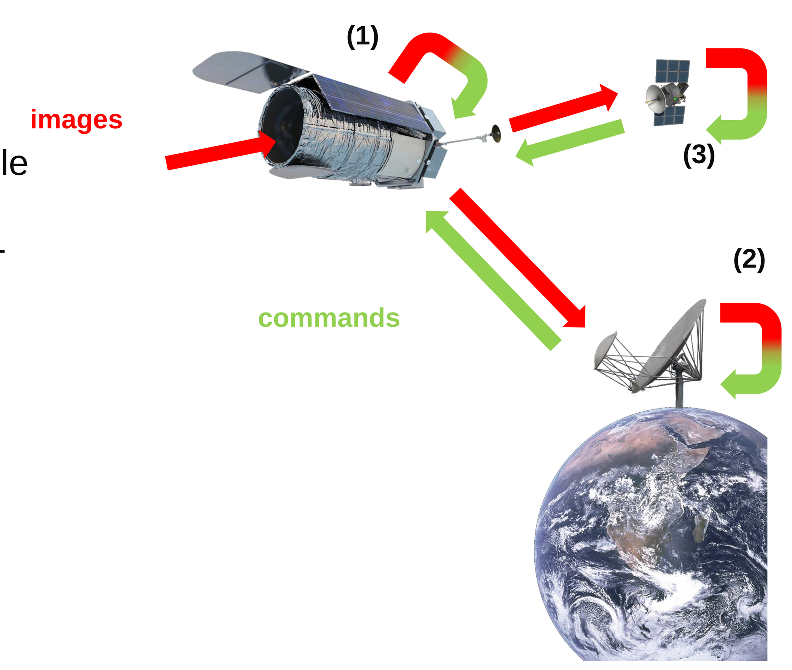
National Aeronautics and Space Administration

Alternative Methods for Acceleration of Wavefront Control Computation for Large Space Telescopes

Principal Investigator: Eric Cady (383); Co-Investigators: Kerri Cahoy (MIT)

Program: FY21 SURP **Strategic Focus Area: Mirror and Aperture Systems, Advanced Optics and Telescopes**

Objectives



The objective of this work was to investigate alternatives to rad-hard processing electronics to enable computationally-intensive operations in flight instruments, with a focus on wavefront control for high-contrast imaging. We compared feasibility and performance of:

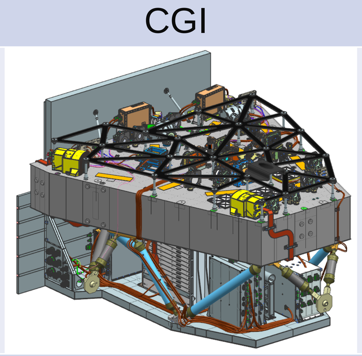
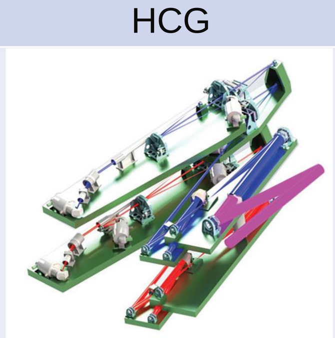
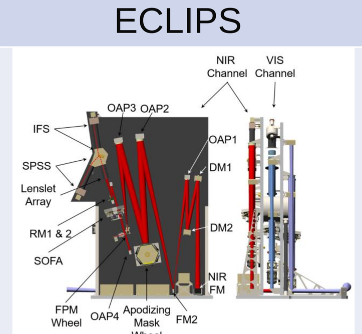
1) auxiliary COTS processors onboard with radiation-mitigation techniques
2) transmission of data to the ground for processing, and
3) co-flying small spacecraft with COTS parts for offloading computation.

Background

Future large telescope mission concepts such as HabEx and LUVOIR are baselining coronagraphic instruments with deformable mirrors and wavefront control systems to do high-contrast imaging of exoplanetary systems with a goal of seeing reflected light from Earth-size planets around other nearby stars. These instruments will use larger deformable mirrors and larger focal-plane arrays than previous missions to take full advantage of the larger telescope apertures.

High-contrast imaging requires high-order wavefront control algorithms that use those deformable mirrors to create areas with minimal starlight on those focal-plane arrays. Those algorithms have computational and memory costs which scale steeply with deformable mirror size: for an NxN DM, we expect scalings of N^4 to N^6 in number of floating-point operations and N^4 in storage requirements.

The baseline computational approach for HabEx and LUVOIR instruments is to do these computations on-board with rad-hard parts. Unfortunately, rad-hard electronics capability lags commercial processor capability by a decade or more, and performing these computations on even near-future rad-hard processors may consume significant observation time for computation.

	Roman Space Telescope (Roman)	Habitable Exoplanet Observer (HabEx)	Large UV-Optical-Infrared Surveyor (LUVOIR)
Instrument	CGI	HCG	ECLIPS
			
Status	In development at JPL	Proposed	Proposed
WFSC computation baseline	Ground-in-the-loop (was on-board rad-hard avionics)	On-board rad-hard avionics	On-board rad-hard avionics
Deformable mirror size (N×N)	2 48x48 DMs	2 64x64 DMs	2 128x128 DMs
Computation/storage cost relative to SOA (N^4 - N^6)	1	3.2 - 5.6×	50.6 - 359.6×

Approach and Results

The approach taken was to invest heavily in framework which would be common for evaluation of both the baseline and the three alternatives. This framework included:

- Literature and community research to identify key wavefront sensing and control algorithms of current and potential future value
- Computational complexity evaluation of each of the key algorithms
- Literature and community research to identify the computational and memory capability of key processors that are candidates for future flight projects

This work was then used to build tools to parametrically evaluate performance for different use-cases (e.g. HabEx, LUVOIR) as a function of algorithm and processing architecture. With these tools we could combine the processor and memory capability with the computational complexity of the algorithms for an example case, and look at the time required to reach a nominal benchmark performance level. This analysis was also used to build link budgets for the evaluation of off-board computing architectures, the performance of which depends on distance and communications system assumptions.

The bulk of the computation time is spent on precomputation activities, which for either rad-hard or COTS parts will take from several days to several weeks of wall-clock time. Per-iteration computation times are orders of magnitude smaller. This is consistent with JPL experience on Roman Coronagraph, where operational workarounds and FPGA acceleration of specific pre-computation activities was required to do the WFSC precomputation in an acceptable time.

Given today's technology and algorithms, performing on-board HOWFSC with radiation-harded components is barely feasible on HabEx and infeasible for LUVOIR. For example, creating or re-touching the dark hole of LUVOIR using standard EFC may require days to weeks of computation on the space-rated BAE RAD5545 processor. While space-rated processor technology will evolve before the launch of such missions, their final flight hardware will be selected several years before launch. Our worst-case estimates suggest that even a ten-fold improvement in processing and memory-access speeds will be insufficient to create a dark hole on LUVOIR in less than ten hours. In order to fully assess the computational risks for future missions, due to large performance uncertainties from low-level detail such cache utilization, vectorization, and compiler optimization, HOWFSC approaches would need to be tested on rad-hard processors. Even for a purely rad-hard design, more modern processors such as the RAD5545 should be preferred.

Onboard rad-tolerant hardware approaches are too risky for on-board flight hardware given the Class A risk classification of flagship missions. The risks associated with limited on-board processing power with rad-hard processors should be mitigatable by one or more of the following approaches:

- offloading computation to the ground
- offloading computation to co-flying processors
- developing efficient HOWFS algorithms which are optimized to be either less memory-intensive or more parallelizable, and increasing payload flight software risk tolerance to enable higher levels of compiler optimization or the use of off-the-shelf software libraries

Note that this third option was not part of the original trade study, but was identified over the course of the work.

Algorithm	HabEx time estimates (hr) **best est.** (min/max)	LUVOIR time estimates (hr) **best est.** (min/max)	Memory req. (GB) for HabEx/ LUVOIR	Data uplink time (hr) for HabEx/ LUVOIR
Fourier Optics	**40** (0.1/300)	**150** (0.4/1.5k)	15/250	150/2k
	80 (3/400)	**350** (10/2k)		
20 iterations of EM (Sun et al.)	**3** (0.01/30)	**50** (0.15/500)		0
	7 (0.2/35)	**100** (4/600)		

Estimates of one-time requirements for Jacobian calculation. Jacobian calculation via propagation of Fourier Optics is the standard method used by Roman Coronagraph. Expectation Minimization (EM) is a novel method proposed in Sun et al. 2018. The times are based on estimates of: number of operations for each algorithm, HabEx and LUVOIR dark hole parameters, execution and memory access times of the NXP LX2160A (black on light gray) and BAE RAD5545 (white on dark gray) processors, and their worst and best cases. This wide range emphasizes the importance of testing to reduce these uncertainties. The memory requirement is for storing the Jacobian. Uplink time is based on 256 kbps rate from DSN.

Algorithm	HabEx time estimates (hr) **best est.** (min/max)	LUVOIR time estimates (hr) **best est.** (min/max)	Memory req. (GB) for HabEx/ LUVOIR	Data transfer time (hr) for HabEx/ LUVOIR
Classical EFC - 4 iterations	**0.3** (<0.01/3)	**20** (0.05/200)	0.2/3	0.1/0.3
	0.7 (0.03/4)	**45** (1.5/200)		
Adjoint-based EFC - 4 iterations	<**0.01** (<0.01/0.07)	**0.04** (<0.01/0.3)	0.002/0.01	
	0.02 (<0.01/0.1)	**0.07** (<0.01/0.4)		
Precomputed EFC inverse - 4 iterations	**0.02** (<0.01/0.2)	**0.3** (<0.01/3)	60/1000	600/8k
	0.04 (<0.01/0.2)	**0.7** (0.03/4)		
Precomputing 4 EFC inverses	**0.6** (<0.01/5)	**40** (0.1/350)		
	1.5 (0.05/7)	**90** (3/450)		

Estimates of the requirements and gains of the EFC step of dark hole creation (the requirements of the estimation step are negligible in comparison). As with Jacobian calculation, these ranges emphasize the importance of testing to reduce uncertainties. Classical EFC is use by Roman Coronagraph; it can be accelerated by precomputing a matrix inverse for each regularization parameter (bottom two rows). Adjoint-based EFC is a novel algorithm propose in Will et al. 2021. The times are based on estimates of: number of operations for each algorithm, HabEx and LUVOIR dark hole parameters, execution and memory access times of the NXP LX2160A (black on light gray) and BAE RAD5545 (white on dark gray) processors, and their worst and best cases. Our best estimates suggest that given the current state of technology, HOWFSC is barely feasible on HabEx and infeasible for LUVOIR. Data transfer times include the downlinking of 7 probes images for each EFC iteration.

Significance/Benefits to JPL and NASA

Ground-in-the-loop (GITL) control is the best currently available alternative to on-board HOWFSC. Roman experience indicates that the iteration speed in GITL is primarily due to data transfer bottlenecks rather than computation time; early attention to ground system architecture in a GITL context could reduce delay considerably.

Co-flying computers in close orbits can accelerate computations to the point where HOWFSC computations no longer affect observation schedule. The co-flying mission may be developed at a lower risk-level than the telescope, and COTS components can be upscreened for relatively low cost for use with a computational co-flyer architecture. Redundant spacecraft or replacement launches may be needed to keep the main telescope serviced continuously, but at lower cost versus the main mission.

Novel algorithms such as adjoint-based EFC have potential for speedup but are not yet tested on space-rated processors. The use of compiler optimization, memory prefetching, and vectorization onboard could potentially improve estimates of computation time by at least an order of magnitude.

This work suggests that mission concepts with JPL involvement, such as HabEx, should start early definition of HOWFSC computational architecture, as high observation efficiencies will require computation strategies to be drivers of the overall system architecture rather than afterthoughts.

Acknowledgments

Thanks to the MIT students and postdocs who have worked on this SURP over the past two years: Christian Haughwout, Leonid Pogorelyuk, Nicholas Belsten, Greg Allan, Yinzi Xin, Rachel Morgan, and Jennifer Gubner.

Publications

[A] Leonid Pogorelyuk, Christian Haughwout, Nicholas Belsten, Eric Cady, Kerri Cahoy, "Computational Requirements of Image Plane Algorithms for High Contrast Imaging in Space Telescopes," submitted to JATIS

[B] Nicholas Belsten, Leonid Pogorelyuk, Christian Haughwout, Eric Cady, Kerri Cahoy, "Strategies for High Order Wavefront Sensing and Control (HOWFSC) Computation on Future Space Telescopes", Proceedings of the SPIE, San Diego, CA 118231J (2021)

National Aeronautics and Space Administration **www.nasa.gov**

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PI/Task Mgr Contact
Email: Eric.J.Cady@jpl.nasa.gov

Clearance Number:
RPC/JPL Task Number: SP20011