volume

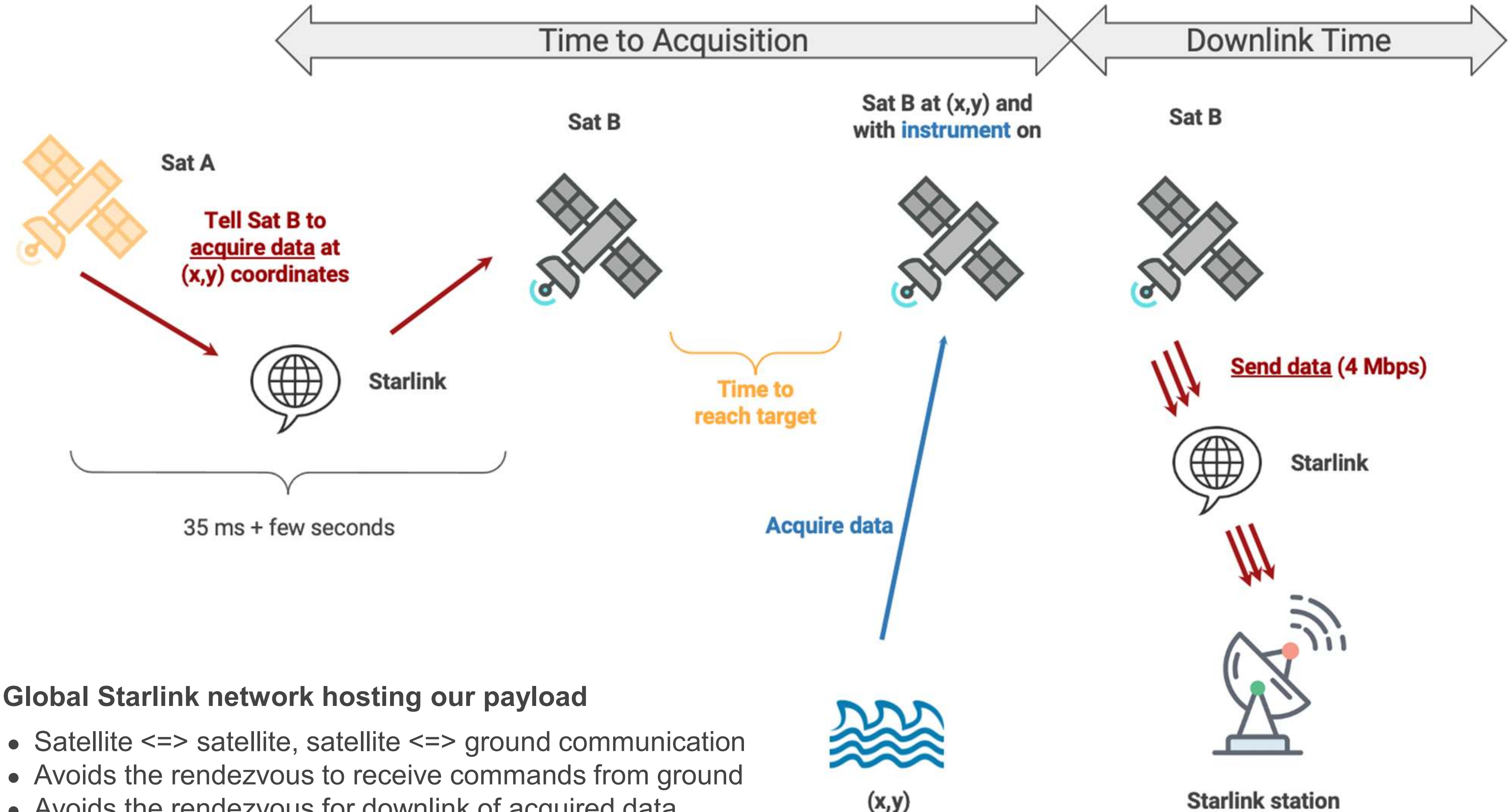




Strategy #1: Coordination through Ground



Strategy #2: Autonomous Coordination



Global Starlink network hosting our payload

- Satellite <=> satellite, satellite <=> ground communication
- Avoids the rendezvous to receive commands from ground
- Avoids the rendezvous for downlink of acquired data
- Avoids the use of NEN ground stations
- Remaining latency source: time to reach target

In progress: Prototype Implementations

Goal: To facilitate the evaluation/testing of computation/coordination strategies

- Implement satellite and ground station operations
- Developed in Python, packaged as Docker containers for VCE
- Communication through ZeroMQ (retransmit until delivered)
- Emulate computation for image analysis/compression
- Monitor GPS, wait for target coordinates to be within FOV
- Easily configurable to test different scenarios

VCE Enhancement: Support for global communication networks

Presentation Contents

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

Summary of Accomplishments and Future Plans

- Summary of Current State
  - Pipeline delivered with proxy data
  - Testing on Dev boards
  - VCE model of constellation started
- Future Work Plans
  - Complete integration and validate end-to-end (TRL=5)
  - Prove Leader-Follower concept
  - Install on SpaceCube and test (TRL=6) ← Potential Covid-19 Impact
  - Explore constellation concepts on VCE
    - Add global network simulation to VCE
    - Resources vs. CONOPS vs. Constellation trades
  - Publish our work
    - Application/SpaceCube paper
    - Constellation paper

Presentation Contents

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

Publications

- Carr, J., C. Wilson, D. Wu, M. French, and M. Kelly, "AN INNOVATIVE SPACECUBE APPLICATION FOR ATMOSPHERIC SCIENCE", Session on New Observing Strategies, Paper 3643, IGARSS 2020, October 2020.

- Carr, J., C. Wilson, D. Wu, M. French, and M. Kelly, "StereoBit: Onboard Intelligence for a Stereo Winds Constellation", New Observing Strategies for Earth Science eLightning, IN019-12, AGU 2020, December 2020.

List of Acronyms

3D	Three-Dimensional
AIST	Advanced Information Systems Technology
APL	Applied Physics Lab
cFE	Core Flight Executive
cFS	Core Flight System
CMIS	Compact Mid-wave IR System
CPU	Central Processing Unit
CTI	Compact Thermal Imager
ESTO	Earth Science Technology Office
FPGA	Field Programmable Gate Array
GEO	Geostationary Orbit
GOES-R	Geostationary Operational Environment Satellite R-Series
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HARP	Hyper-Angular Rainbow Polarimeter
HLS	High Level Synthesis
IGARSS	IEEE Geoscience and Remote Sensing Society
IRAD	Internal Research and Development
ISI	Information Sciences Institute
ISS	International Space Station
JHU	Johns Hopkins University
JPEG-LS	JPEG Lossless Compression
JPL	Jet Propulsion Laboratory
LEO	Low-Earth Orbit
MISR	Multi-Angle Imaging Spectro-Radiometer
MWIR	Middle Wavelength Infrared
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOS	New Observing Strategies
PACE	Plankton, Aerosol, Cloud, Oceanic Ecosystems
PI	Principal Investigator
RRM3	Robotic Refueling Mission 3
SfM	Structure for Motion
SME	Subject Matter Expert
SORCE	Solar Radiation & Climate Experiment
STAR	Satellite Applications and Research
T2SL	Type-2 Super Lattice
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TRL	Technology Readiness Level
TSIS	Total and Spectral Solar Irradiance Sensor
USC	University of Southern California
VCE	Virtual Constellation Engineer

SPCTOR: Sensing-Policy Controller and OptimizeR

Mahta Moghaddam[1], PI
Dara Entekhabi[2], Co-I
Agnelo R. Silva[3], Consultant
Ruzbeh Akbar[2]
Sam Prager[1]

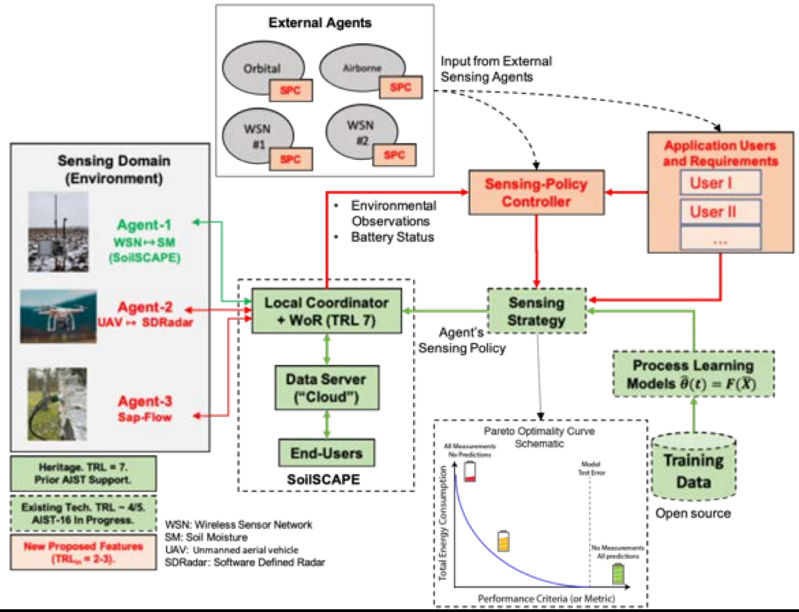
[1]University of Southern California, Los Angeles, CA, USA
[2]MIT, Cambridge, MA, USA
[3]METER Group Inc. Pullman, WA, USA

Annual Review Presentation
04 January 2021

SPCTOR: Sensing-Policy ConTroller and OptimizeR
PI: Mahta Moghaddam, USC

Objective
Develop a framework to coordinate and optimize sensing strategies, in particular for soil moisture profiles, across multiple Agents by means of a new machine-learning-based entity. Specific objectives are:

1. Develop a Sensing-Policy Controller (SPC) for multi-Agent observation strategy coordination and optimization. (NOS elements b and c).
2. Develop and demonstrate integrated operations between in situ wireless sensor networks and unmanned aerial vehicle (UAV) based software defined radars (SDRadars) for optimized spatiotemporal root-zone soil moisture observations (NOS element a)



Approach
1. Define in-situ networks and UAV-based sensors as "Agents" providing complementary spatial and temporal samples of science quantity under observation; targeted quantity is surface-to-root-zone profiles of soil moisture
2. Build upon existing SoilSCAPE (TRL ~ 7) heritage and expand Local Coordinator (LC) to interoperate with UAVs
3. Integrate SDRadar as a payload into UAV
4. Generate "Pareto Curves" – energy vs performance – for different Agents based on Application Users
5. Generate and Optimize "Contract Curve" between Agents
6. Using new observations and updated application requirements, optimize/update/coordinate observation strategies between Agents, including optimal UAV path planning

Co-Is/Partners: Dara Entekhabi (MIT), Agnelo Silva, (METER)
Ruzbeh Akbar (Postdoc, MIT)

Key Milestones (** Covid modified)

• Define target user application scenarios of SPC	01/20
• Develop Sensing Policy pareto-optimal curves for WSN and UAV; develop trade-off framework using ML approaches	06/20
• UAV-SDRadar and UDS integration: software demo	12/20**
• Assemble UAV-SDRadar and integrate LC-WoR with UAV	03/21**
• Lab demonstration of WSN-LC and UAV communication	05/21**
• Lab/Indoor Demonstration of 2-way communication of WSN-LC, LC-WoR, two UAVs and SDRadar	10/21**
• WSN-UAV interoperation demo in the field (Tonzi, or WG)	04/22**

SPC TRL_{in} = 2   WSN-UAV TRL_{in} = 4

Team Members: Students and Post-Docs

Ruzbeh Akbar

Postdoctoral Research Associate, MIT

Sam Prager

PhD Candidate, USC

Negar Golestani

PhD Candidate, USC

Asem Melebari

PhD Candidate, USC

Emma Gronstad

BS Student, USC

Rajan Paul

BS Student, USC

Will start PhD in SP'21

Archana Kannan

MS Student, USC

Presentation Overview

- Project Background and Objectives
- Technical Progress To-date
  - Integration of SoilSCAPE and UAV
  - UAV-SDRadar
  - UAV Path Planning
- TRL assessment
- Project Schedule

Background

- 2018 Decadal Survey identifies soil moisture, and related sensing technologies, as a “Primary Targeted Observable”

- Multiple missions are currently observing, or planning to observe, soil moisture: SMAP, CYGNSS, SMOS, NISAR, ALOS-2, AMSR-E, Sentinel-1, etc.

- Soil moisture has multiple scales of variability in both space and time; highly heterogeneous; more so for root-zone soil moisture due to the 3rd spatial dimension of variability

- Observation technologies for soil moisture need to be space/time adaptive and accommodate such variabilities

- We build on existing ESTO-developed soil moisture in-situ sensor network technologies (SoilSCAPE suite) by defining **“Agents” that cooperate** to cover the space/time scales and sampling needs of missions in a dynamic architecture that includes both fixed in-situ sensors and mobile UAV-based sensors

- Soil moisture is not the only Earth system variable with these heterogeneous properties; proposed technology has utility for other observations as well (e.g., freeze/thaw, permafrost, wetland state, vegetation (esp. crops and regrowth), surface deformation, and others)

Project Objectives

Objective 1: Develop a Sensing-Policy Controller (SPC) for multi-Agent observation strategy coordination and optimization

- *SPC's task: coordinate observation strategies between multiple sensing agents*
- *Learns from recent data and observations, considers Agents' energy constraints, and respective application (or science) based performance metrics, and then makes the determination on whether to update an Agent's observation strategy.*

Objective 2: Develop and demonstrate integrated operations between in-situ WSN and networks of UAV-SDRadars based on SPC commands

- *Expand in situ sensor network capabilities to enable integration, interaction, and interoperability between ground sensor networks and UAV-based software-defined radars (SDRadars)*
- Objective addresses the requirement for adaptive and heterogeneous sampling in space and time

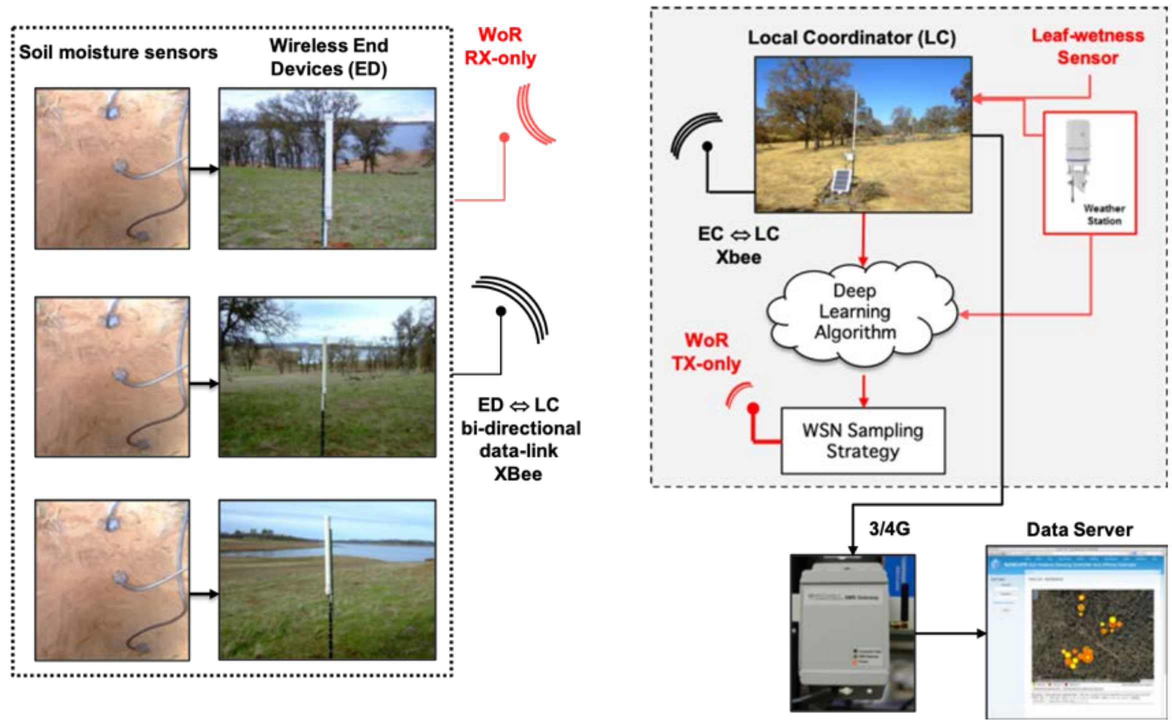
Both address **ESTO-AIST-NOS objectives**:

a. Evaluation/comparison of alternative observing [sensing] strategies (Obj. 1).
b. Estimation of science value to enable comparison of observing strategies (Obj. 1).
c. Integrated operation of different types of instruments or at different vantage points (Obj. 2).

Previous Work (1)

Existing technology heritage in Wireless Sensor Networks (WSN)

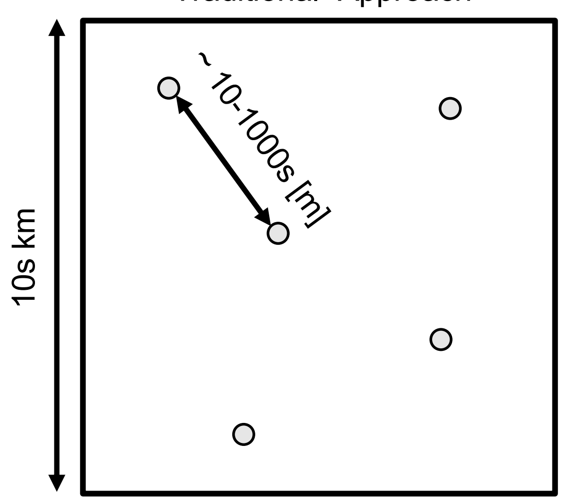
- **SoilSCAPE**: Soil Moisture Sensing Controller and Optimal Estimator (TRL 7)
- Clusters of medium-scale (< 500 [m]) *in situ* (WSN)
- Measure and report near real-time surface-to-root zone soil moisture (top 5 [cm] – 100 [cm])
- SoilSCAPE primary objectives:
  - Advancement in low-power wireless sensing technologies.
  - *Ground truth soil moisture for NASA Earth Science missions → SMAP, AirMOSS, and recently CYNGSS!*
- Implementation
  - Custom made low-power “wireless dataloggers.”
  - Wireless network commutation protocols and data-delivery.
- Recent developments:
  - “Wakeup-on-Radio” (WoR) Concept: on-demand sensor command and control, e.g., event-based reaction
  - Machine Learning based sensor automation



Role of WSN and UAV in Remote Sensing

- Landscape heterogeneity of soil moisture is integrated (or averaged) within satellite FOV (typically a few km)
- The challenge in validating remote sensing products *is adequate and representative sampling of heterogenous ground conditions.*
- Distributed WSNs within FOV will increase representativeness. Yet, WSN are “static”.
    - Network deployment considers many different factors (topography, land cover, etc.)
    - Limited capabilities in wide-spread sensor networks that adequately cover and measure heterogenous landscape soil moisture
- UAVs are mobile and can “gap fill”/complement WSN.
    - However, ***UAV and WSN actions must be coordinated***.

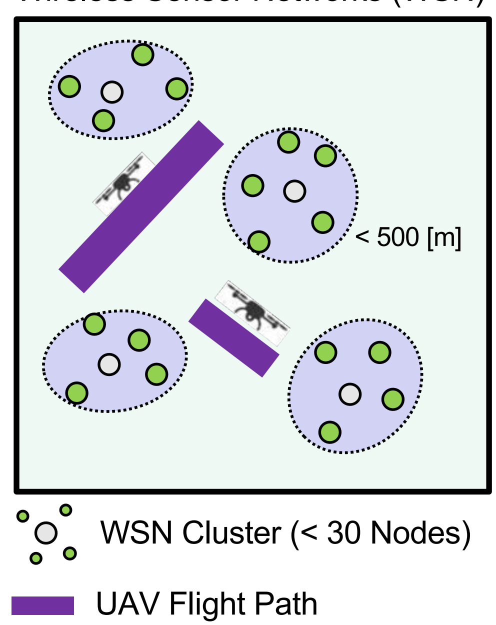
“Traditional” Approach



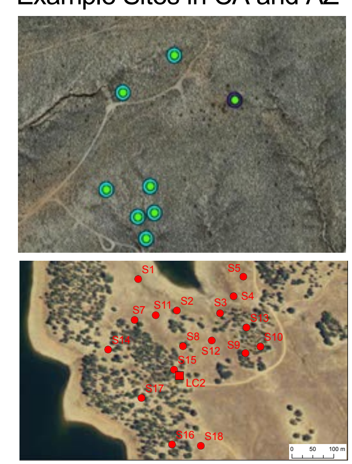
○ Single (Point) Soil Moisture station

https://www.ncdc.noaa.gov/crn/

Wireless Sensor Networks (WSN)



Example Sites in CA and AZ



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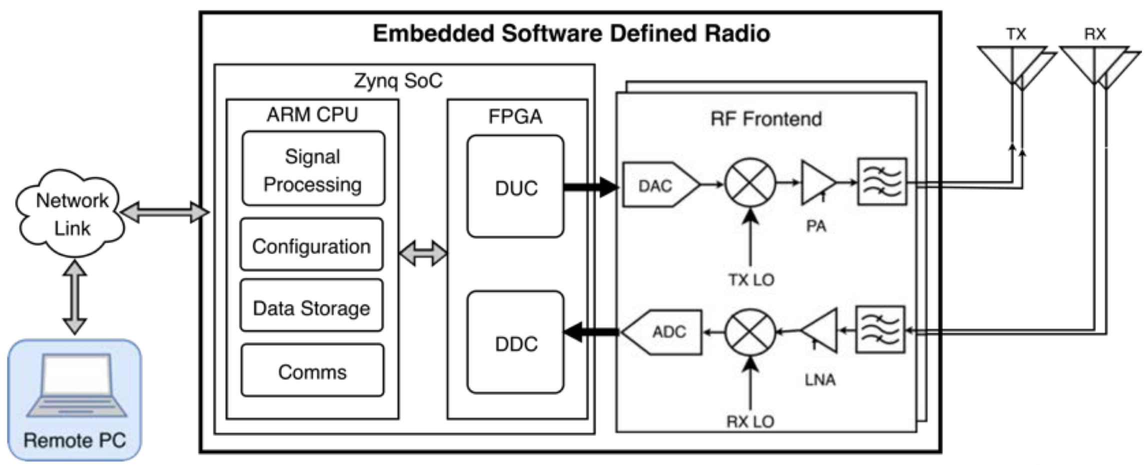
- TRL assessment



Integration of SoilSCAPE and UAV for combined operations

- <u>Objective</u>: enable UAV flights based on SoilSCAPE wireless sensor measurements
- Each system (SoilSCAPE and UAV) was <u>independently developed</u>.

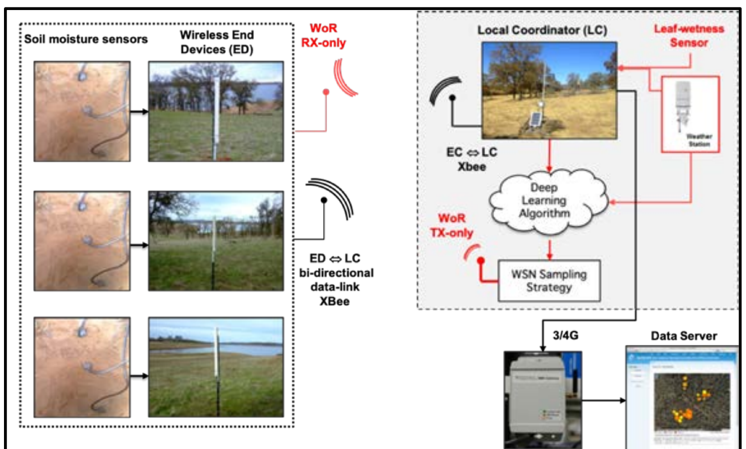
Proposed solution:

- Custom electronics required as the interface between SoilSCAPE Local Coordinator (LC) and UAV Manifold: *UDS board*
- Software configurable to handle two-way data and message passing between LC and UAV.
- Raspberry Pi micro-computer enabled

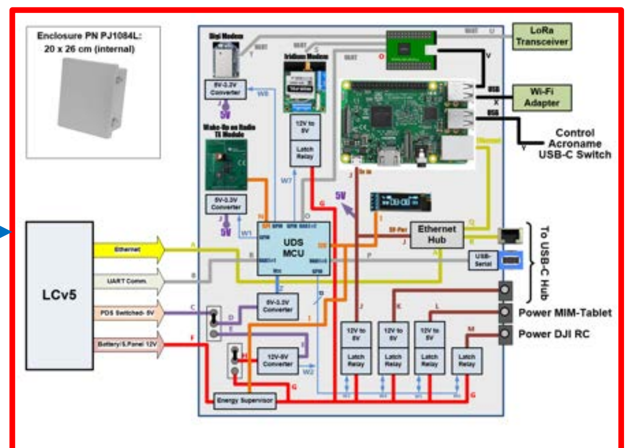
Demo in a few slides

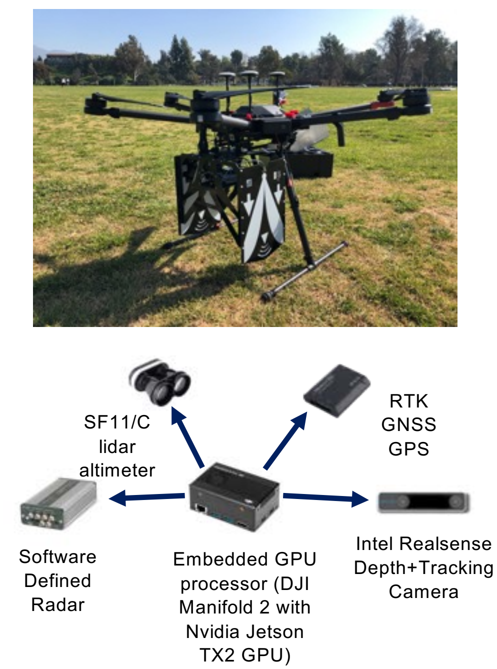
UAV-SDRadar (TRL 4)

SoilSCAPE (TRL 7)



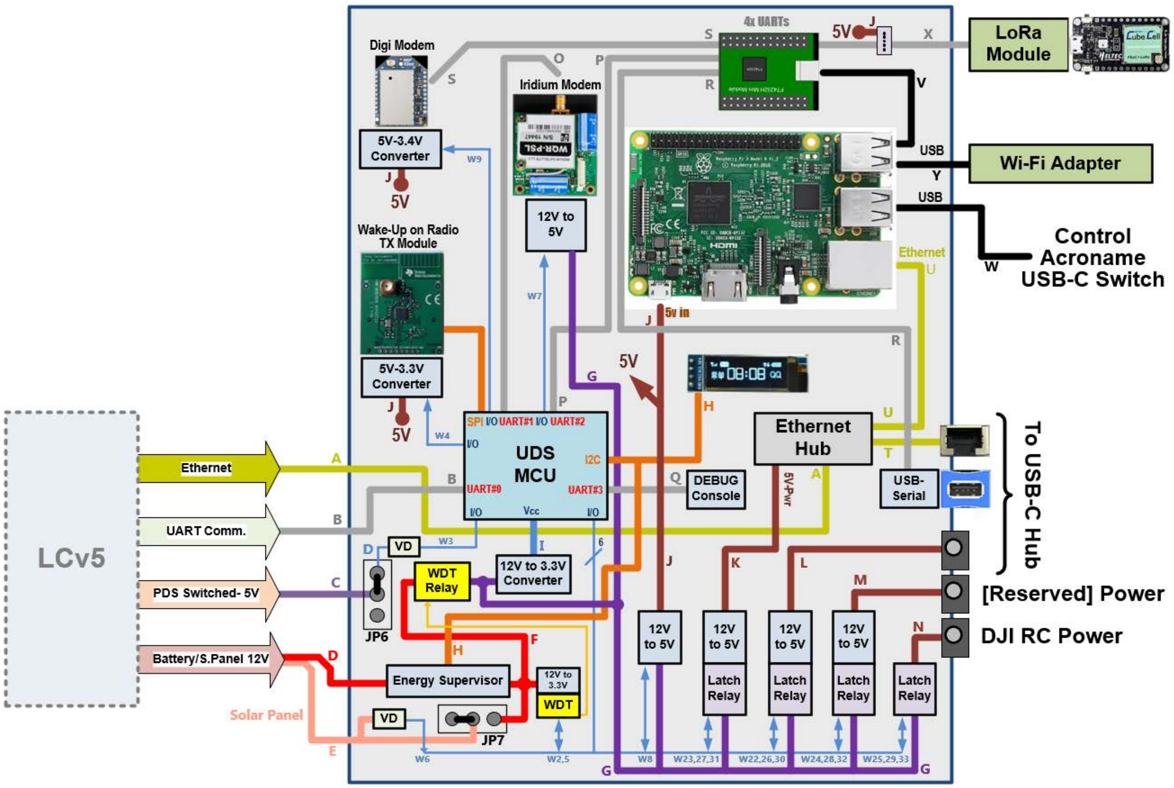
UAV Data-server Board (UDS)

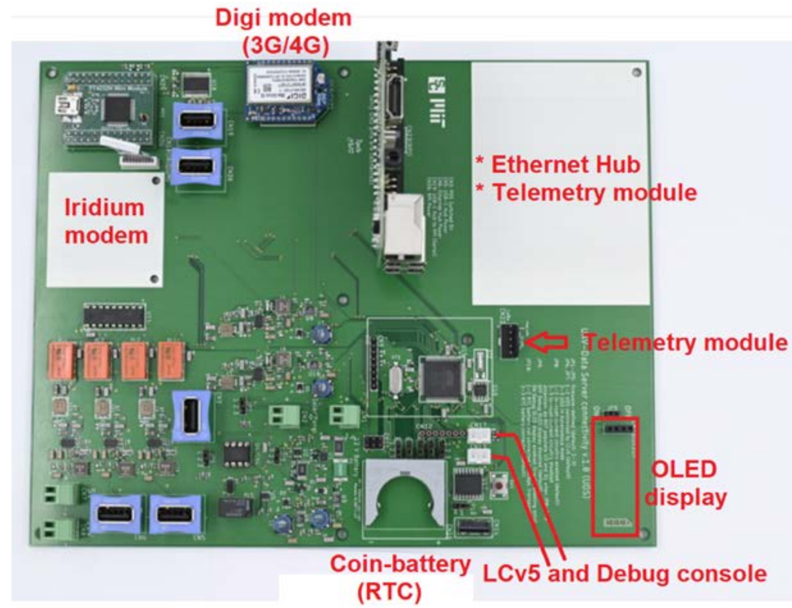




Next generation UAV-SDRadar sensor payload

UDS Board
Overall Architecture





Three parallel communications channels

1. Physical serial and ethernet for failsafe reliable control and high bandwidth data transfer
2. WiFi Local Area Network (WLAN) for flexible control and medium bandwidth data transfer when UAV docked
3. LoRa radio for long range control, status, and low bandwidth data transfer when UAV in flight

Presentation Overview

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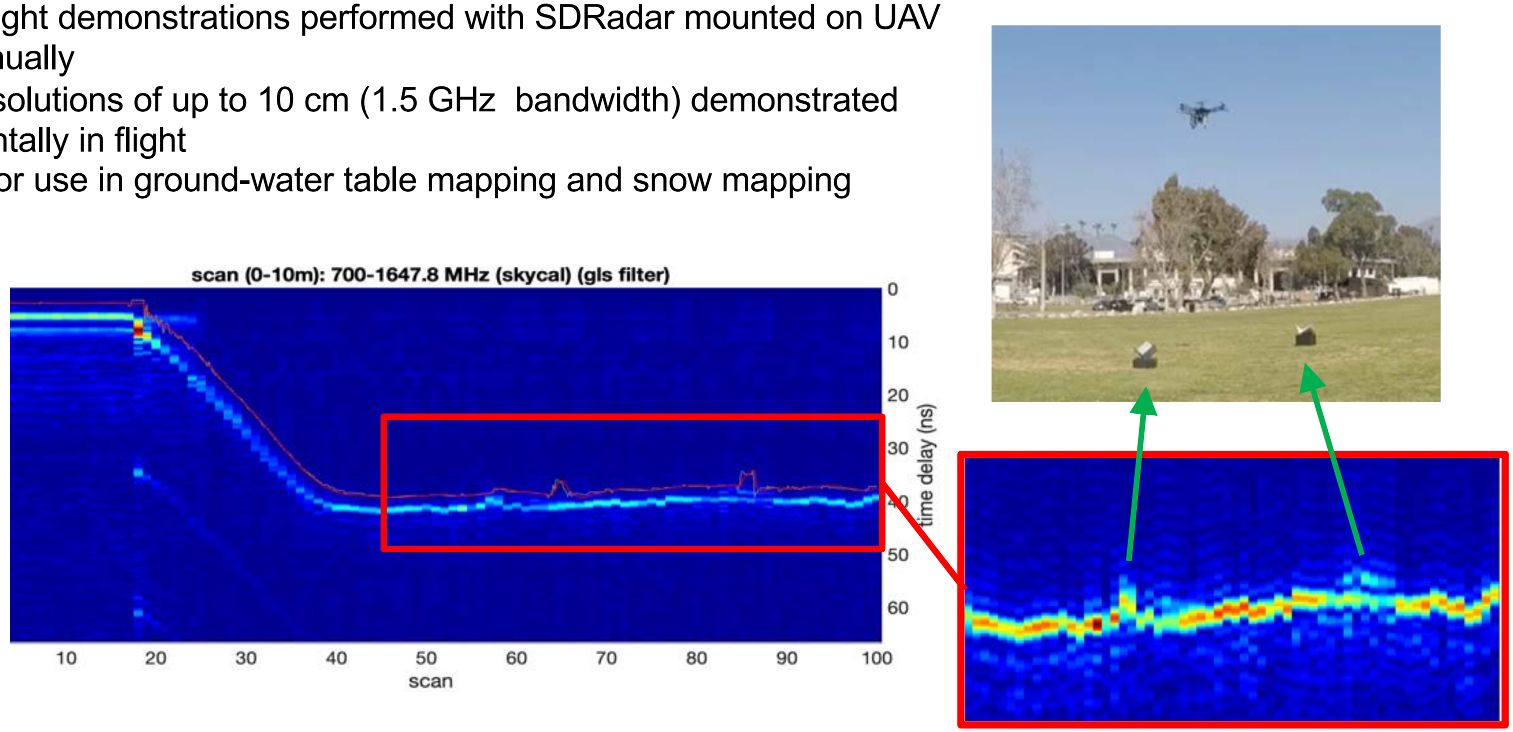
SDRadar and UAV System Overview

- Software defined radar (SDRadar) implemented in low-cost battery-powered software defined radio (SDR)
  - Implements frequency-stepped synthetic wideband waveform techniques to achieve arbitrary radar resolution performance
  - Fully configurable at run-time
  - Capable of robust independent operation in event of communication dropout
  - Software basis allows for tiered data processing modes
- Additional onboard embedded Jetson TX-2 GPU-based processor for UAV flight control, Radar data processing, and future autonomy and machine learning functionalities
- Multiple flight demonstrations performed with SDRadar mounted on UAV flown manually
- Range resolutions of up to 10 cm (1.5 GHz bandwidth) demonstrated experimentally in flight
- Planned for use in ground-water table mapping and snow mapping (USGS)

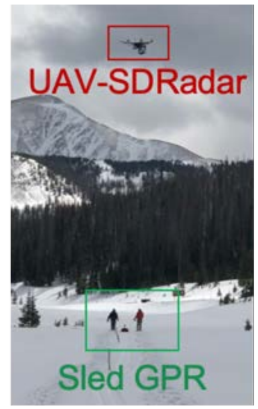
UAV with SDRadar mounted

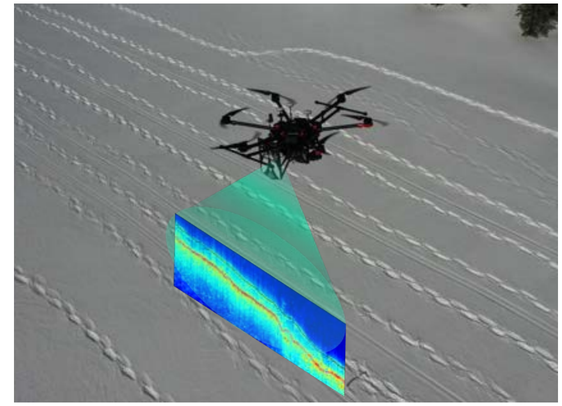


Results of Flight Demonstration. Radargram shows the surface return as well as the presence of two small corner reflectors.

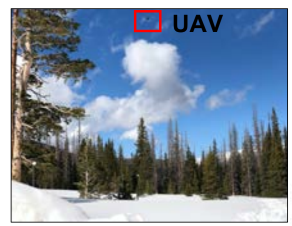
UASnow 2020 Field Campaign: Cameron Pass, CO

- Under joint NASA/ESTO/Ames and USGS Innovation Center support, UAV-SDRadar was flown in March 2020 to image snow fields in Cameron Pass, Colorado [*]
- Two transects flown:
  - **Michigan River Site (Meadow transect)**
  - **Joe Wright Site (Forest transect)**
- USGS/CSU collected GPR and multi-angle optical imagery (SFM)
- Novel Synthetic Wideband Waveform Reconstruction used to synthesize up to 1.5 GHz BW (10 cm radar resolution)
- Successful imaging of ground and snow surface layers
- Two-way travel time (TWT) compared with 'ground truth' GPR measurements
- Snow pit sub-surface layers imaged at Michigan River Site

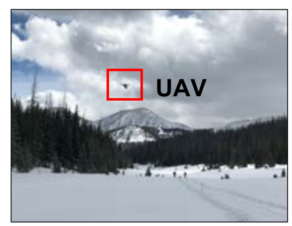


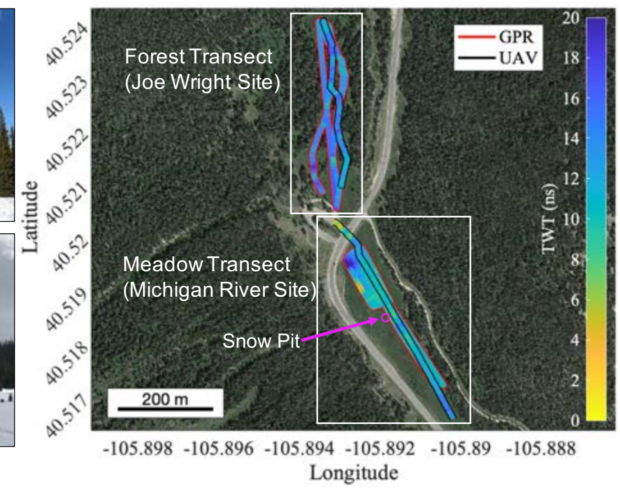


Forest transect



Meadow transect

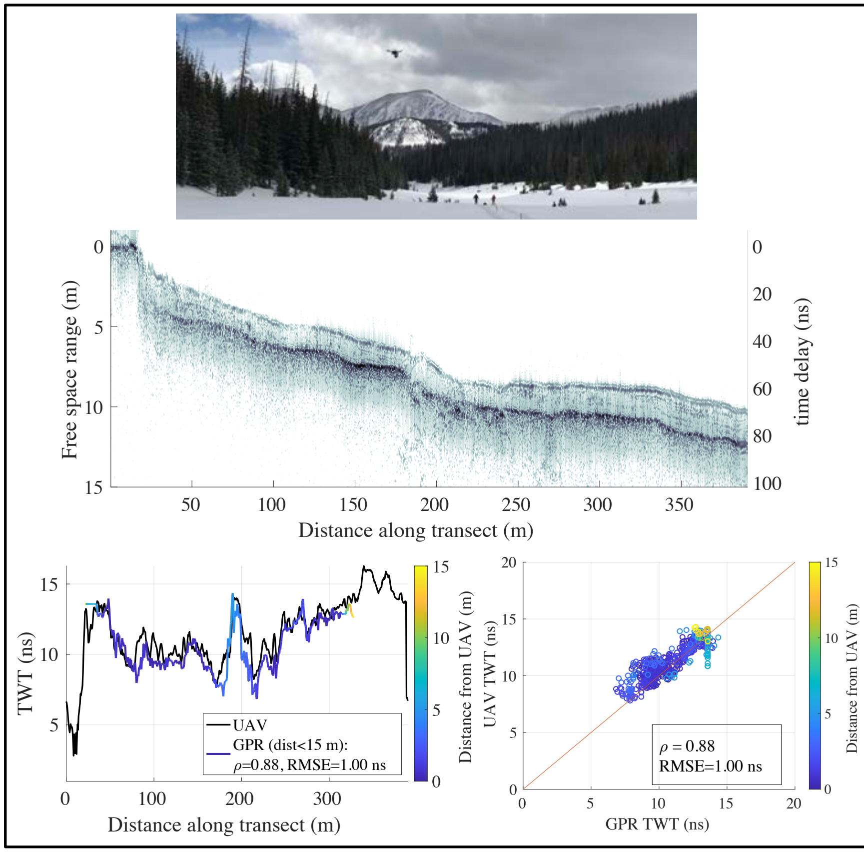




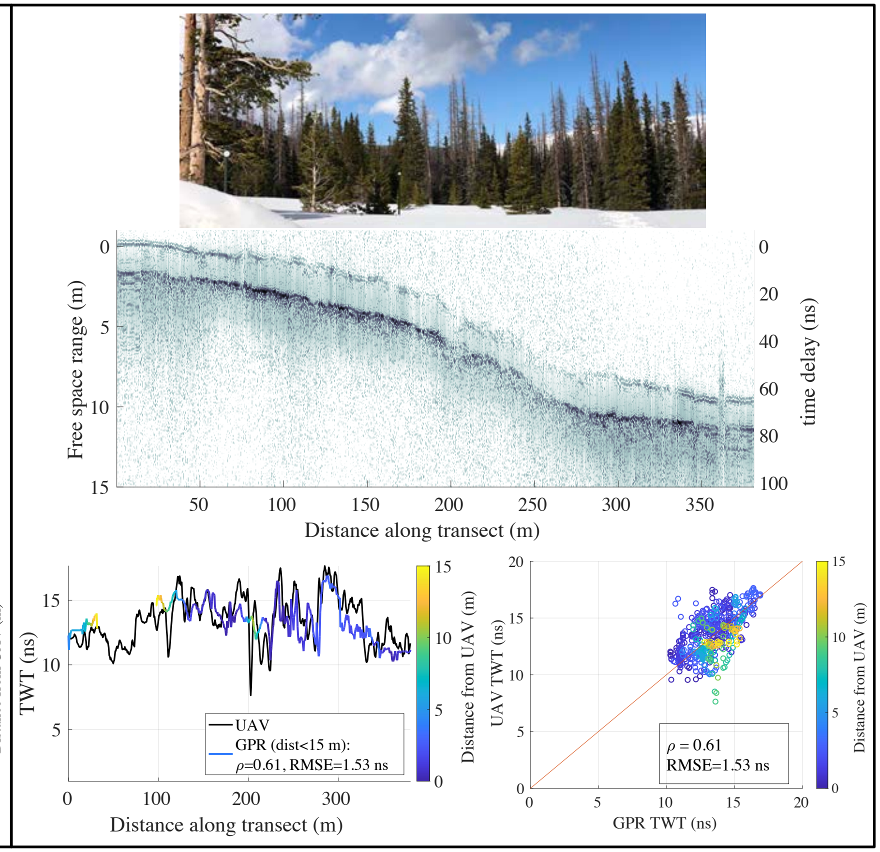
[*] Prager et al., "Snowpack Imaging with Autonomous UAV-mounted Software Defined Radar," Manuscript in Preparation, 2020

UAsnow 2020 Field Campaign: UAV-SDRadar Sample Science Data

Meadow transect



Forest transect



Motion-compensated radargram

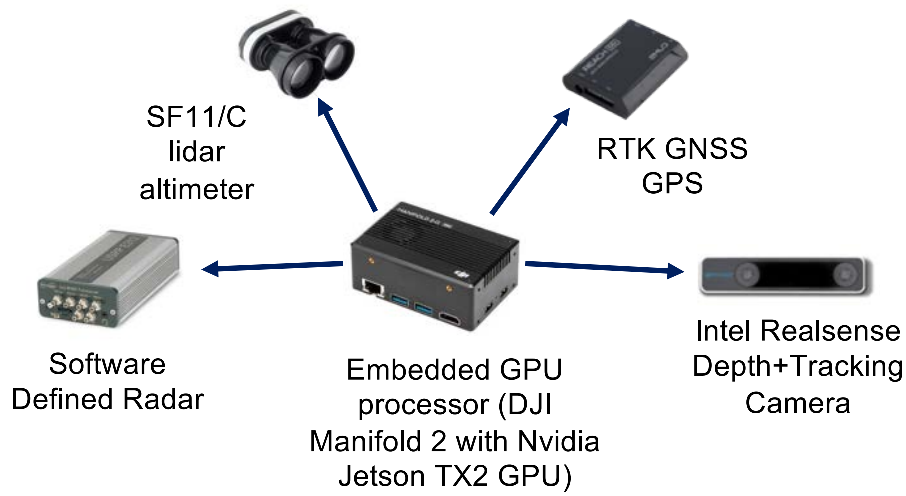
UAV-SDRadar and GPR TWT measurements

Next generation UAV-SDRadar sensor payload

Onboard GPU processor will handle:

- Onboard flight planning, precision landing on UAV Docking Station (UDS), and autonomous flight control
- Sensor management and data fusion
- Radar data processing and compression
- Communication with Local Coordinator (LC)

Integration with UAV docking station charging electronics (Purchased from Skysense)

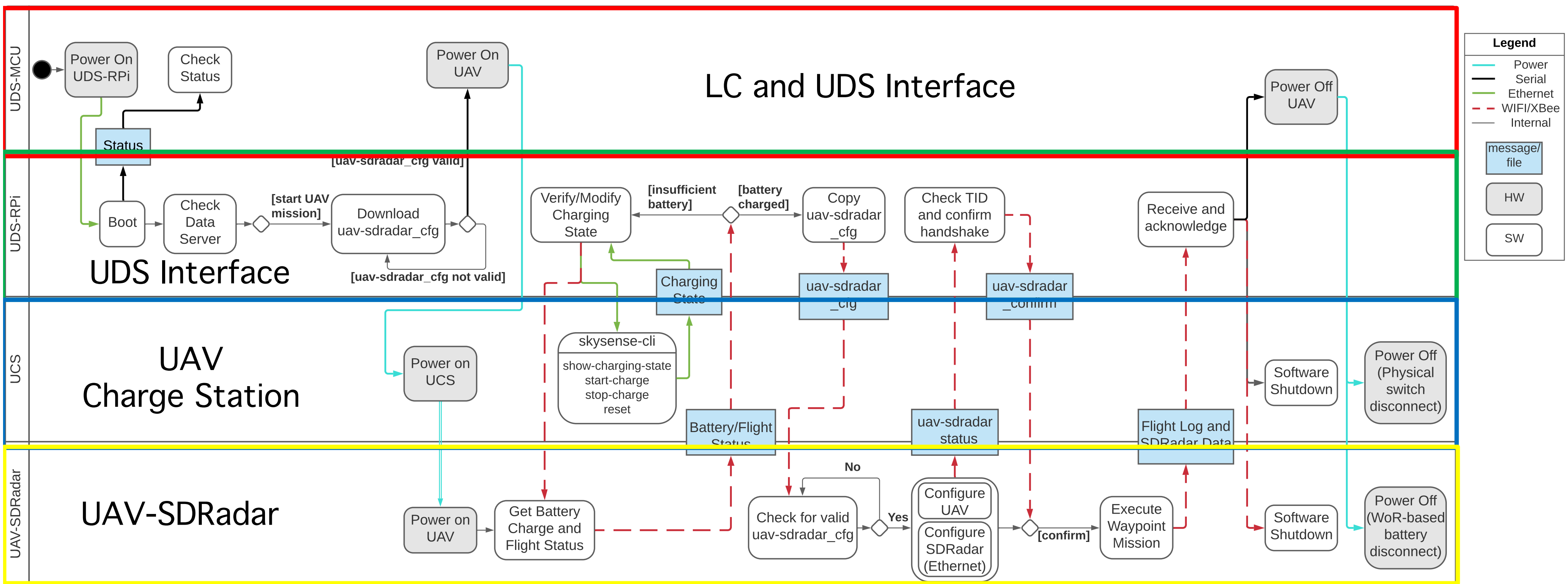


Next generation UAV-SDRadar sensor payload

Existing Desktop/Laptop SDRadar Client Control GUI Application

- **SDRadar Client Control App** developed for Android
- C++ backend, Java front-end
- Communicates with SDRadar via TCP-IP
- N Clients can connect to a single SDRadar sensor simultaneously
- Expanding to support transparent serial/LoRa-based communication

LC-UDS-UAV
Process diagram



Time →

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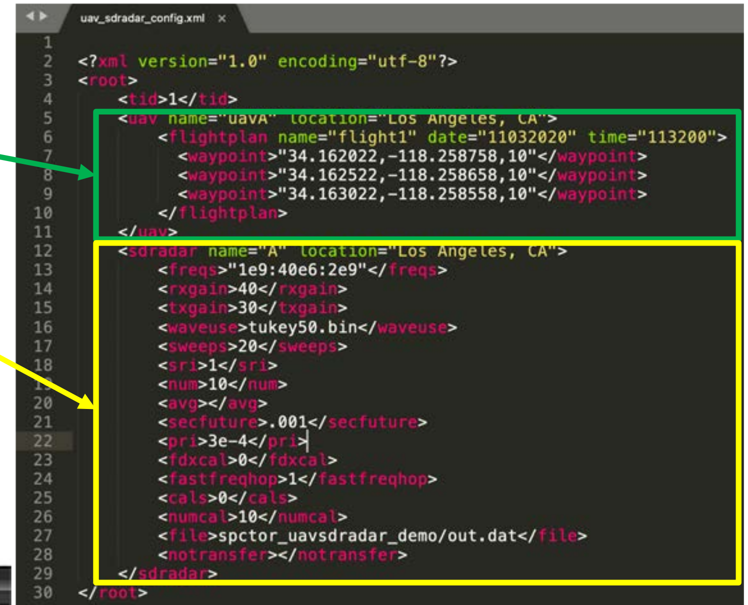
Demo:
message and data passing between
LC and UAV using the UDS Board

Please contact the PI for a copy of the demo

LC-UDS-UAV Demo Setup

- Config file generated at data server
  - UAV GPS waypoints from path planner
  - SDRadar settings and parameter
- LC, UDS, UAV working in tandem to
  - Initialize UAV and SDRadar
  - Execute radar collection and flight plan

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            <waypoint>"34.162522,-118.258658,10"</waypoint>
            <waypoint>"34.163022,-118.258558,10"</waypoint>
        </flightplan>
    </uav>
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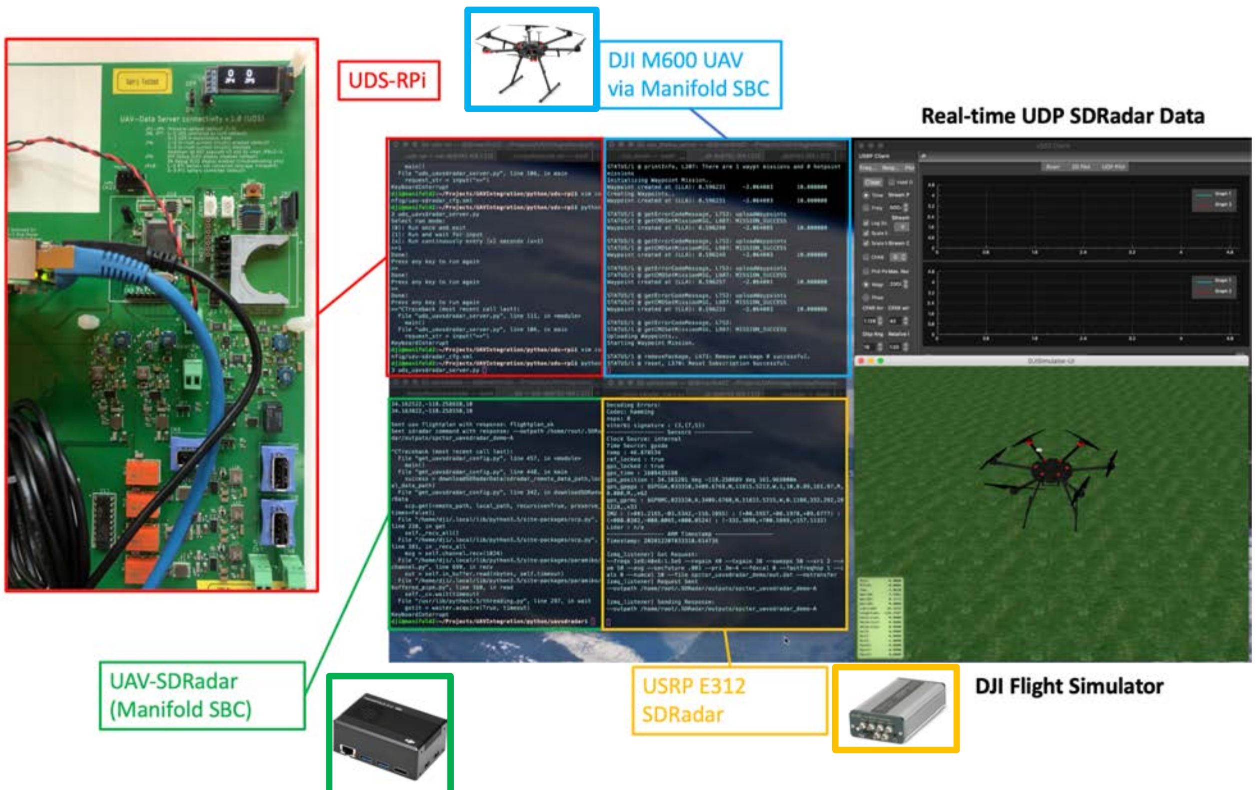

Hardware Components at work:

- Data Server
- SoilSCAPE LC
- UDS interface board
- UAV Manifold and SDRadar

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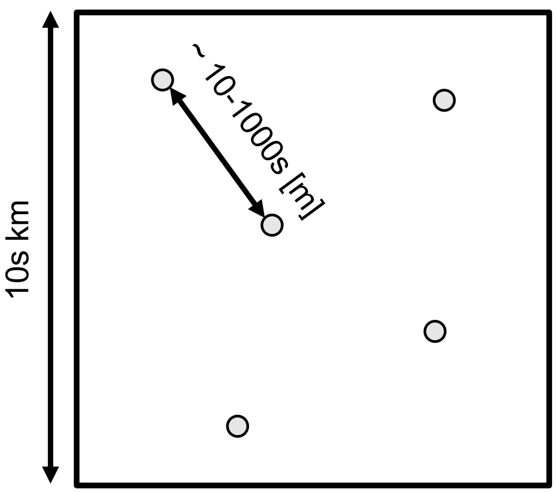
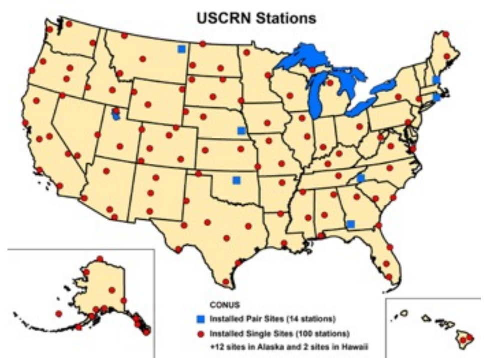
Role of WSN and UAV in Remote Sensing

- Distributed WSNs within FOV will increase representativeness. Yet, WSN are "static".
  - Network deployment considers many different factors (topography, land cover, etc.)
  - Limited capabilities in wide-spread sensor networks that adequately cover and measure heterogenous landscape soil moisture
- **UAVs are mobile and can "gap fill"/complement WSN.**
  - However, ***UAV and WSN actions must be coordinated***.

"Traditional" Approach

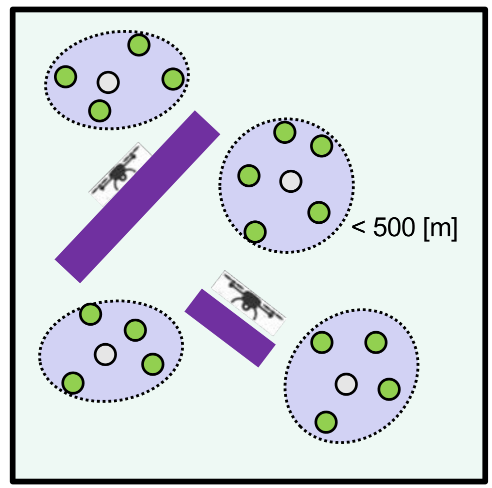


Single (Point) Soil Moisture station



https://www.ncdc.noaa.gov/crn/

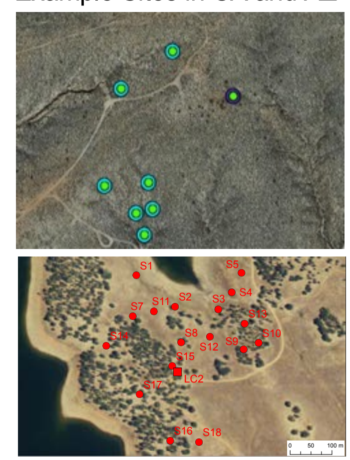
Wireless Sensor Networks (WSN)



WSN Cluster (< 30 Nodes)

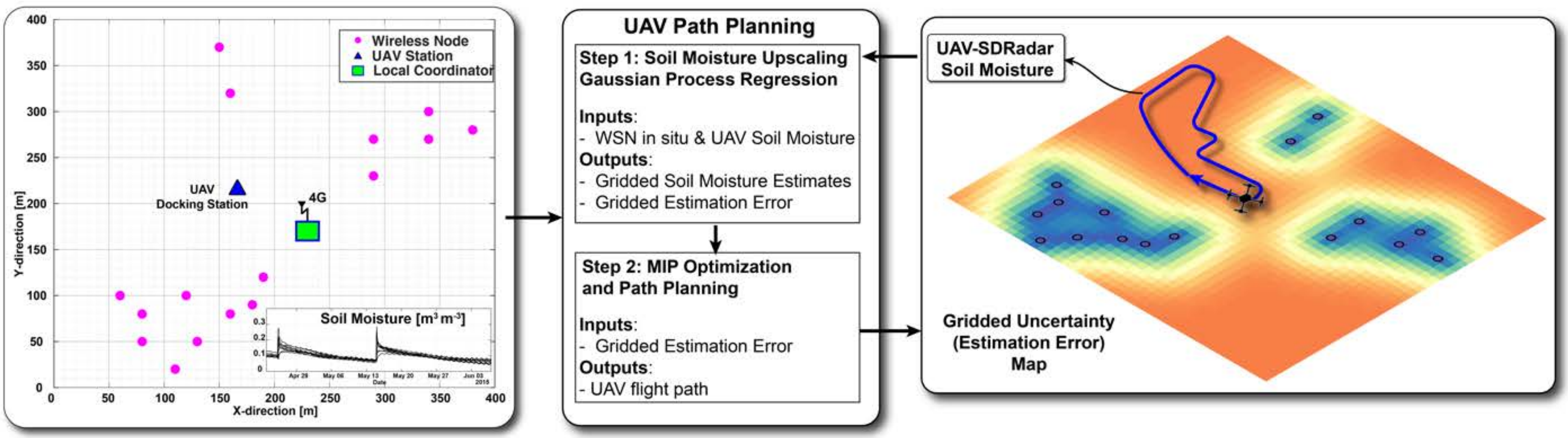
UAV Flight Path

Example Sites in CA and AZ



UAV Path Planning (v.1)
Building Blocks

1. Soil Moisture **Uncertainty** Map within Domain
   - From point (in situ) measurements to upscaled – gridded – soil moisture
   - Currently considering Gaussian Process Regression (GPR)
2. UAV Planner/Coordinator:
   - Goal: Send UAV to regions within domain with highest uncertainty
   - **Science value: by sampling most uncertain regions, overall upscaled estimates will improve**
3. Implementation
   - Linear Integer Optimization Problem
   - Maximize path over uncertain regions
   - Subject to specific constraints (including UAV limitations)

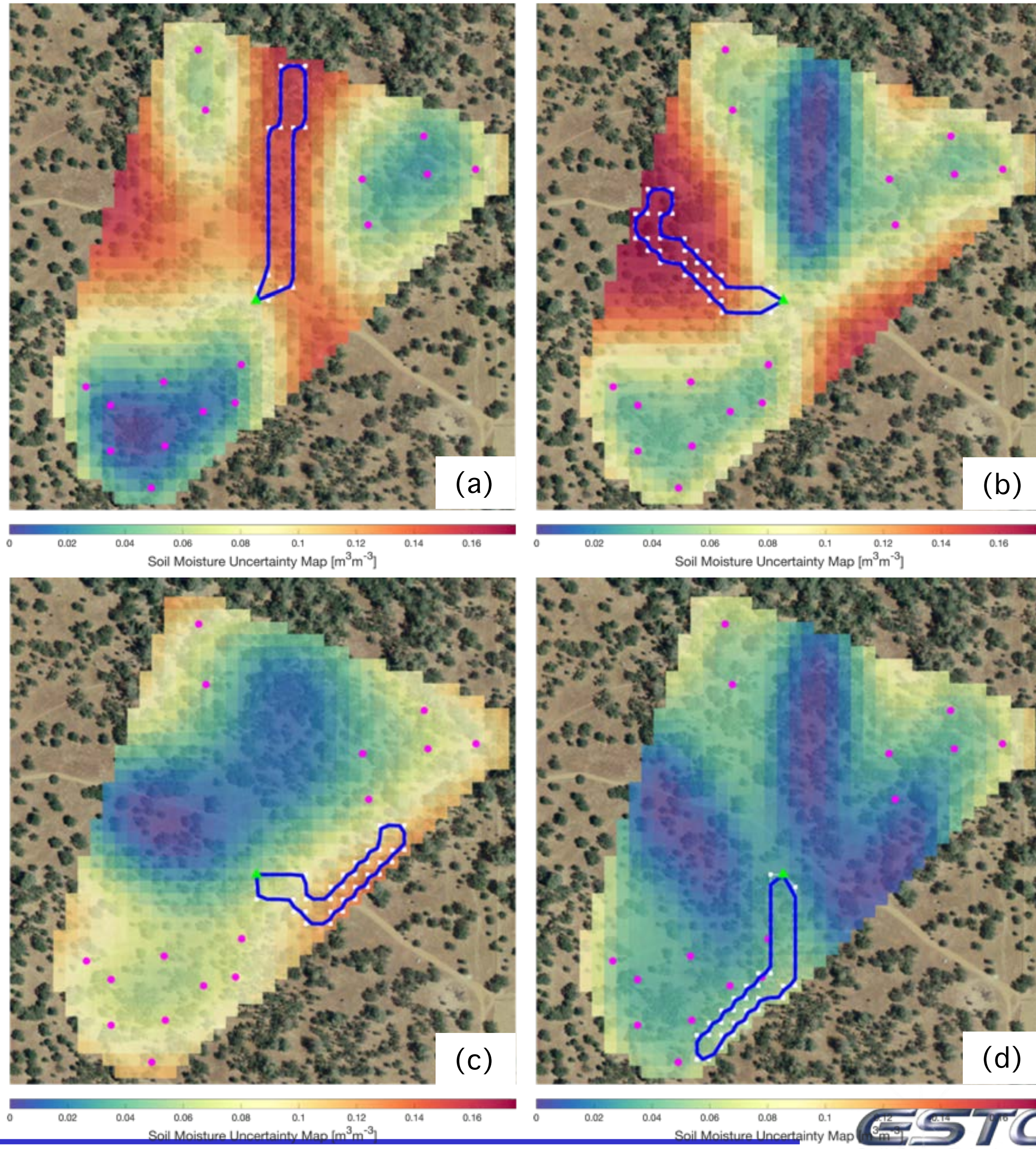


UAV Path Planning (v.1)
Initial Results with Real-world Data

Recursive UAV path planning:
(a) first iteration UAV path based on WSN information only
(b)-(d) sequence of dynamic planning were:
- for each iteration, the UAV-based soil moisture from the previous iteration is re-integrated into GPR to update *U*, and hence a new path.
- As the UAV makes more trips, *U* gradually decreases since actual soil moisture is now being measured.

In all cases white markers are the GPS waypoints, **blue** lines indicate the cubic B-spline smoothed UAV trajectory

- Sensor positions are indicated by purple markers
- the docking station by green triangle.
- The domain is 400 [m] large with 10 [m] resolution and the UAV is limited to 450 [m] trip. This example uses real soil moisture data from Tonzi Ranch from May 13th, 2015.



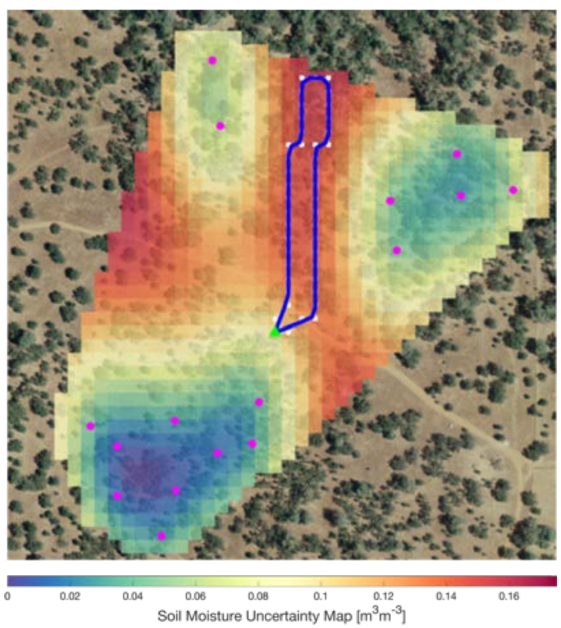
UAV Path Planning (v.1)
Initial Results with Real-world Data – Movie

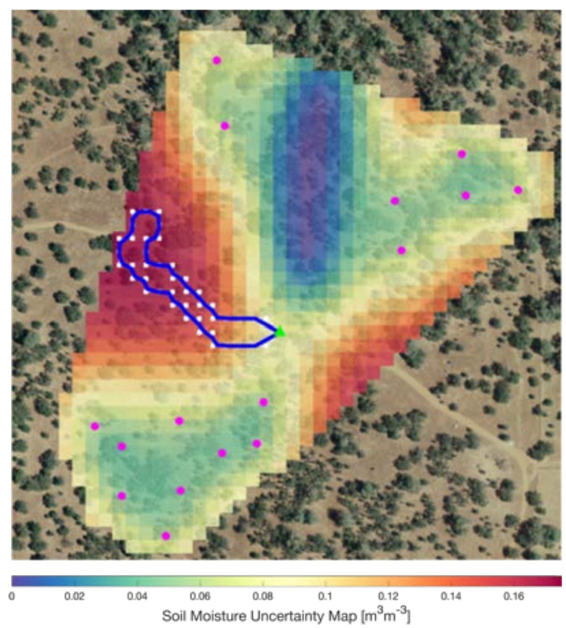
UAV Path Planning (v.1)
Next Steps

- Incorporate UAV flight dynamics into planning model
- UAV battery model (or if possible, measure actual usage)
- Extend Optimization to include multiple UAVs

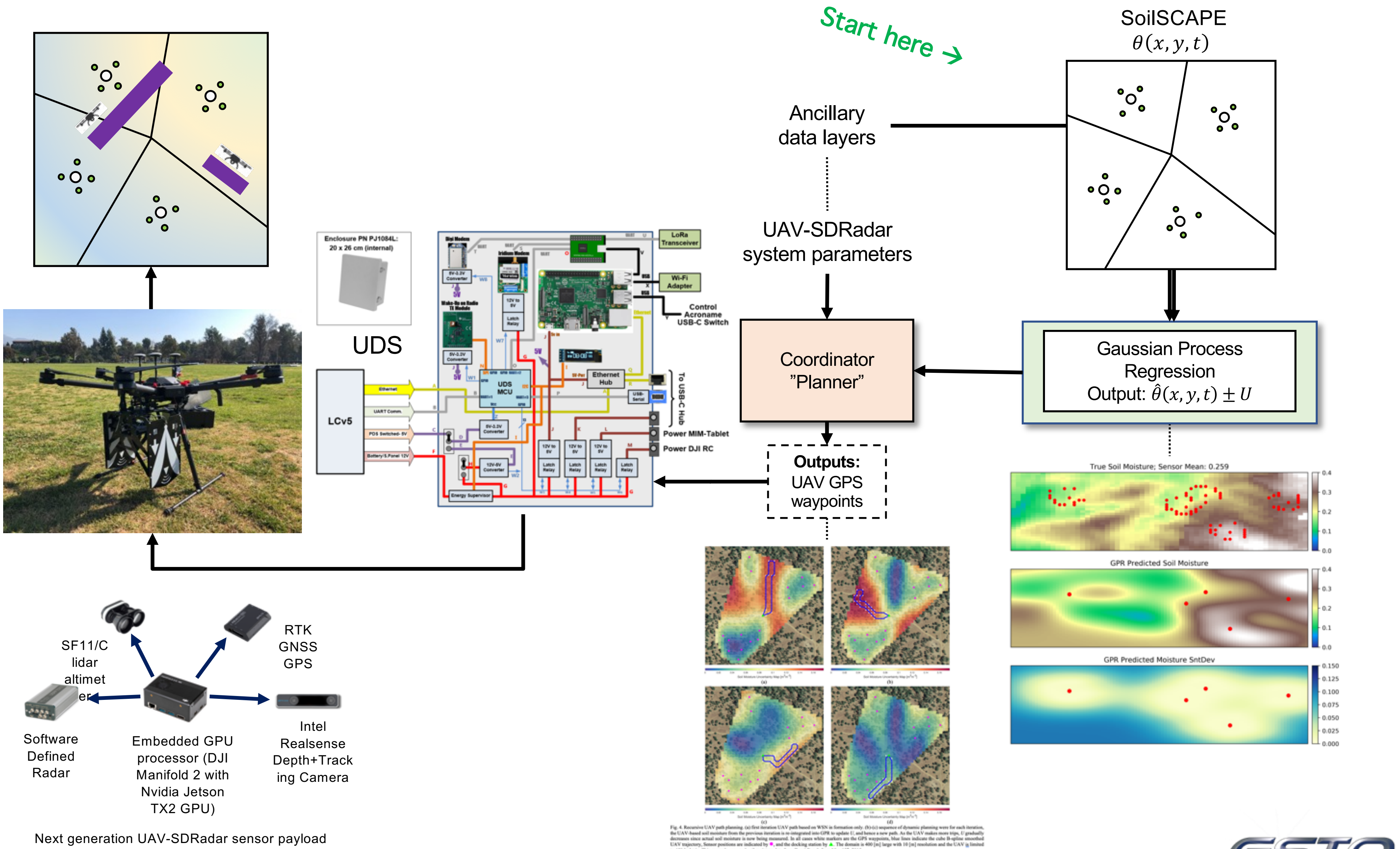
Multi-UAV Considerations:

- Resource dependent constraint (battery, memory, etc.)
- Collision avoidance
- Route separation (each path covers a different section)
- One, or multi-depot (all UAVs at same location, or multiple stations?)





SoilSCAPE + UAV-SDRadar + Path Planning
Putting everything together



Summary of Accomplishments and Future Plans

Yr-1 Highlights:

- Combined SoilSCAPE and UAV Operations:
  - Custom electronics (UDS board) that interfaces between SoilSCAPE LC and UAV for data and message passing
  - Demonstration of UAV configuration, way-point setting and flight using UDS
  - UDS board has independent data-server connectivity for redundancy
- SoilSCAPE-based UAV path planning:
  - Gaussian Process (GP) Regression for soil moisture upscaling using SoilSCAPE point-measurements.
  - MIP based optimization for UAV path planning: maximize coverage over areas where GP model under-performs

Plans for Yr-2:

- <u>Complete end-to-end hardware and field demo</u>
- Transparent Protocol design for UAV-SDRadar interface with LC
  - Use of three parallel communications channels (Physical, WLAN, LoRa) to optimize communications tasks to meet requirements
- Improvements to path planning: alternate utility functions, multiple UAVs

List of Publications

Journal papers:

Akbar, R., et al. “Wireless Sensor Network Informed UAV Path Planning for Soil Moisture Mapping”, IEEE TGRS (in preparation)

Prager, S., M. Haynes, and M. Moghaddam, “Wireless Sub-Nanosecond RF Synchronization for Ultra-Wideband Coherent MIMO Software Defined Radar,” IEEE T-MTT, accepted, July 2020.

Conference papers:

Prager, S., B. Hawkins, and M. Moghaddam, “Arbitrary nonlinear FM waveform construction and ultra-wideband synthesis,” presented at IGARSS’20 online symposium (finalist in Student Paper Prize Competition).

Moghaddam, M., R. Akbar, S. Prager, A. Silva, and D. Entekhabi, “SPCTOR: sensing policy controller and optimizer,” presented at IGARSS’20 online symposium.

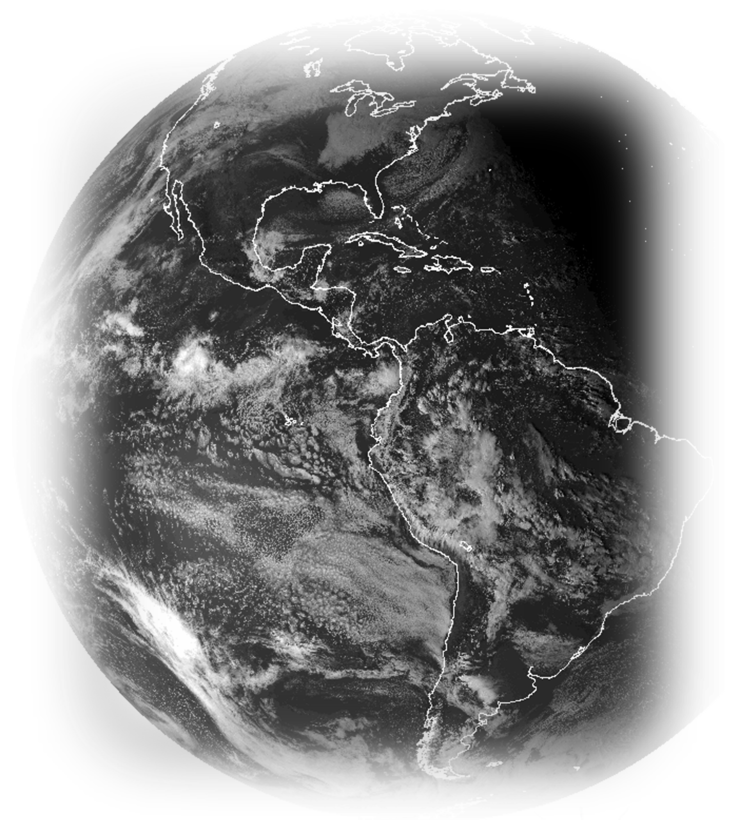
Moghaddam, M., R. Akbar, A. Silva, S. Prager, and D. Entekhabi, “Multi-agent multi-scale observations of soil moisture via SPCTOR: sensing policy controller and optimizer,” submitted to AGU Fall 2020 meeting.

List of Acronyms

AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
AU	Application User
DS	Data Server
ED	End Device
LC	Local Coordinator
LC-RPi	LC Raspberry-Pi
ML	Machine Learning
MOO	Multi-Objective Optimization
MSE	Mean Squared Error
NISAR	NASA ISRO Synthetic Aperture Radar
RZSM	Root Zone Soil Moisture
SDRadar	Software Defined Radar
SMAP	Soil Moisture Active Passive
SoilSCAPE	Soil moisture Sensing Controller and oPtimal Estimator
SPC	Sensing Policy Controller
SPCTOR	Sensing Policy Controller and OptimizeR
SR	Santa Rita
TZ	Tonzi Ranch
UAV	Unmanned Aerial Vehicle
UDS	UAV-Data Server Board
WG	Walnut Gulch
WoR	Wake-up on Radio
WSN	Wireless Sensor Network

Ground Stations as a Service (GSaS) for Near Real-time Direct Broadcast Earth Science Satellite Data

Louis Nguyen
Thad Chee
Andrei Vakhnin
Jason Barnett



AIST-QRS-20-0003

Jan 4, 2021

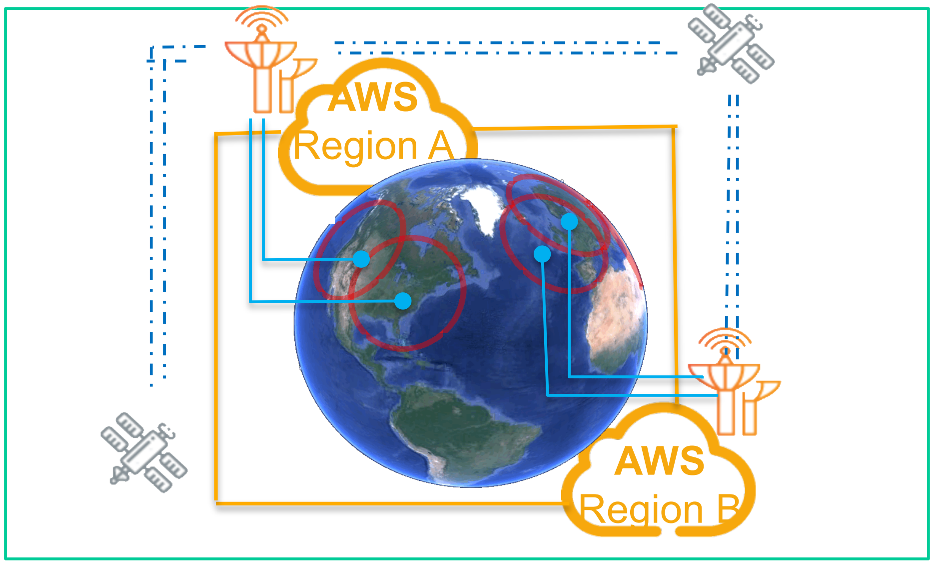
Ground Station as a Service (GSaS) for Near Real-Time Direct Broadcast Earth Science Satellite Data

PI: Louis Nguyen, NASA Langley Research Center

Objective

Develop a Ground Station as a Service (GSaS) Framework to receive direct broadcast (DB) data from Earth Observing Satellites (EOS) to significantly reduce latency associated with acquiring Low Earth Orbit (LEO) satellite observations. Near real-time (NRT) EOS are critical to support weather diagnoses and forecasting, disaster management, airborne science research and other applications. GSaS framework will:

- Provide ability to receive low latency LEO data (ie. MODIS/ VIIRS/ CrIS) without owning/maintaining DB ground station
- Reduce typical LEO Data Latency from 3-6 hours to 20-25 mins
- Provide New Observing Strategy Testbed (NOS-T) with capability to schedule, coordinate, receive, and process DB data from EOS



Amazon Ground Station as a Service (GSaS) System

Approach

- Leverage Amazon Web Services (AWS) Compute/Storage infrastructure, AWS GSaS, AWS CloudWatch Services, NASA Direct Readout Laboratory (DRL) technologies, and satellite prediction calculator to deploy a cloud-based system with integrated services
- Onboard satellites of interest (NPP, JSPP-1, AQUA, TERRA) into the GSaS system and integrate NASA DRL DB receiving and processing software for each satellite
- Automate the scheduling and DB overpass reservation system via utilization of the satellite prediction calculator through the AWS GSaS API
- Work with science community to develop appropriate triggers for use in New Observing Strategy Testbed (NOS-T)

Co-Is: A. Vakhnin, T. Chee, SSAI; J. Barnett, Booz Allen Hamilton

Key Milestones

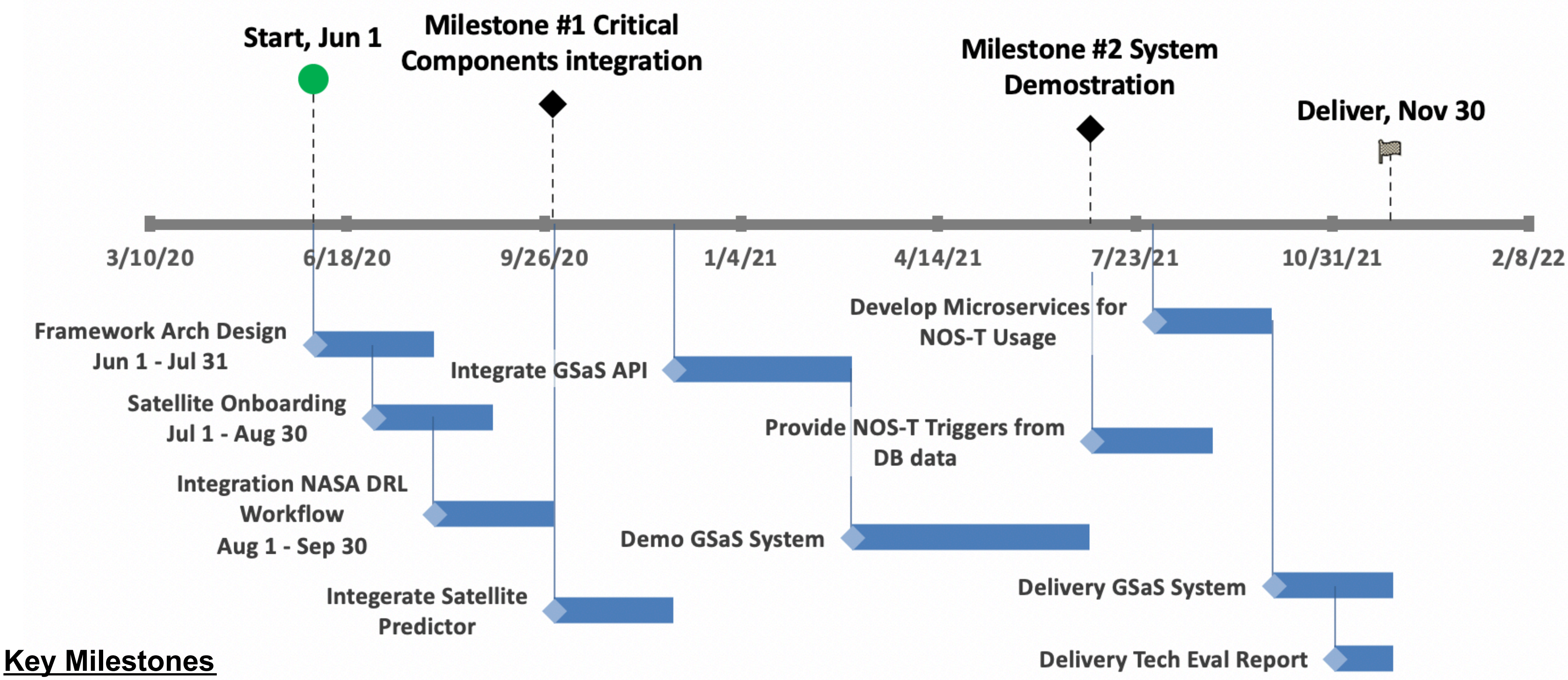
• Finalize system framework architecture design	07/20
• Onboarding for DB reception of NPP, JSPP-1, AQUA, and TERRA data	08/20
• Integrate NASA DRL software workflow	09/20
• Integrate LaRC Satellite Prediction calculator	11/20
• Integrate AWS GSaS API	02/21
• Demonstration of GSaS system	06/21
• Develop microservices/interface for use by NOS-T nodes	08/21
• Delivery of GSaS system and tech eval report	11/21

TRL_{in} = 3 **$TRL_{current}$ = 3**

ESTO Earth Science Technology Office

Project Schedule

GSaS Schedule Timeline



Key Milestones

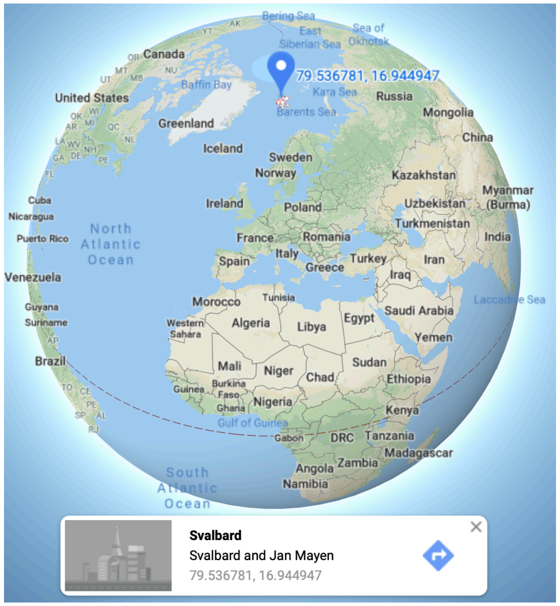
1. Finalize system framework architecture design 07/20
2. Onboarding for DB reception of NPP, JSPP-1, AQUA, and TERRA data 08/20
3. Integrate NASA DRL software workflow 09/20
4. Integrate LaRC Satellite Prediction calculator 11/20
5. Integrate AWS GSaS API 02/21
6. Demonstration of GSaS system 06/21
7. Provide NOS-T triggers from DB data 08/21
8. Develop microservices/interfaces/security for use by NOS-T node 09/21
9. Delivery of GSaS system 11/21
10. Delivery of Technology Evaluation Report 11/21

Background

This project will develop a system to address the "**Data Latency**" issues associated with acquiring LEO satellite data and demonstrate how AWS Ground Station as a Service (GSaS) network can be used to receive near real-time Direct Broadcast (DB) data. With connectivity to Amazon's computing infrastructure (network, compute, and storage), this cloud-based system, along with GSaS, will enable low latency DB data from EOS to be received, processed, and delivered to end users and near real-time applications.

Motivation:

- Data latency issue (3 more hours) poses a significant impact on data product optimal use due to delay in use of single receiving station
- Real-time observation from LEO satellites are needed to better support weather diagnoses and forecasting, disaster management, airborne science research, and other Earth Science applications



Svalbard receiving station in Norway acquires NASA EOS data and sends it to Data Center at GSFC with data latency.

Background

Current Solution for Acquiring NRT DB Data

Direct Broadcast Ground Sites with X-band and Direct Readout

- Requires DB ground site to receive low latency data
- Expensive to operate and maintain
- Access to local DB data is private, limited and/or restricted
- No efficient platform for data distribution and sharing

Objectives

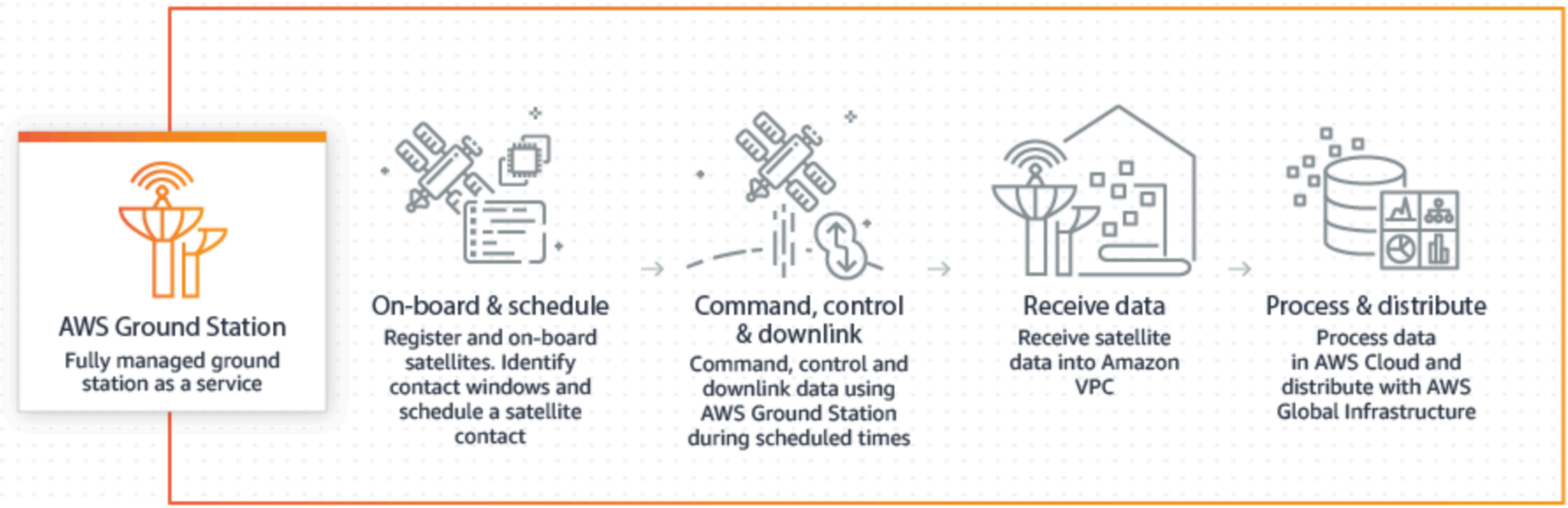
Our Goals:

- Utilize GSaS to receive near real-time DB data without the need to own/maintain DB ground station
- Reduce LEO data latency to 20-25 minutes; improve NASA Earth Science applications ability to deliver lower latency data and products to end users
- Provide GSaS capabilities to acquire DB data from AQUA, TERRA, NPP, and JPSS-1
- Extend GSaS capabilities to include micro services and interfaces for use by NOS Testbed nodes to schedule, coordinate, reserve, received, process, and deliver low latency DB satellite data and products
- Provide workflow for processing triggers (events) from DB data (MODIS/VIIRS) for NOS-T nodes within the GSaS system framework

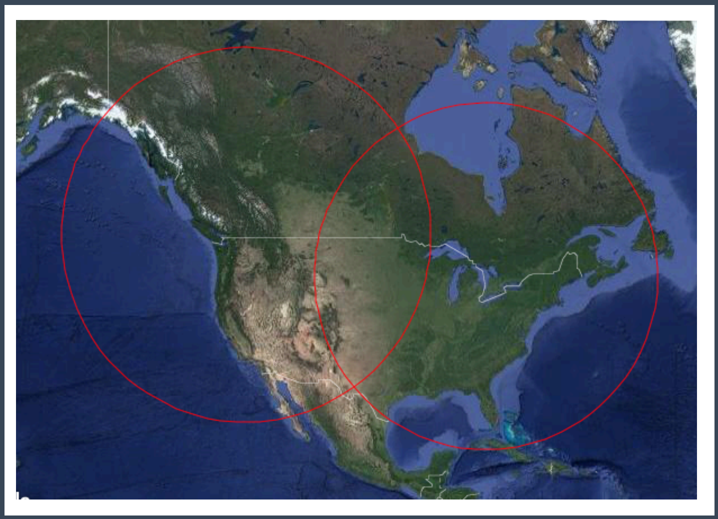
Amazon Ground Station as a Service (GSaS)

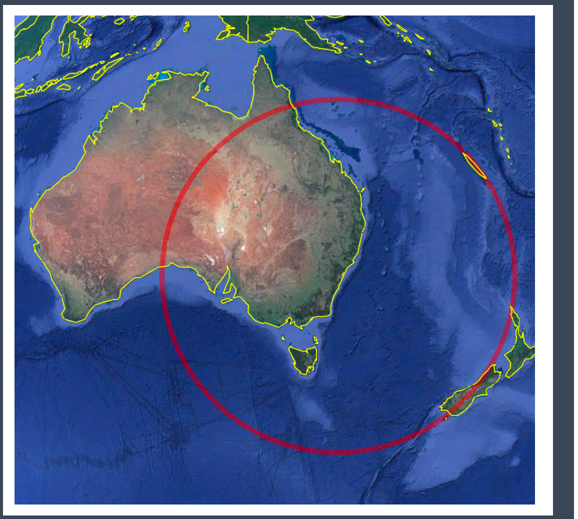
How GSaS works

- Provides global network of ground stations
- On-boarding and Scheduling
- Downlink direct broadcast data
- Allows uplink for command and control
- DB data received by VPC instance
- Data delivered to S3 for processing and distribution



AWS Ground Station Regional Coverage



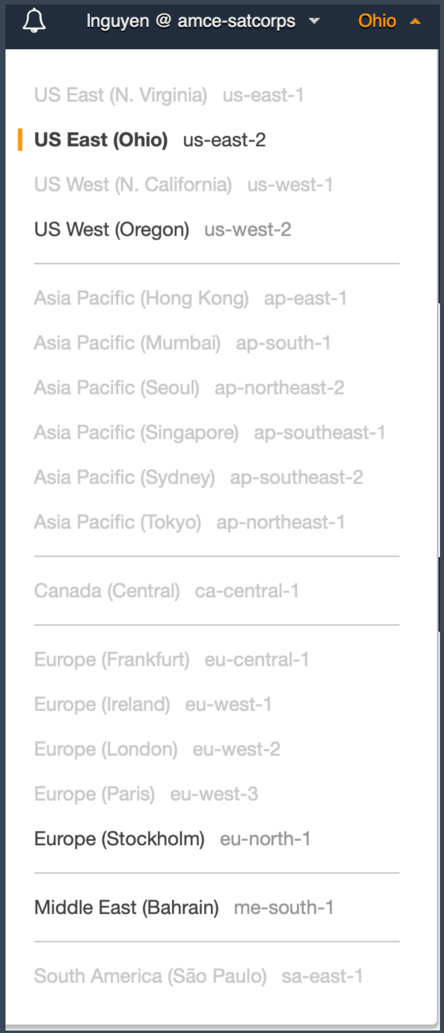


- AWS currently have 6 operational GS: Ohio, Oregon, Bahrain, Stockholm, Dublin, Sydney
    - GS network expected to expand to over 12 AWS Regions worldwide
- DB can be received within the ~2000km range of each GS; Reduced latency < 25min
    - Capable of receiving X- and S- Band frequencies from LEO and MEO
- Proposed GSaS system provides access to request DB satellite data downlink
    - Coordinate, schedule, receive, process, and deliver low latency data

ESTO
Earth Science Technology Office

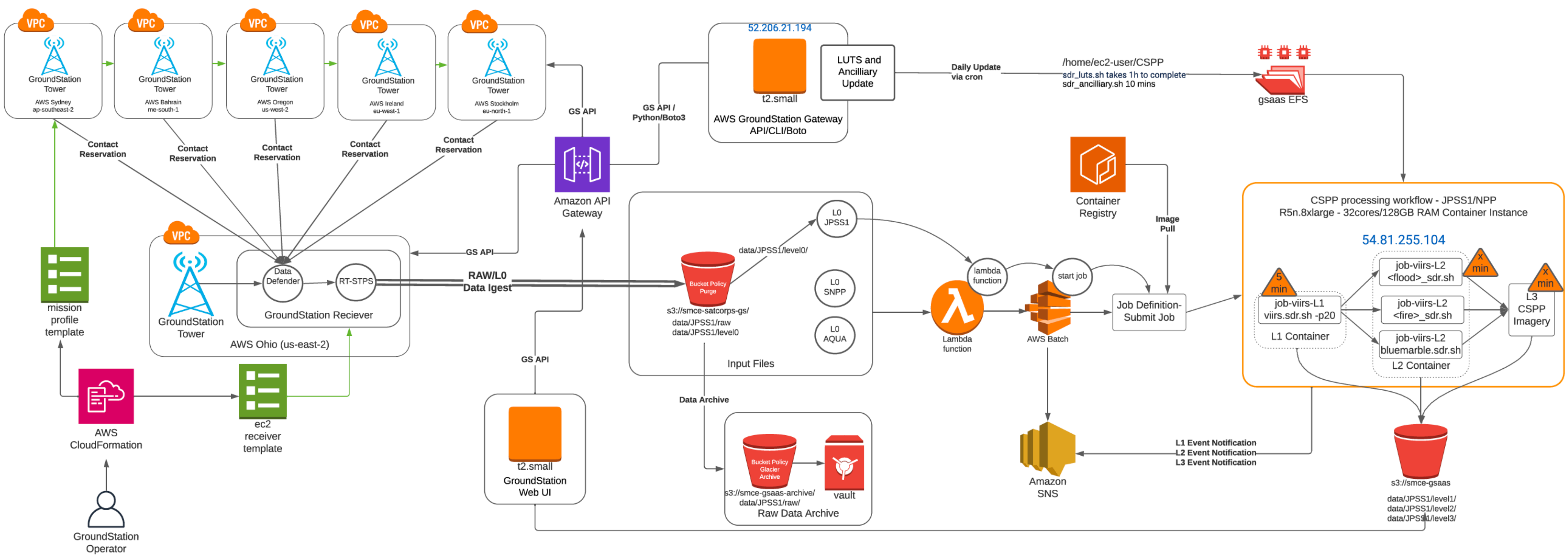
Planned Global Coverage of AWS GS

- Expand to ~12 GS worldwide within the next year
- Pay as you go service for use of antenna
  - charged by the minute
  - reserved cost~$3 per min and more for on-demand
- More opportunities for uplinks; command/control for targeting



ESTO Earth Science Technology Office

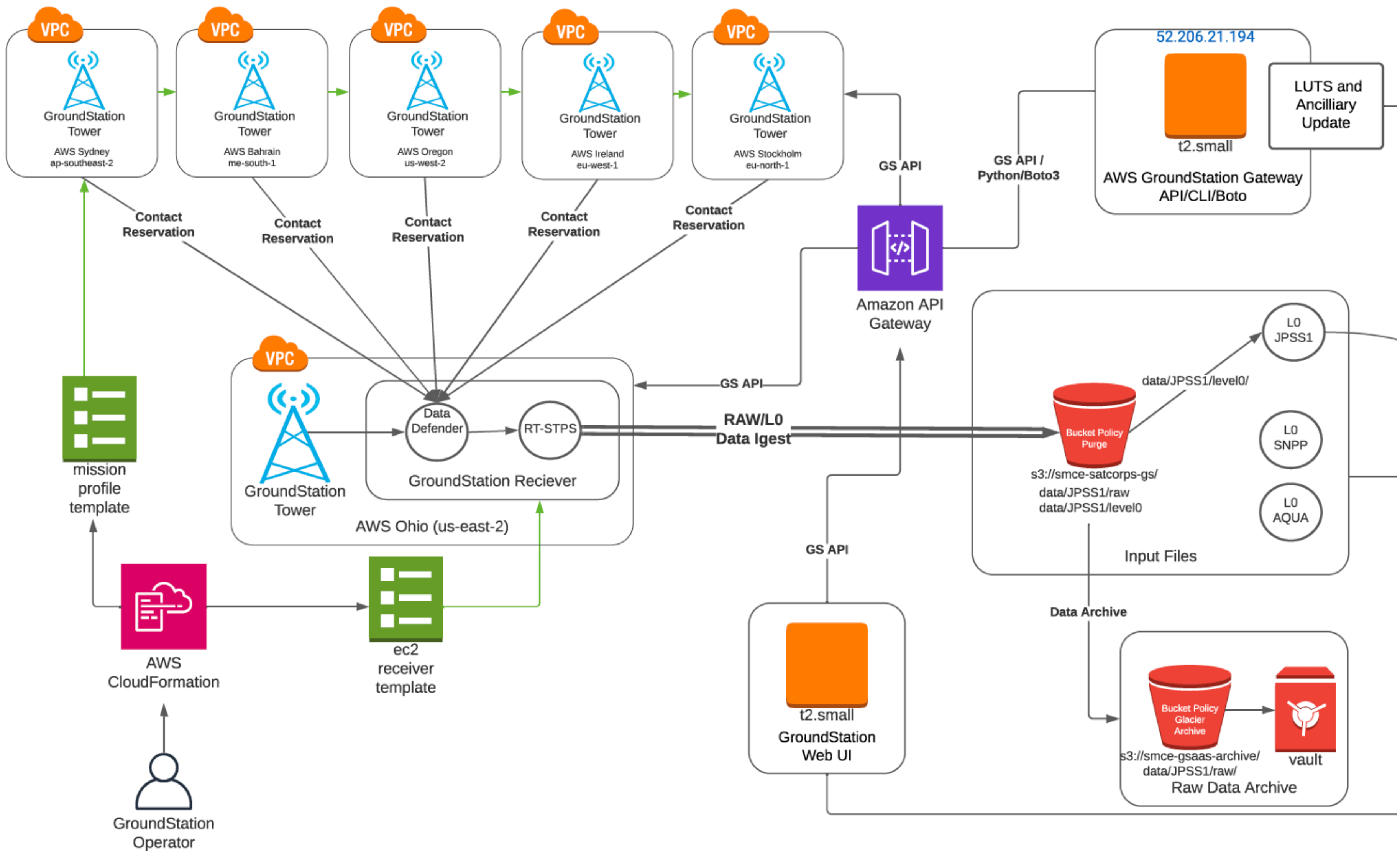
GSaS System Architecture



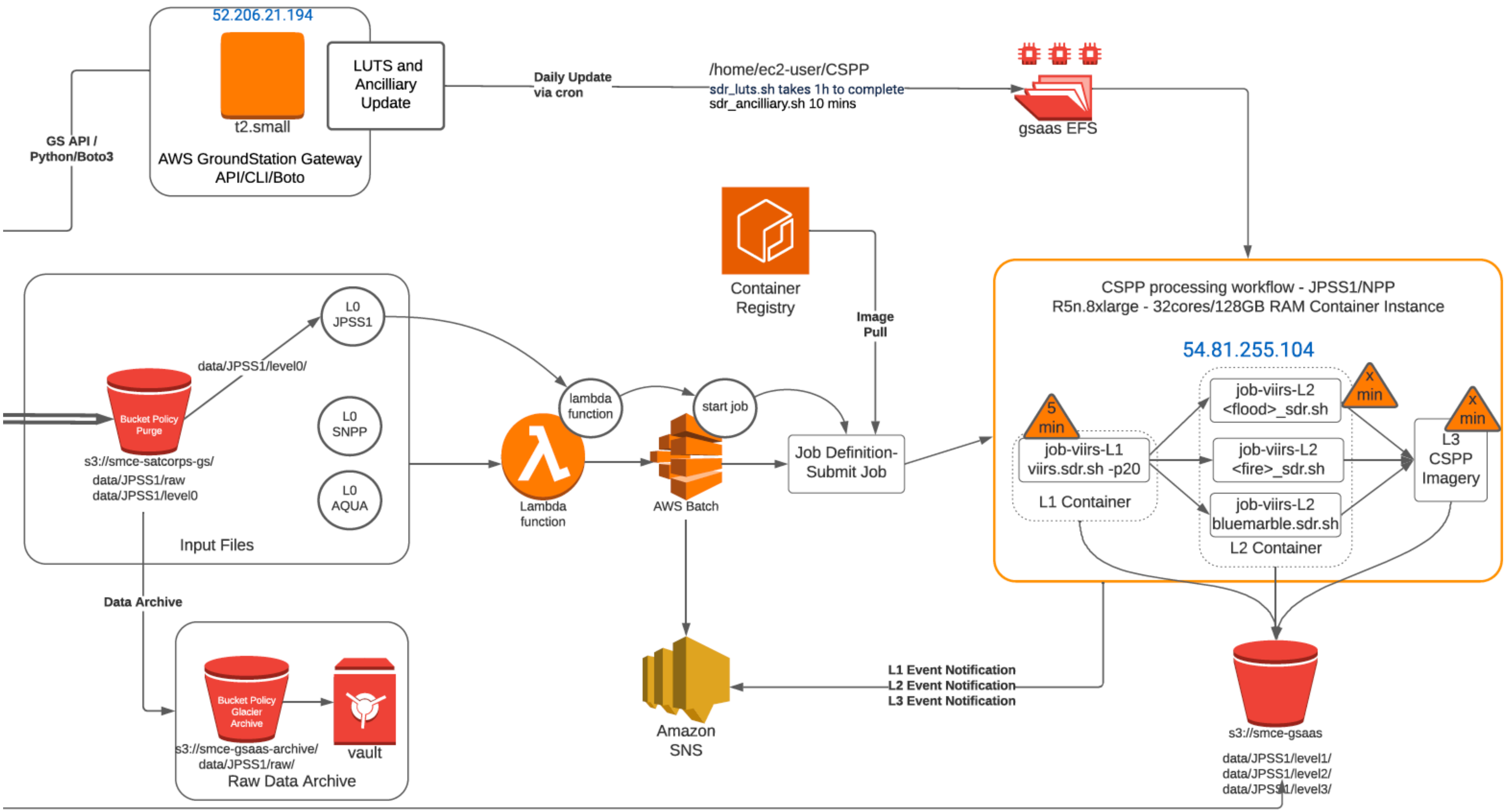
Data Reception
Raw->Level 0

Data Processing
L0->L1->L2/L3

GSaS System Architecture (Data Reception)



GSaS System Architecture (Data Processing)



Direct Broadcast Products

NRT DB products derived from publicly available algorithms:

- NPP & NOAA-20 VIIRS Flood Detection
  - 375m Floodwater Fraction of confident (0-100%)
  - GeoTIFF output

- NPP and N20 VIIRS Active Fire products
  - 375m and 750m fire masks
  - GeoTIFF and ASCII text

- NOAA Clouds from AVHRR Extended (CLAVR-x) Retrieval
  - Cloud Retrievals such as cloud top/phase/optical properties

- Hyper-Spectral Enterprise Algorithm Package (HEAP) Atmospheric profiles of temperature, moisture, trace gases and radiances

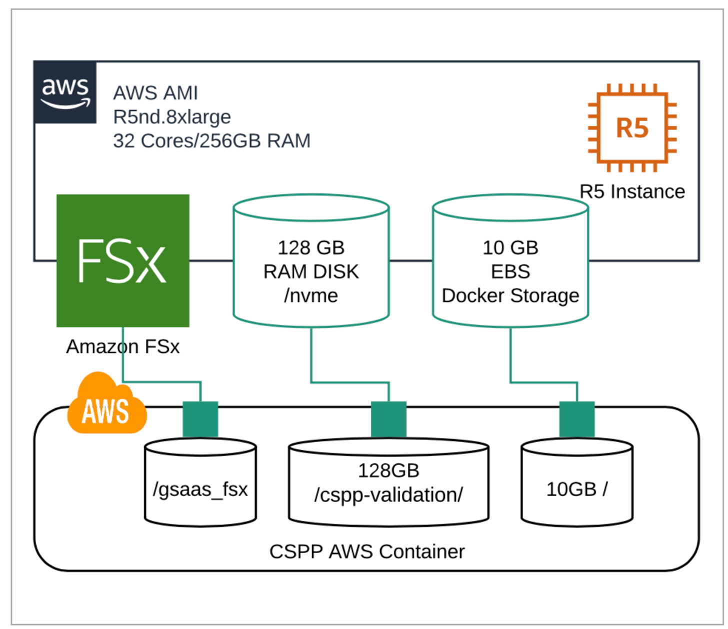
GSaS Framework allows for easy integration/inclusion of other processing pipeline via Docker Containers

Improving Level 1 Processing Time

Run Test	Instance ID	NVMe	RAM	vCPU	FSx Lustre Shared Filesystem	SDR Times	L1/L2	Number of Processes	Notes	CPU Utilization	Memory Utilization
#8	cspp-r5-16c-dev02 R5 Intel Memory Optimized (Cascade Lake)	Work Directory /cspp-validation/work RAM DISK tmpfs 96G	128GB (32)	16 cores	CSPP home Directory /gsaas_fsx	10 mins	L1	-p 4		50 %	12 %
#9	**cspp-r5-32c-dev02 R5 Intel Memory Optimized (Cascade Lake)**	**Work Directory /cspp-validation/work RAM DISK tmpfs 96G**	**256GB (96G RAMDISK)**	**32 cores**	**CSPP home Directory /gsaas_fsx**	**3 mins**	**L1**	**-p 20**		**62%**	**60 %**
#10	**cspp-r5-32c-dev02 R5 Intel Memory Optimized (Cascade Lake)**	**Work Directory /cspp-validation/work 2x 600 GB**	**256GB**	**32 cores**	**CSPP home Directory /gsaas_fsx**	**4 mins**	**L1**				

CSPP AMI Recommendations

RAM disk - /cspp-validation
Execution time- 3mins



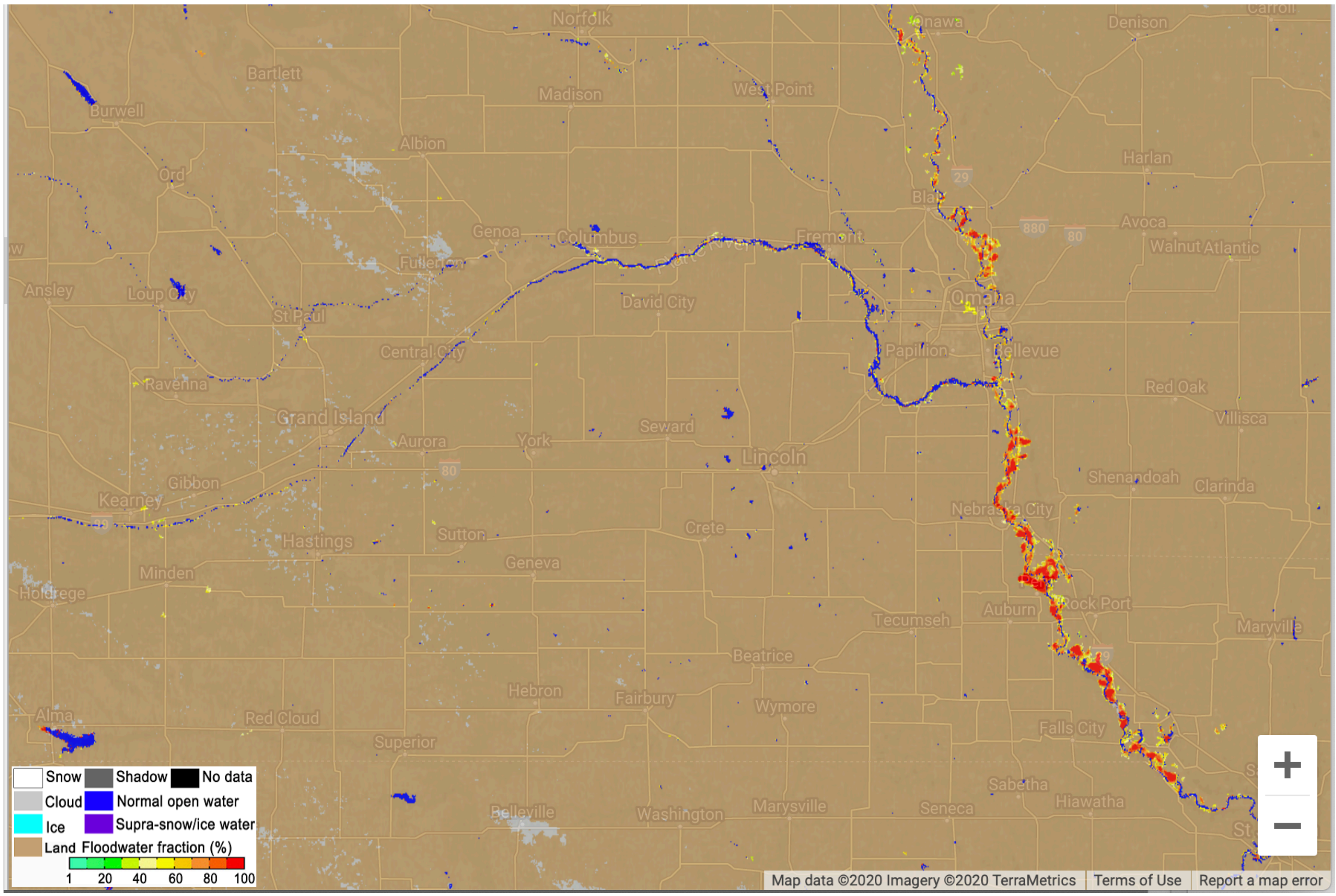
Summary of Accomplishments

- Designed and deployed GSaS system architecture on AWS
- Onboarding of DB reception of VIIRS and MODIS data using AWS GS
- Integrated NASA Direct Readout Laboratory (DRL) RT-STPS
- Integrated Univ Wisc SSEC CSPP (Community Satellite Processing Package)
- Integrated LaRC Satellite Calculator/Predictor
- Developed initial workflow to automatically process Level 0->1->2/3
- Captured DB data from AQUA, JPSS-1, NPP
- Able to process VIIRS Active Fire products and VIIRS Floodwater Maps
    - Provided VIIRS Flood triggers for a case study day demo
- Improved processing speed to delivery products in under 25mins
- Started initial work on GSaS API and integration of AWS API services

Summary of Accomplishments

Level 2 products derived from GSaS System

NPP & N20 VIIRS Flood Detection Map 375m resolution for Nov 19, 2019

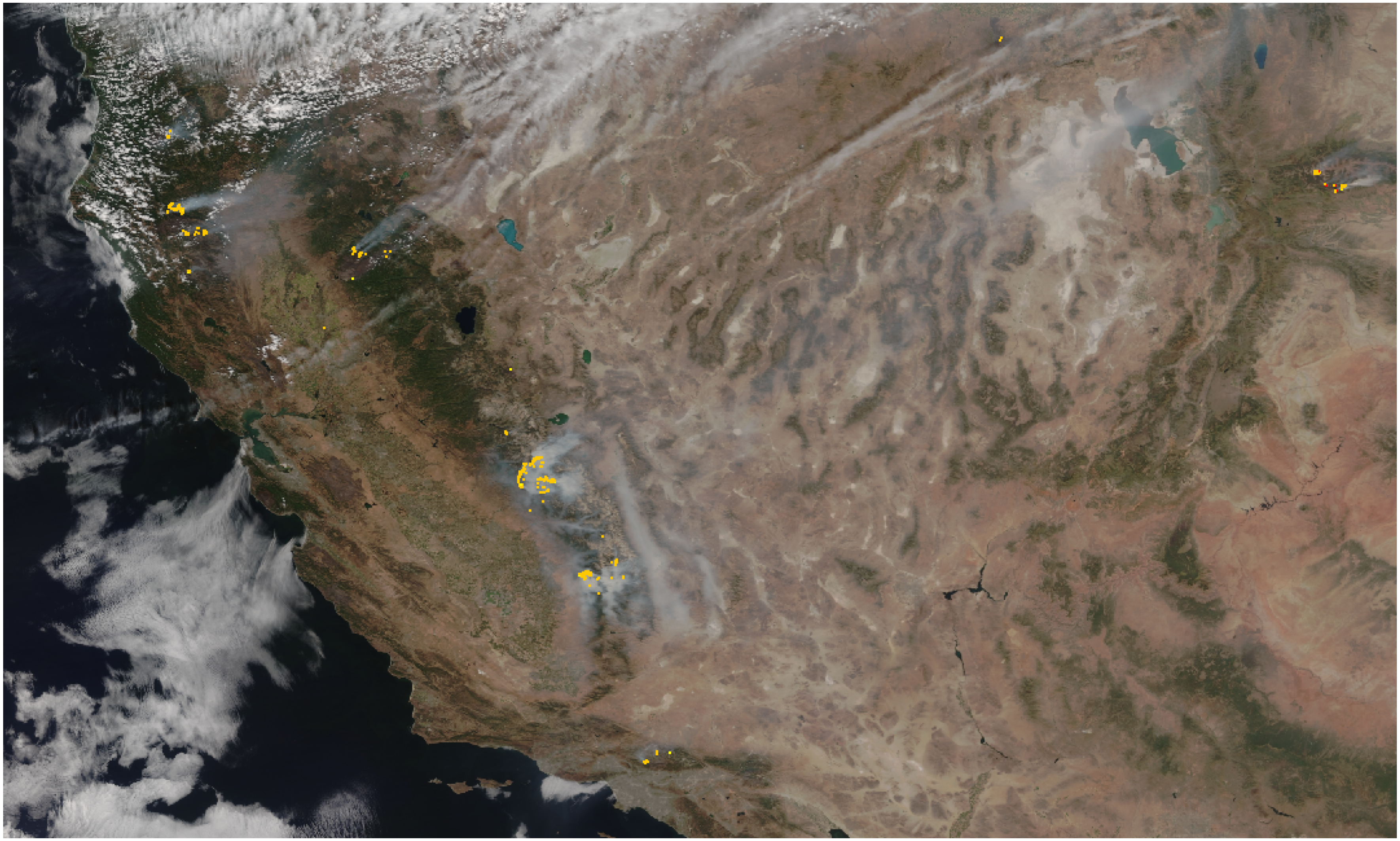


Level 1→ 2 Flooding processing time ~10-12min

Summary of Accomplishments

Level 2 products derived from GSaS System

Fire Burn Map over California from DB data via AWS GSaS; JPSS-1 Sept 24, 2020



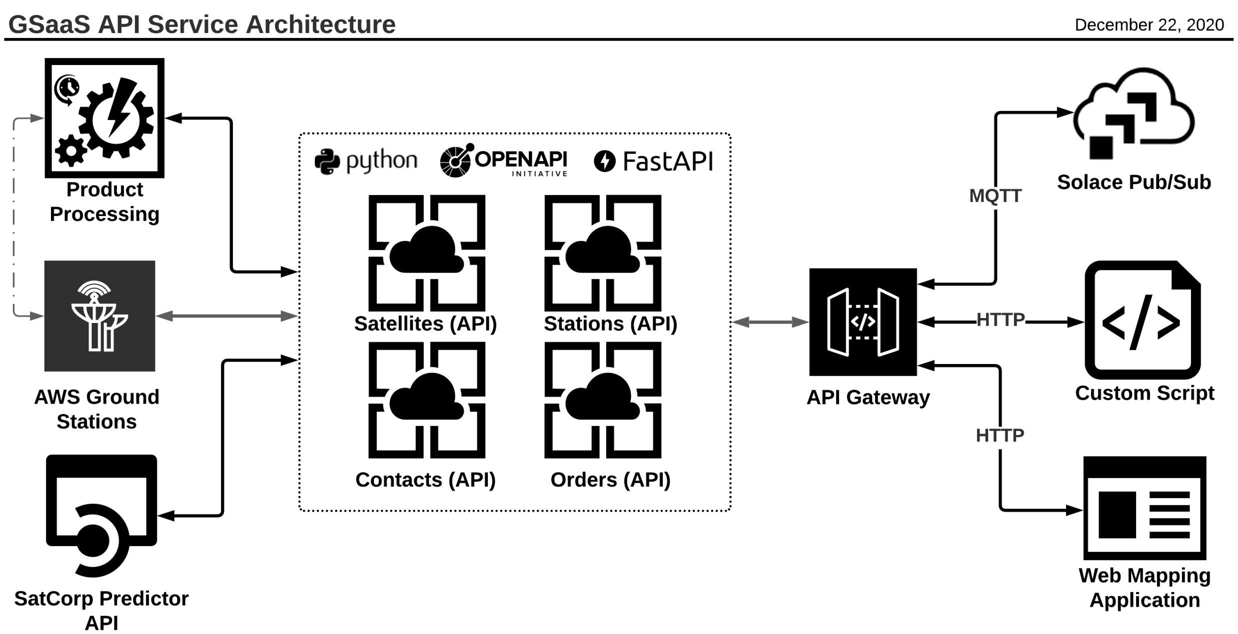
Level 1→ 2 Fire processing time 3-4 mins

Future Plans

- Participate in NOS-T live demo
  - Provide near real-time flood products triggers from VIIRS
- Complete AWS GS API integration
- Build out GSaS API to allow NOS-T nodes to schedule and reserve DB data and products

Service Layer Architecture

Providing self-describing and modern RESTFul APIs in alignment with the OpenAPI Specification



NCSA Data Fusion Visualization for NASA CAMP2Ex Field Campaign

Larry Di Girolamo (PI, University of Illinois at Urbana-Champaign)
Donna Cox (Co-I, University of Illinois at Urbana-Champaign)

AIST-QRS-20-0002 Annual Technical Review
1/4/2021

CAMP2Ex-Illinois
Larry Di Girolamo
Bob Rauber
Steve Nesbitt
Yulan Hong
Dongwei Fu
Puja Roy
Jesse Loveridge
Arka Mitra
Rose Miller
Piyush Garg

Advanced Visualization Lab
Donna Cox
Robert Patterson
Stuart Levy
Kalina Borkiewicz
AJ Christensen
Jeff Carpenter

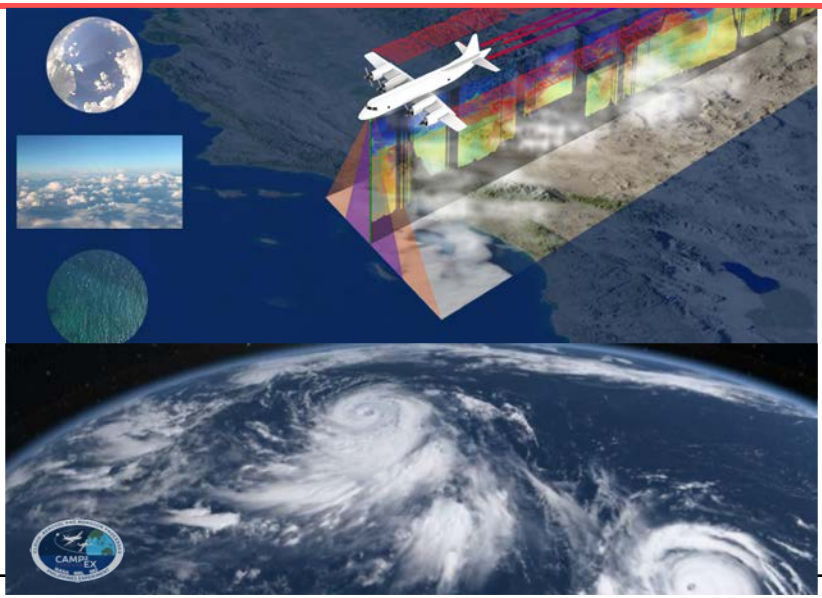
NCSA Data Fusion Visualization for NASA CAMP2Ex Field Campaign

PI: Larry Di Girolamo, University of Illinois at Urbana-Champaign

Objective

The National Center for Supercomputing Applications (NCSA) Advanced Visualization Lab (AVL) will prototype visualizations, fusing data from field campaign instruments, to ease the exploration of the data by scientists, to provide insights, ideas and to highlight important features from aircraft, ground, and satellite data that the field campaign was targeting.

- Help understand the effort needed to design and achieve the long-term goal to develop a new flight-campaign interactive software visualization system that draws data from multiple collaborative sensor nodes.



Approach

- Explore data from a variety of aircraft instruments, understand important features and use requirements from the scientific community and stakeholders.
- Develop methods for data ingestion, conversion, fusion, integration and temporal management.
- Develop visualization methods for the various instrument data, data fusion, and experiment with design layout.
- Work with scientists to refine visualization representations to ensure visualizations meet the needs of the scientists.
- Deliver pre-rendered movies to NASA and the community that demonstrate visual summaries of the aircraft data for scientific analysis and exposition of the field campaign.

Co-Is/Partners: D. Cox, UIUC; CAMP2Ex-Illinois group

Key Milestones

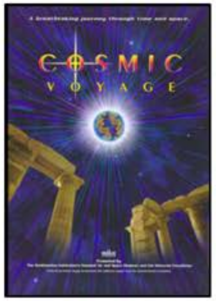
- CAMP2Ex-Illinois Group Workshops on Exploring and understanding CAMP2Ex data — 11/20
- Data management codes complete — 01/21
- Visualization prototypes complete for a single CAMP2Ex Research Flight — 02/21
- AVL + CAMP2Ex-Illinois Group Workshops on visualization refinements — 04/21
- Submit final demonstration and movies to NASA and community — 06/21

TRL_{in} = 2 **TRL_{out} = 5**

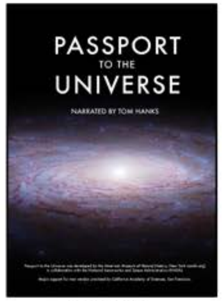
Presentation Contents

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

Background: Past Work



1997

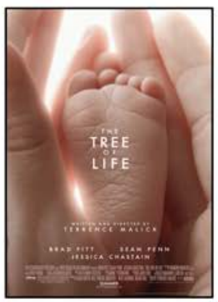


2000

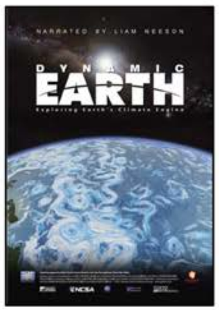
2006

2010

2010

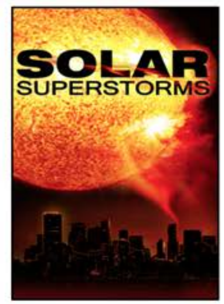


2011



2012

2012

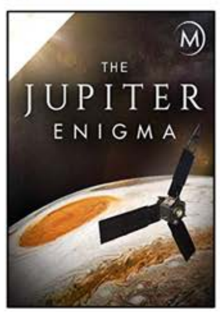


2015

2016

2016

2017



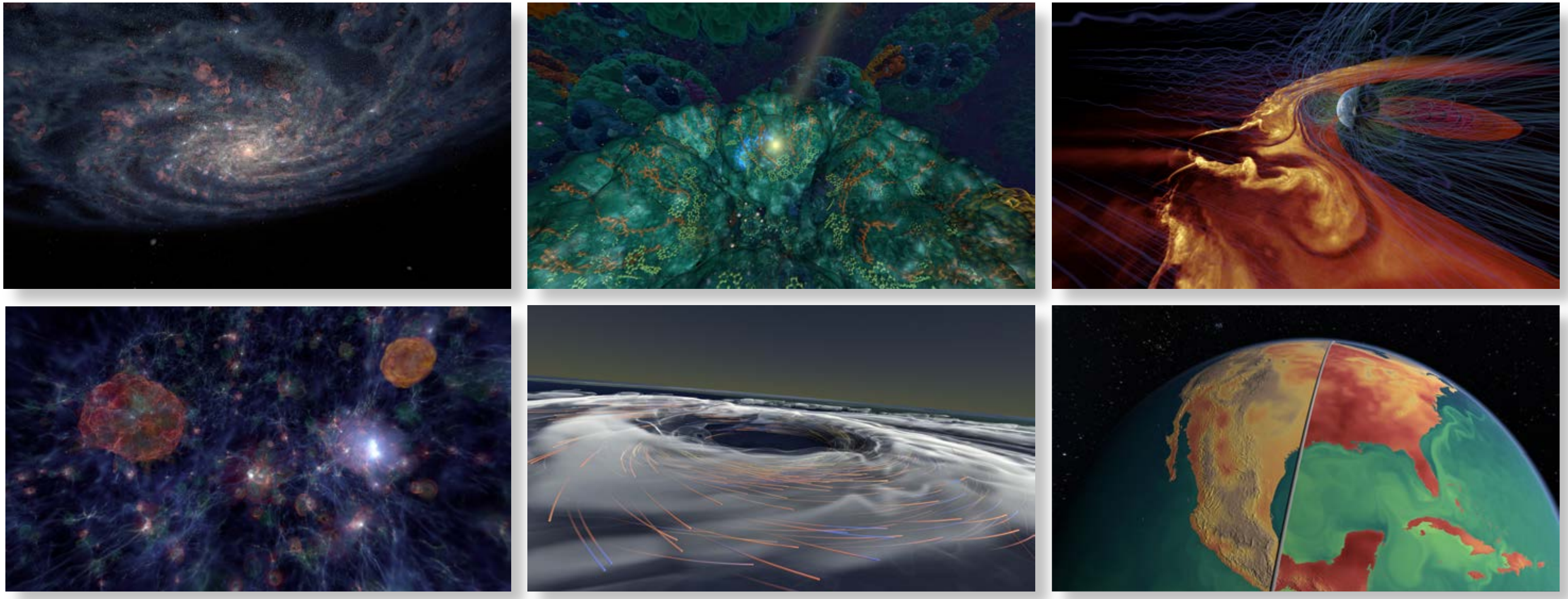
2018

2018

2019

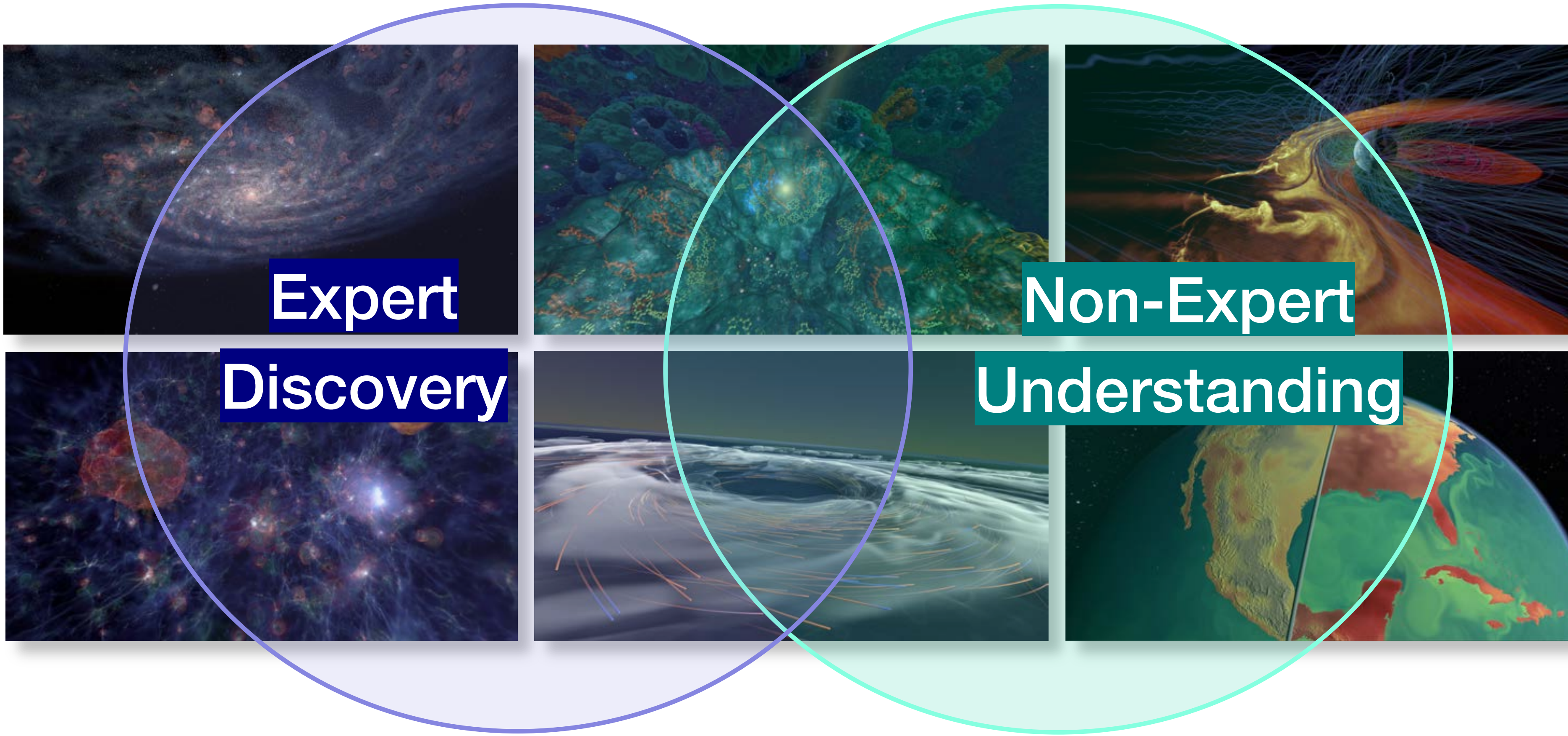
2019

Background: Expository Visualization

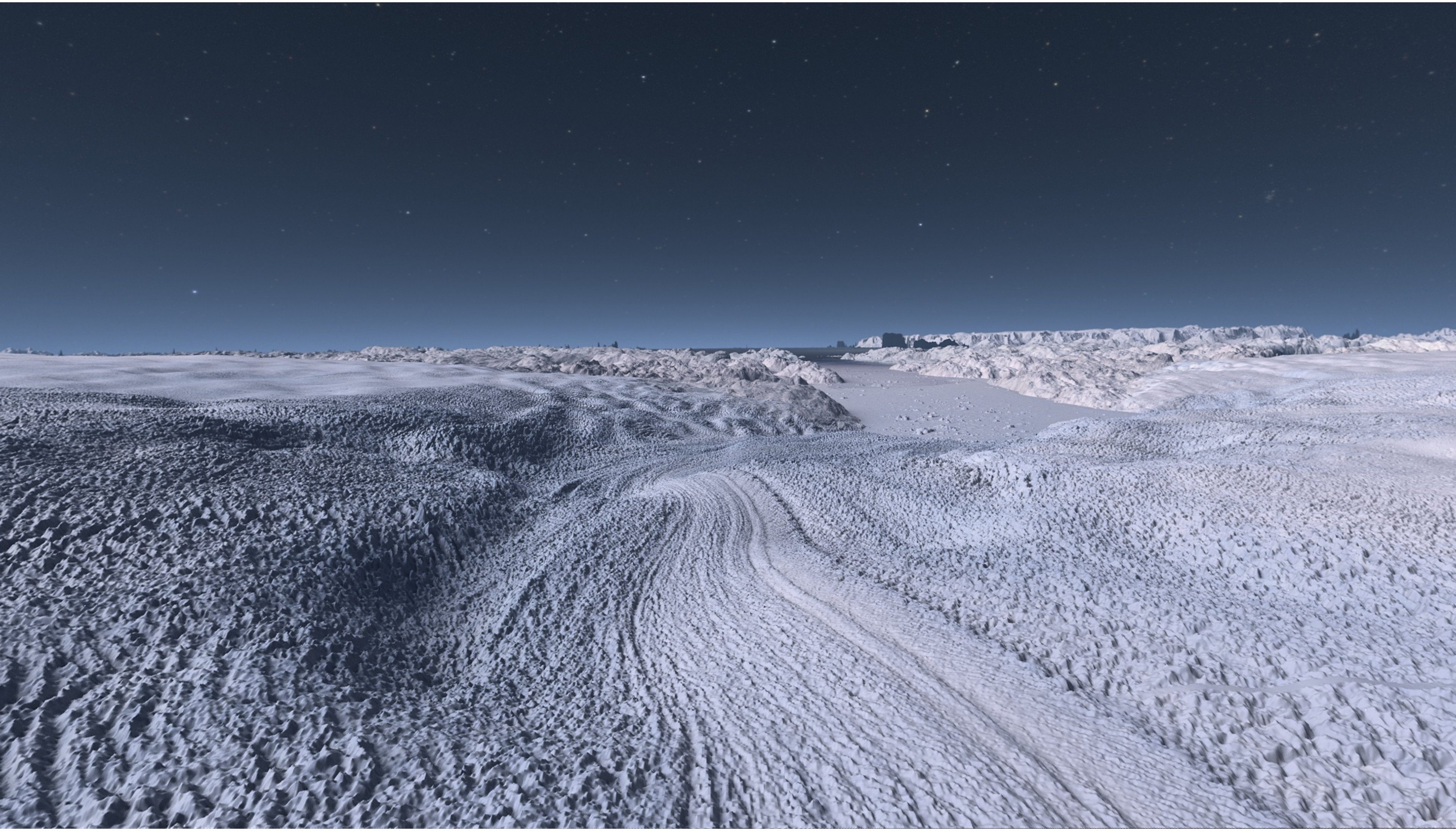


Scientific discovery and public presentation

Background: Expository Visualization



Background: ArcticDEM

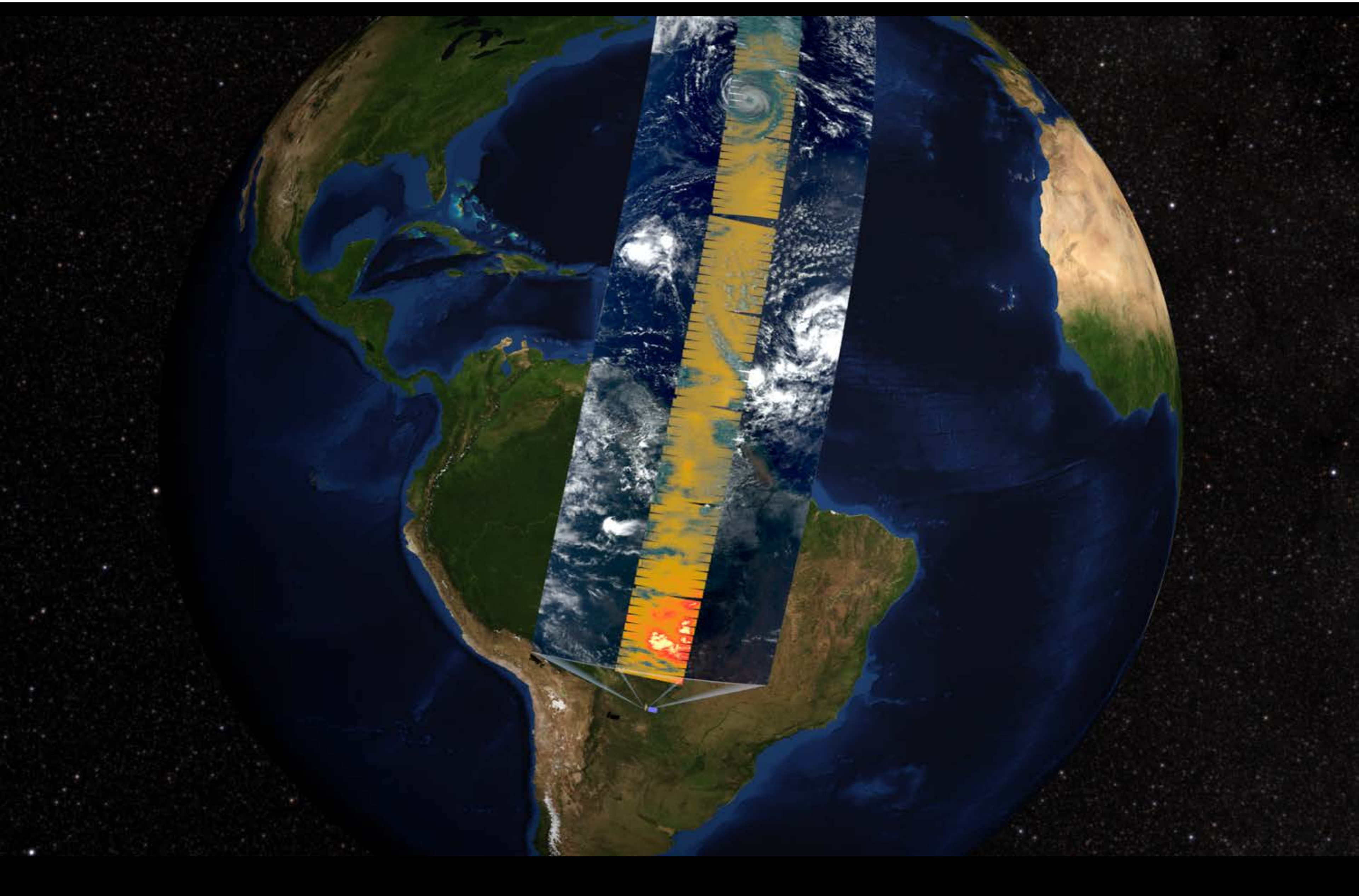


Full dome and flat-screen visualizations of Jakobshavn glacier in Greenland
showing fusion of dynamic ArcticDEM and LANDSAT data

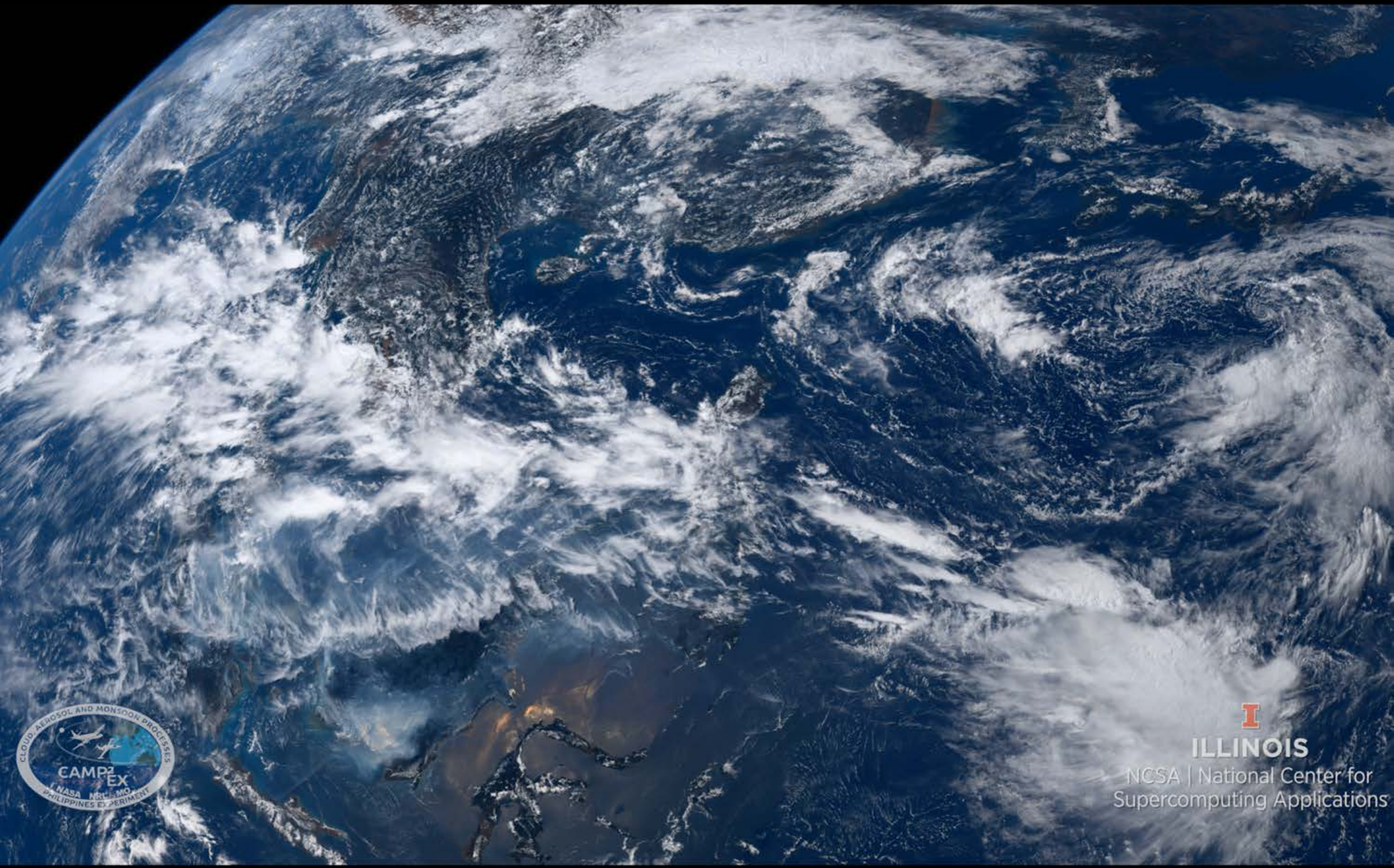
Jakobshavn Glacier visualization
Fulldome format

Background: Collaborating since 2002

Background: Terra Satellite Visualization



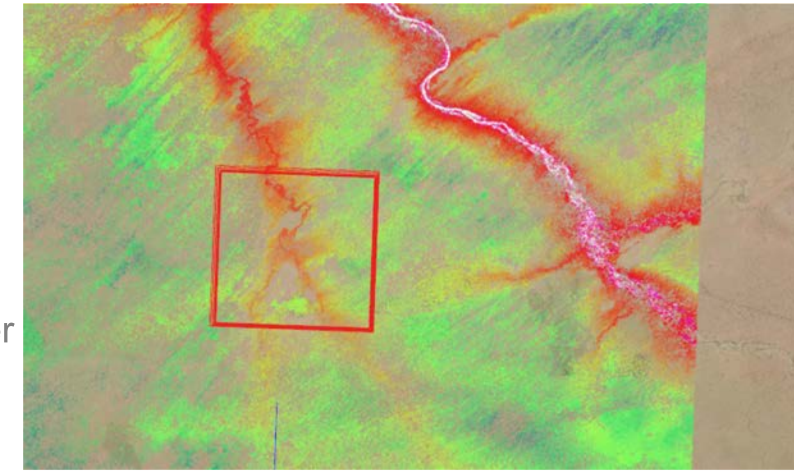
Background: AHI Visualization



Background: Visualization Software

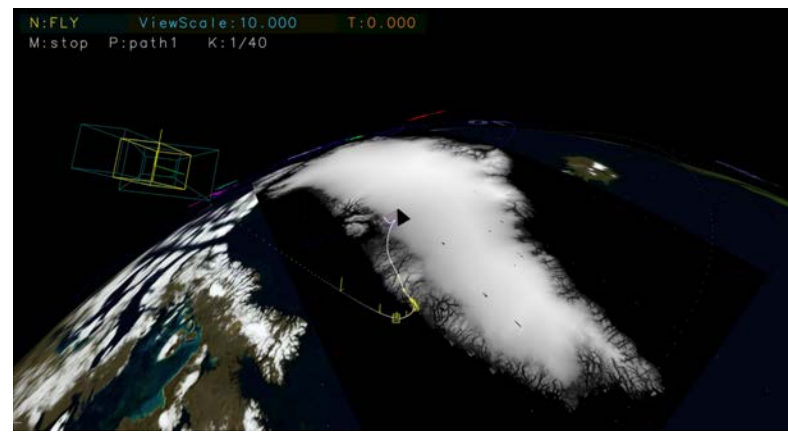
AVL software

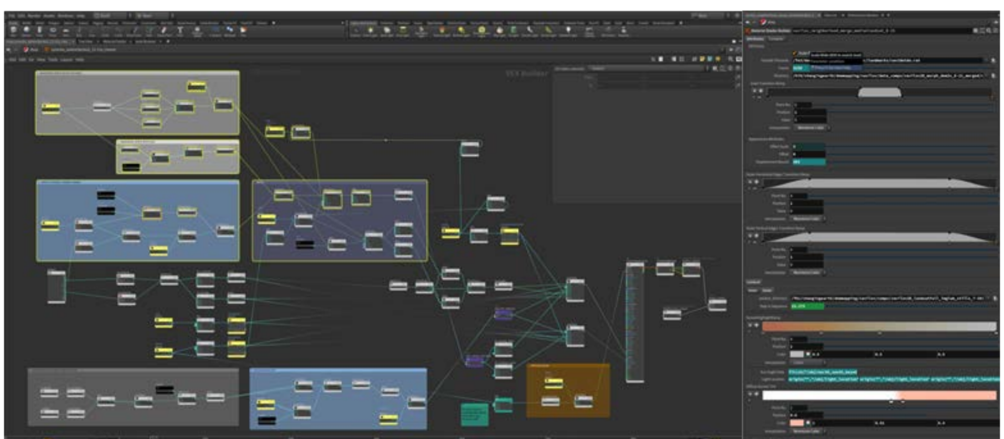
- Partiview - Interactive data exploration
- Virtual Director - Interactive camera direction
- Ytini - Data reading middleware for Houdini
- Blurend - Rendering on Blue Waters supercomputer
- Data processing utilities



Commercial software

- Houdini - 3D procedural modeling and rendering
  - Custom data visualization plugins
- Nuke - 2D image compositing





Background: Field campaign data fusion visualization

- Exploring field campaign data from multiple instruments and multiple platforms (surface, aircraft, satellite) in tandem is extraordinarily tedious and time consuming. This greatly limits scientific advancement and returns on NASA investments in field campaigns.

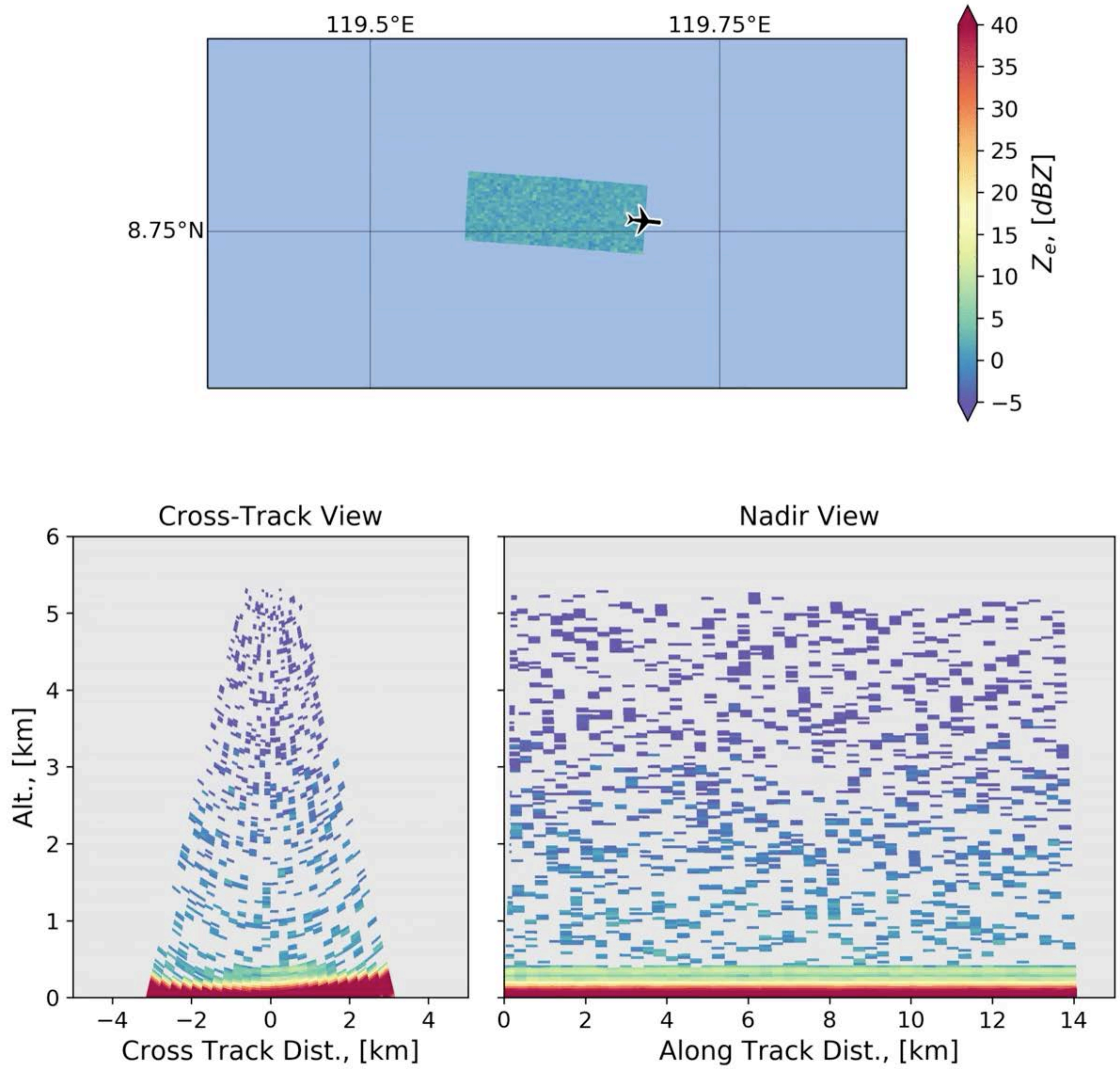
- Individual investigators are left on their own to figure out how to fuse field data for visualization.

- Field campaign data archives are left as mostly raw data with no easy way to access visualization summary of the data records.

- Public outreach on NASA field campaigns would greatly benefit from better data visualization.

- There is no visualization software tailored to field campaign data fusion, nor approaches for visualizing the the data from a range of diverse instruments in tandem.

Background: Field campaign data fusion visualization



Objectives

Objective:
Prototype the design and time-evolving visualizations using the fusion of data from field campaign instruments to provide insights and to highlight important features from the aircraft, ground and satellite data that the field campaign was targeting.

Short-Term Goals:

1. Data exploration and gathering scientific requirements.
2. Data ingestion, conversion, and integration.
3. Visualization development and design.
4. Visualization refinement with scientists.
5. Product delivery: pre-rendered visualization movies as "visual summaries" for scientific analysis and exposition.

Phases:

1. Development of visualization for the science community.
2. Exposition of the field campaign data as an educational product, as a pre-rendered short movie capable of reaching a broader audience.

Long-Term Goal (follow-on project, not in current scope):
Help understand the effort needed to design and achieve the long-term goal to develop a new flight-campaign interactive software visualization system that draws data from multiple collaborative sensor nodes.

Presentation Contents

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

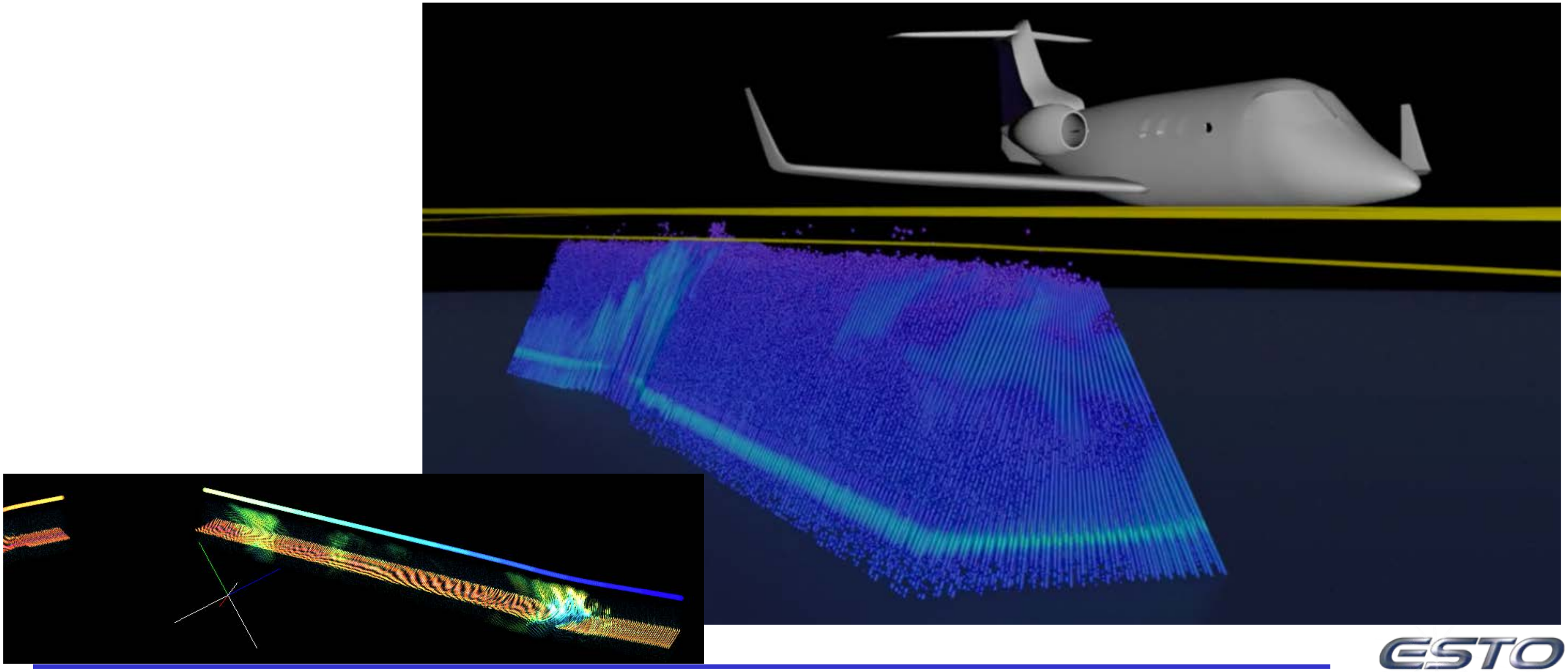
Technical and Science Advancements

The exploration and design of “visual summaries” of field data and develop visualization data fusion prototype

Presentation Contents

Summary of Accomplishments

- Data ingest code for most instruments complete
- Early visualization design concepts explored, but ongoing
- Consulted with atmospheric science researcher on APR-3 radar, HSRL lidar, video, etc.
- Acquired sample data for several instruments, studied data descriptions
- Explored data, made pre-visualizations
- Created higher-quality test animations, employing AVL visualization pipeline



Presentation Contents

- Background and Objectives
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Acronyms

List of Acronyms

- 1D One-dimensional
- 2D Two-dimensional
- 3D Three-dimensional
- AHI Advanced Himawari Imager
- AVL Advanced Visualization Lab
- DEM Digital Elevation Model
- NCSA National Center for Supercomputing Applications
- UIUC University of Illinois at Urbana-Champaign