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

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EXECUTIVE SUMMARY:

This project is advancing a petascale planning framework that is broadly applicable across space-based Earth observation systems design. We made substantial progress toward 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 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.

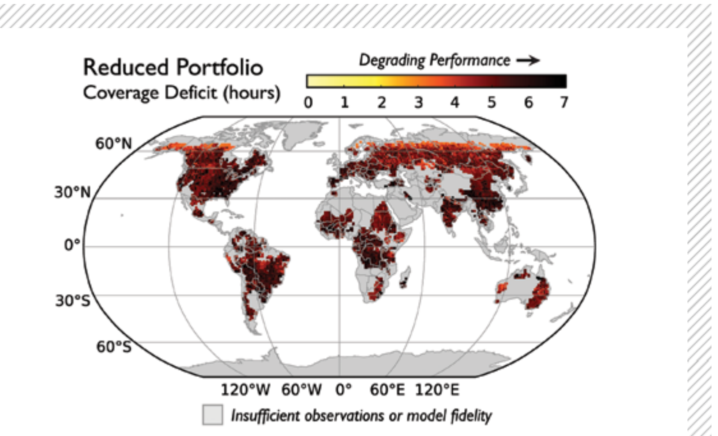

FIGURE 1: Global map of coverage deficits that emerge if the current four precipitation missions beyond their design life are lost (i.e. the reduced portfolio). Coverage deficits represent worst-case periods of missing data.

INTRODUCTION

Our 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 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. 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 to 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.

METHODS & RESULTS

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 satellite-based observation frequencies of precipitation on global drought and flood forecasting.

1. With respect to many-objective design evaluation, we 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 approached theoretically ideal performance. These results are the best benchmark ever attained for the challenge problem of focus and provide a strong foundation for our future tradeoff analyses.

2. In the context of passive control, our preliminary results focused on the patented four-satellite "Draim" constellation. Our Draim results revealed that carefully optimizing an initial orbital geometry to exploit natural perturbations (e.g., effects of Sun, Moon, etc.) yields passively controlled satellite constellations that maintain near-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 stepping 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 were 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 suggested 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 of floods and droughts.

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 been fundamental requirements for 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 level dataset that will be of broad interest in a variety of Earth science and engineering applications. Our satellite design trade-off analysis 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 used.

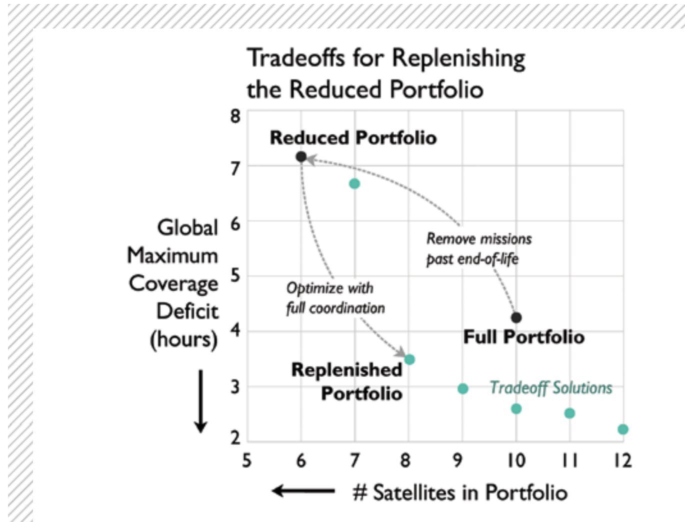

FIGURE 2: Tradeoffs between satellite count and coverage deficit for the full portfolio, the reduced portfolio, and a highlighted replenished portfolio. With coordination in planning, the replenished portfolio's eight satellites outperform the ten satellites of the full portfolio.

PUBLICATIONS

Chaney, N., J. Herman, P. Reed, and E. F. Wood, Flood and Drought Hydrologic Monitoring: The Role of Model Parameter Uncertainty. *Hydrol. Earth Syst. Sci. Discuss.*, 12 (2015), pp. 1697–1728.

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