Astro2020 Activity Proposal: Affordable Large Space Observatories

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Summary: Apply photonics and mass manufacturing to afford post-LUVOIR observatories.

New architectures and technologies are needed to make feasible the very large space observatories expected to appear on NASA’s planning horizon over the next decades. By exploiting emergent photonics technologies, mass manufacturing, launch-as-cargo, and on-orbit automated assembly, new architectures for large space observatories will reduce project costs and development durations, making very large post-LUVOIR space observatories possible in acceptable time frames and with affordable cost envelopes. This whitepaper advocates a NASA activity aimed at capturing the opportunity to develop and deploy needed capabilities for mid-century space astrophysics without executing overwhelmingly large and programmatically risky projects.

I. ACTIVITY PROPOSAL

We advocate that the Decadal Survey propose a NASA-led activity that will:

• Serve as a development home for technologies and architectures aimed at enabling very large space observatories.

• Create new telescope architectures exploiting large numbers of mass-produced identical units;

• Provide impetus for standardized launch-as-cargo and on-orbit assembly infrastructure;

• Demonstrate optical interferometric imaging as an integrated photonics system in a laboratory testbed, iterating over time to progressively approach quantum-limited performance;

• Build upon, accelerate, and extend existing NASA efforts to mature flight photonics capabilities for remote sensing applied to NASA’s missions;

• Assemble an experience base of flight photonics, focusing initially at the component and instrument level and applied to advanced sensor capabilities;

• Define and implement standardized photonic interfaces to back-ends operating on photons collected/derived from the source radiation field itself;

• Develop paths for other observatory functions to be implemented via common photonics/electronics materials platforms and fabrication technologies;
• Foster infusion of developed capabilities across the NASA enterprise;

• Partner with industry, academia, and other government efforts where parallel and synergistic efforts are being undertaken to achieve development economies with mutual benefit;

with the goal of programmatically enabling a highly capable post-\textit{LUVOIR}-class mission.

Key technical capabilities that will need to be demonstrated include achieving the spectral and spatial resolution, throughput, optical bandpass, and noise performance of a classical telescope. The technologies developed will be widely applicable throughout NASA’s portfolio, further enhancing the value of this activity (for a current view, see \cite{1}).

This activity can be expected to span the intervening decades and cost upwards of 100’s of millions of dollars, representing an annual spending rate of 1 to a few percent of NASA’s $1.2 B FY2019 space astrophysics budget \cite{2}. Preliminary to implementing a concrete program, a modest study will need to refine the scope of the activity and its profile so that it can be included in NASA planning.

We fully endorse the complementary Activity Proposal “\textit{Enabling the next generation of scientific discoveries by embracing photonic technologies}” \cite{3}, which describes in detail the photonics state of the art applied to instrumentation. In this whitepaper we focus on economic and architectural aspects at the observatory scale.

\section{II. THE CHALLENGE OF EVER LARGER}

As NASA enters the \textit{JWST} era and lays plans for the future, we are faced with a grand challenge: given expected funding wedges and technical approaches, post-\textit{LUVOIR} observatories will cost many tens of billions of dollars and take decades to become operational. As space telescopes grow ever larger and implementation schedules ever longer, the path we are on will eventually become programmatically untenable: small annual cancellation risks will add up; spending profiles will inefficiently allow only incremental annual progress; design decisions and technologies will be frozen-in decades before launch; the timescale to complete will approach if not exceed the length of political, management, engineering and scientific careers; NASA priorities will evolve; and other investigational approaches to the problems of the day will yield fruit. Simply put, the current approach to space telescopes will eventually become unsustainable in the face of the demand for ever larger apertures because it is too slow, expensive, and risky under reasonably foreseeable funding scenarios. Similar scenarios have unfolded in diverse domains \cite{4}, driven by the demand for ever greater performance in the presence of resource constraints.

In astrophysics stringent demands may be expected \cite{5} to include high-cadence ultra-high-SNR spectroscopy for deep explorations of exoplanet atmospheres \cite{6}, harvesting Earth-like planets via ultra-high contrast imaging of distant planetary systems \cite{7}, precision time and spectral domain stellar astrophysics enabling exquisite understanding of stellar populations and their histories in nearby galaxies \cite{8}, and mapping the assembly histories of black holes from their environments throughout cosmic time \cite{9}. More speculative future needs include exploiting entanglement and higher-order correlations in photon statistics enabling new sensing modalities \cite{10} applied to astrophysical problems.

A different way to achieve the very large collecting areas needed to address future questions must be found. This new way must dramatically lower cost and development time. This new way is not likely be an incremental or even evolutionary approach based on current flight architectures and practices because the gap between abil-
ity and need will become too large because of their mismatched timescales, though incremental and evolutionary approaches \[11, 12\] are likely to be viable for a few decades longer.

### III. APPLYING PHOTONICS, A RAPIDLY MATURING TECHNOLOGY

Already some key aspects of a solution are coming into focus. The Square Kilometer Array interferometric radio-telescope is in part comprised of thousands of mass-produced identical units, demonstrating an architecture achieving significant manufacturing economy of scale. Established and emergent photonics capabilities needed to form an interferometric optical telescope \[13\] include efficient optical antennae to couple incident radiation into planar devices \[14\]; low-loss interconnects allowing assembly of individual units into a larger system \[15\]; wavefront/aberration correction \[16\]; static \[17\] and active \[18\] delay lines and phased arrays \[19\] to provide pointing, beam combiners \[20\], and beam splitters \[21\] to form interferometric elements; and photon state sorters for momentum, energy, and angular momentum \[22, 23\] to prepare the signal for coupling into a backend which will generate astrophysical measurements in spatial, spectral, polarization and time domains. Already the Lockheed SPIDER effort has integrated enough components to enable interferometric synthetic imaging with a laboratory hybrid photonics device \[24\].

Combining optical functions with electronic functions on a common wafer \[24\] will allow a photonic observatory to be architected as interconnected panels (facets), the system rigidized as necessary by structural elements. Making use of future launch-as-cargo, in-space assembly, test-as-you-build techniques, and taking advantage of expected future high-orbit or cis-lunar infrastructure will reduce emplacement costs (we can expect these services to become available as a matter of course, driven by larger economic forces).

An intriguing possibility, awaiting technology maturation driven by industry, is to implement the backed as a photonic quantum computer \[26, 27\]. Directly coupling astrophysical photons and making quantum mechanical measurements upon them could preserve information \[28\] now lost when photons are binned into classical spatial, spectral, polarization, and temporal phase space bins. New sensing modalities exploiting quantum mechanical aspects will then become available \[10\].

### IV. EXPLOITING SCALE AND EXPONENTIAL PROCESSES

**Advantage of mass production.** An inkling of the magnitude of cost improvements available through mass manufacturing can be had by comparing the per-unit-collecting-area cost of JWST with a COTS system comprised of a consumer action camera flown on a drone. Many high-level functions are similar: communication, tasking, mobility and navigation, pointing, imaging, finished data products. Using rough numbers \[29\], the COTS system is 2% the per-unit-collecting-area cost, reinforcing the idea that there are significant cost advantages available by adopting an architecture permitting the use of large numbers of identical mass produced units. A similar exercise \[30\] comparing JWST with a significantly higher payload capacity drone and a thermal infrared imager with a piggyback visible camera targeted at demanding search and rescue operations gives a roughly 20% COTS to JWST ratio. The difference between these two COTS systems illustrates the dramatic effects of technology maturity, per-unit mass or size, and production quantity \[31\].

Another perspective comes from looking at photovoltaics (PV) and solar power installation economics. For PV installations per-
formance is directly related to area, as is also true for telescopes and their collecting areas. Mass production of PV panels and improvements in installation methods have driven an annual reduction in PV panel per-unit-area cost in real year dollars of about 6% \cite{32}. Improvements have been even more rapid for the panels themselves, which at present account for well under 1/3 of the installed cost.

**Advantage of photonics.** As photonics technologies mature, manufacturing costs per unit function are expected to decrease, especially when implemented using a platform common with electronics fabrication. Industry estimates are that the 2024 global photonics market will be > \$780B/year \cite{33}, a volume which will continue to generate significant year-over-year cost improvements reminiscent of Moore’s Law. Historically, the annual pace of photonics technology progression is about half that for electronics wafers \cite{34}, but nearly an order of magnitude greater than for space telescopes whose 3% annual improvement \cite{35} is insufficient to keep up with the 7% annual growth in the demand for larger collecting areas \cite{36,37}.

**Common platform advantage.** There are opportunities to move multiple observatory functions into or integrate on-chip with photonics, e.g. telecom, power, avionics, guidance, navigation, and control. Adopting photonics technology more broadly than for the telescope alone, which in current architectures accounts for only a small fraction of overall observatory cost, provides further advantage by eliminating large numbers of process and integration steps.

We don’t need to capture the full extent of these advantages to attain the programmatic capability to carry out post-\textit{LUVOIR}-class science, all we need to do is modestly overcome the annual growth in demand for collecting area. Because there is a large potential improvement available by adopting a mass-produced unit-cell architecture, a 20-ish percent annual improvement available by adopting a technology following a Moore’s law-like trajectory, and a significant opportunity to shed a large fraction of manufacturing and integration steps, there are compelling reasons for optimism that the proposed activity targeting photonics technology will be successful in enabling very large space observatories.

**V. A LATE-CENTURY PHOTONIC OBSERVATORY FOR ASTROPHYSICS**

**Architecture.** This describes a candidate observatory architecture for a very large space observatory employing photonics, after a fully successful execution of the proposed activity and several generations of photonics observatories post-\textit{LUVOIR}. The observatory is comprised of thousands of identical mechanically interlocked and optically interconnected facets tiling the surface of a hemisphere, forming an optical interferometer. Facets are combined in various configurations to form apertures, each of which serves as the front-end for a separate telescope, allowing simultaneous observations of multiple targets. Each facet is essentially two-dimensional \cite{38} and has a thin stack of photonic wafers fixed in a mechanical frame which in turn has both actuated components and mechanical latches to neighboring facets. These wafers are manufactured using available chipfab technologies analogous to today’s silicon wafer manufacturing. The top wafer in the stack of each facet hosts an optical antenna array coherently coupling the incident light field into photonic waveguides. The antenna array has a filling factor of 80%, similar to present-day space telescopes, leaving area for metrology and observatory functions requiring a view outward to deep space. The antenna array and waveguides together form the telescope front-end. The front-end passes light to the next set of functions on the wafer below which has optical interconnects with neighboring facets and uses delay lines, splitters, mixers, and other photonic components to establish precision path-
length control and perform spatial sorting and path integration. This is the part of the architecture that permits a set of interconnected facets to become a single telescope, coherently forming the astrophysical signal. The coherent signal is then passed on to the measurement functions in the backend third wafer. This backend operates on the signal photons to generate the scientific content of a telemetry stream, including images, spectra, time-series, and (speculatively) quantum mechanical measurements allowing non-classical sensing modalities. The telemetry stream is handed off to an optical communications system in the bottom and fourth wafer for transmission to the ground. Other observatory functions implemented in the bottom wafer of the stack include communications, power generation, thermal control, guidance, navigation, attitude control, and other avionics. Where cost effective, observatory functions are provided by electronics rather than photonics.

Optical metrology [39] combined with small-stroke actuation of each facet’s structural elements supplemented by non-mechanical active delay lines maintain the optical rigidity of the aperture, attaining the pathlength stability needed for ultra-high-contrast imaging. Phased array fine steering replaces mechanical pointing. An aperture will typically be as large as a steradian of the hemisphere, while other facets of the hemisphere will form additional, simultaneously operating apertures thereby allowing the observatory to carry out multiple investigations at once. The observatory is assembled at L2 from mass-manufactured units after being launched as cargo to an established assembly facility.

Programmatics. This describes the ROM programmatic with simple assumptions using present-day cost numbers to remove inflation from the analysis. A 64 meter diameter hemispherical observatory assembled from $6,000 \times 1 \text{ m}^2$ facets with an assumed manufacturing through delivery cost of $400K each represents a ready-to-fly hardware cost of $2.40 \text{ B}$. By comparison, current cost projections for 450 mm Silicon wafer fab are $\approx 10 - 50 \text{ K/ m}^2$ [40] in today’s dollars. This represents two orders of magnitude lower per-unit-area cost than current meter-class flight mirrors in their mounts [41]. The remainder of the facet cost [42] is accounted for by structure, actuators, latches and interconnects. Assuming a packaged launch mass of 10 kg/facet, 3 Falcon Heavy launches are needed, which today would cost $0.45 \text{ B}$ [43]. Adopting $1 \text{ B}$ for on-orbit assembly services and a similar amount for design plus software results in a ROM cost estimate of $5 \text{ B}$. This cost could be accommodated over the course of a decade at a rate lower than recent JWST spending.

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3 Enabling the next generation of scientific discoveries by embracing photonic technologies.


5 It is of course impossible to predict the large questions decades from now, but it is certain that answering them will require highly advanced capabilities.


12 Many of the recommendations made by Feinberg et al deriving from the JWST experience are adopted by the approach advocated in this whitepaper.


[27] This suggests a more speculative activity component:

- Incorporate photonic quantum computing backends from the instrument to observatory level as industrial capabilities mature;

[28] In terms of maximally descriptive photon state eigenvectors.

[29] Rough numbers: *JWST* is $10 B, 25 m^2 aperture while a 1.2 cm^2 aperture COTS action camera on a drone is $1 K for an areal cost ratio of COTS/JWST=0.02.

[30] A FLIR thermal infrared video imager with a 1.9 cm^2 aperture is $6.7 K, Beetlecopter drone $6.5 K.

[31] This COTS vs COTS comparison illustrates the utility of strategies which use technology to reduce cost rather than extend capability.


[36] Estimating from *Hubble* to *LUVOIR* ca 25 yrs post *JWST*, the areal demand grows at about 7% per year.

[37] Our appetites double every 10 years while our capabilities double every 24.

[38] Standard optical instruments are equivalent to complex valued diagonal matrices in between Fourier or Fresnel propagations, while advanced photonic devices allow gen-
eral linear operations in a physically compact package.


[41] JPL HabEx Lite internal studies.

[42] Assumptions: $ 50 K for each of the facet’s wafers, hexapod articulation stage $60 K, latches $3 \times $20 K, interconnects $50 K, static structure $5 K, thermal hardware $5 K, packaging $10 K, assembly, ground test, and delivery to launch site $10 K.

[43] $150 M represents the upper range of press accounts for a Falcon Heavy launch.