DESIGN AND MANAGEMENT OF SATELLITE ASSETS TO ADVANCE SPACE-BASED EARTH SCIENCE

Allocation: NSF/4.53 Mnh
PI: Patrick Reed[1]
Collaborators: Eric F. Wood[2]; Matthew Ferringer[3]

[1]Cornell University
[2]Princeton University
[3]The Aerospace Corporation

SCIENTIFIC GOALS

This project is advancing a petascale planning framework that is broadly applicable across space-based Earth observation systems design. We have made substantial progress towards three transformative contributions: (1) we are the first team to formally link high-resolution astrodynamics design and coordination of space assets with their Earth science impacts within a petascale "many-objective" global optimization framework; (2) we have successfully completed the largest Monte Carlo simulation experiment for evaluating the required satellite frequencies and coverage to maintain acceptable global forecasts of terrestrial hydrology (especially in poorer countries); and (3) we are initiating an evaluation of the limitations and vulnerabilities of the full suite of current satellite precipitation missions including the recently approved Global Precipitation Measurement (GPM) mission. This work will illustrate the tradeoffs and consequences of the GPM mission's current design and its recent budget reductions.

ACCOMPLISHMENTS TO DATE

Our hypotheses related to passive control have required high fidelity astrodynamics simulations that account for orbital perturbations, which dramatically increase serial-design simulation times from minutes to weeks. This project has completed the first 10,000-member Monte Carlo global hydrologic simulation at one-degree resolution that characterizes the uncertain effects of changing the available frequencies of satellite precipitation on drought and flood forecasts. The simulation optimization components of this work have set an initial theoretical baseline for the best possible frequencies and coverages for global precipitation given unlimited investment, broad international coordination in reconfiguring existing assets, and new satellite constellation design objectives informed directly by key global hydrologic forecasting requirements.

We can categorize our project accomplishments to date within three foci: (1) scalable many-objective design optimization benchmarks, (2) advances in the use of high-fidelity astrodynamics simulation to permit passive control (i.e. minimum energy satellite constellations), and (3) benchmark the effects of reduced frequencies of satellite-based precipitation on global drought and flood forecasting.

1. With respect to many-objective design evaluation, we have completed the largest and best benchmark in terms of search quality and scalability for our team's underlying optimization algorithms. The results were made possible by the Blue Waters friendly user period access. At 524,288 cores, our search approaches theoretically ideal performance. These results are the best benchmark ever attained for the challenge problem on which we focus and provide a strong foundation for our future tradeoff analyses.

2. In the context of passive control, our preliminary results focus on the patented four-satellite "Draim" constellation. Our Draim results reveal that carefully optimizing an initial orbital geometry to exploit natural perturbations (e.g., effects of sun, moon, etc.) to maintain continuous global coverage performance as a function of elevation angle. This minimizes propellant and station-keeping requirements to dramatically reduce mission costs while increasing mission duration. The Draim constellation represents a step-

ping stone to the more complex suite of global precipitation missions that will require the analysis of more than ten satellites.

3. We are one of the first teams to show how limits in satellite-based precipitation observations propagate to uncertainties in surface runoff, evaporation, and soil moisture at distinctly different locations globally. Our results are based on the Variable Infiltration Capacity (VIC) global macroscale land surface model at 1.0° spatial resolution. For each realization of the VIC ensemble, each model grid cell's satellite precipitation is resampled at different temporal resolutions and then run through the VIC land surface model. Our results suggest differing effects of spatial and temporal precipitation sampling on each water cycle component. For example, convection plays a dominant role in the tropics and sampling will highly impact the measured precipitation. However, plant transpiration is impacted less by the intensity and frequency of storms than the sufficiency of the total precipitation. These insights have direct relevance to water security concerns in terms floods and droughts.

HOW BLUE WATERS PROJECT STAFF HELPED

The Blue Waters project has played a pivotal role in flexibly working with our team to make sure that we have been able to fully exploit the hardware resources for major computational experiments. The Blue Waters team has aided our group by expanding our data quotas to permit the storage and processing of over 2 PB of output from our experiments. Moreover, the team has facilitated the use of parallel Python analytics as well as the latest data compression technologies in the netCDF file format to make the global ensemble analysis feasible for the first time.

WHY YOUR RESEARCH MATTERS

Our Blue Waters PRAC team is bridging state-of-the-art innovations in satellite constellation design optimization and ensemble-based global terrestrial water and energy prediction to directly clarify satellite systems' value to managing floods and droughts. More broadly, our team is contributing highly flexible petascale space-based observation design tools that

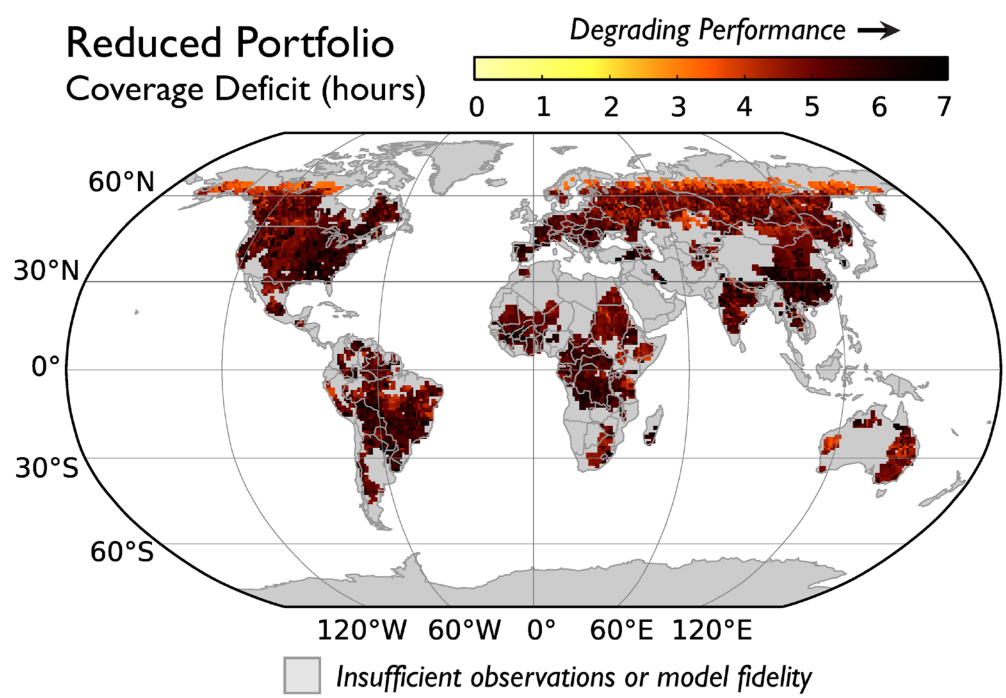

Figure 3. The reduced portfolio's coverage deficits. The color gradient from yellow to dark brown represents increasingly large worst-case data gaps (in hours) that are sufficiently large to degrade surface runoff predictions. The 1-degree global coverage deficits result from a combination of temporal data resolution requirements for the hydrological predictions of surface runoff and constraints on Earth visibility that result from the orbital dynamics. The orbital dynamics are based on the loss of 4 of the 10 current rainfall-focused satellite missions that are currently beyond their design life. The gray portions of the map represent locations where either the hydrologic model lacked acceptable performance relative to historical streamflow observations or a lack of historical data prevented assessments.

can serve a critical role for realizing the integrated global water cycle observatory long sought by the World Climate Research Programme, which to date has eluded the world's space agencies.

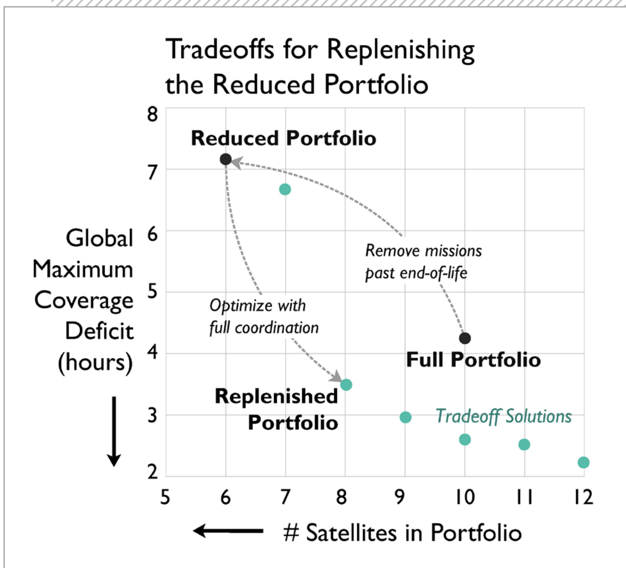

Figure 4. Detailed multi-objective tradeoffs for replenishing the reduced portfolio. Each point represents a portfolio of rainfall observation investments with a number of satellites (horizontal axis) that achieves a certain maximum coverage deficit (vertical axis). Both objectives are to be minimized. The (2 hour, 5 satellite) combination in lower-left corner of the plot is the ideal point. The points shown in black are the full and reduced portfolios, while the green points represent the tradeoff solutions identified via multi-objective optimization. Starting from the reduced portfolio, in theory decision makers can choose any of the green points, which provide additional satellites assuming full coordination of all missions. Note the full portfolio is completely inferior or worse in both objectives relative to the 8 or 9 satellite replenishment case.

WHY BLUE WATERS

In simple terms, the scale and ambition of our computational experiments require that we have the ability to compress years of computational work into minutes of wall-clock time to be feasible. Additionally, our applications are extremely data intensive, so Blue Waters' high core count and high memory have proven to be fundamental requirements to realizing the discoveries sought in our work. Our initial Blue Waters allocation results required over 4.5 million node-hours and the systematic processing of approximately 2 PB of model output to support preliminary contributions to the areas of global hydrology, massively parallel many-objective optimization, and high-fidelity astrodynamics design. The global hydrologic ensemble represents a new benchmark dataset that will be of broad interest in a variety of Earth science and engineering applications. Our satellite design trade-off analysis has clarified how quickly we deviate from the "best case" observation frequencies, with limits on spending, limits in international coordination, neglect of hydrologic objectives, and the simplified astrodynamics simulations currently employed in practice.

PRE-PETASCALE PREPARATION

Our team has actively collaborated over the last five years to prepare to take our analyses to scale on the Blue Waters system. Before our Blue Waters allocation, the National Science Foundation's Extreme Science and Engineering Discovery Environment played a significant role through large resource allocations on the Texas Advanced Computing Center's Stampede system. The transition from Stampede to Blue Waters enabled our team to advance our codes to scale from tens of thousands to hundreds of thousands of cores.

LOOKING FORWARD TO THE NEXT TRACK-1 SYSTEM

Future Track-1 systems will permit our team to explore fundamental contributions through the advancement of a new massively parallel hyper-resolution model of terrestrial water and energy balances called "HydroBloks" that can fundamentally change the value and impact of our proposed OSSE tasks. HydroBloks has extremely broad scientific merit as our Blue Waters team attempts to overcome a grand challenge in hydrology by resolving land surface processes globally at or below the 100 meter spatial scale while accounting for predictive uncertainties using ensemble runs. The size and scope of the HydroBloks experiments are beyond anything that has ever been attempted for global terrestrial hydrology. Moreover, our team intends to broaden our "many-objective" satellite portfolio analysis to consider a more complex mixture of weather missions with relevance to the global water cycle, such as the National Oceanic Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES) family and future concepts for the next generation NOAA architecture. Future Track-1 systems are critical for fully exploiting the unique breadth of our team's expertise in systems engineering, astrodynamics, space operations, high-performance computing, space systems architecture, and global hydrology to transform the next generation of space-based water cycle observation systems.

COMMUNITY IMPACT

Our research is critical for the scientific and space agency communities to overcome current computational barriers to transform the optimization of future satellite constellation architectures for delivering high fidelity data for a broad array of applications. Similarly, we envision that there is a broad array of scientists and users whose future activities will draw upon the project's scientific findings and generated data. As examples, the water-centric stakeholder community desperately requires improved monitoring and assessment of the water cycle for improved decision making related to flooding, droughts, and food and energy security.

PUBLICATIONS

Woodruff, M. J., P. M. Reed, and T. W. Simpson, Many objective visual analytics: rethinking the design of complex engineering systems. *Struct. Multidisc. Optimiz.*, 48:1 (2013), pp. 201-219, doi:10.1007/s00158-013-0891-z.

Ferringer, M., M. DiPrinzio, T. Thompson, K. Hanifen, and P. Reed, A Framework for the Discovery of Passive-Control, Minimum Energy Satellite Constellations. *AIAA/AAS Astrodyn. Specialist Conf.*, San Diego, Calif., August 4-7, 2014, doi:10.2514/6.2014-4158.

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