Cost Estimate

Summary

Although the design of PUMA is at the pre-conceptual level, we may make reasonable, conservative assumptions about scaling and future technology developments to extrapolate from precursor dish array projects and arrive at plausible bounds on the eventual project cost. As the design matures and the project is informed by R&D and experience of precursor Stage I surveys, a more thorough and parametric bottoms-up cost estimate will be developed.

This cost estimate was performed by the Instrumentation Division at Brookhaven National Laboratory in June 2019. We present the cost for PUMA-Full (PF, 32,000 station) array, with the smaller PUMA-Petite (PP, 5,000 station) array as a potential first-stage pathfinder. The base year is 2019; no escalation or contingency is included in the estimate. The top level estimates for both implementation options are presented below:

		FULL			PETITE		
Phase	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)	U.S. Federal ($M)	Non-federal ($M)	Total ($M)
R&D	FY 21-24	15.0	5.0	20.0	15.0	5.0	20.0
Final design and site acquisition	FY 25-26	8.0	2.0	10.0	8.0	2.0	10.0
Construction and commissioning	FY 27-34	313.2	16.5	329.7	52.3	2.8	55.0
Operations	FY 34-38	89.0	9.9	98.9	14.9	1.7	16.5
Science	FY 35-38	103.9	34.6	138.5	17.3	5.8	23.1
TOTAL	FY 21-38	**529.1**	**68.0**	**597.1**	**107.5**	**17.2**	**124.7**

Table 1: summary cost estimate for PUMA

Cost Estimate Detail

The PUMA-FULL experiment is envisioned to need multi-agency funding, nominally at the level of a DOE Major Item of Equipment (MIE) and NSF Major Research Equipment and Facilities Construction (MREFC) project. The smaller PUMA-PETITE program could be carried out by a single agency. In both cases it is assumed that between 5% (construction) and 25% (science) of the funding would be from in-kind contributions from US institutions and international partners.

R&D phase

We assume an aggressive R&D program lasting 4 years, addressing the most critical analysis issues and bringing key technologies to maturity. This is a notional estimate corresponding to roughly 20 scientists, engineers, postdocs, and students working full time on PUMA. At the conclusion of this phase the project would be ready for site-specific agency reviews (DOE-CD1, NSF-PDR).

Final design phase

In this 2-year phase we envision negotiations with the host country over site acquisition, in parallel with the final design effort leading to an approved baseline budget and schedule (DOE-CD2/CD3a, NSF-PDR).

Construction phase

Unlike other Cosmic Frontier projects, the Stage-2 experiment does not require exotic semiconductor/ superconductor components, does not need cryogenic cooling, and can effectively take advantage of economies of scale for the RF and digital electronics driven by the widespread deployment of wireless communications. There are no precision mechanical tolerances involved in mass manufacturing of the dish elements. Finally, onsite construction can be largely accomplished with host-country technician labor; the low-tech nature of the receiver stations should require a much lower level of engineering effort during construction than has been the case for optical astronomy and accelerator-based projects.

We project the construction and commissioning of PUMA-PETITE to require 4 years. A subsequent build-out of PUMA-FULL could occur without completely disrupting the operation of PP, for instance by observing at night only.

We model the following elements in the attached spreadsheet PUMA_ConstructionCostBreakdown.xlsx :

Site upgrade

We assume an existing radio-quiet site with road, power, and fiberoptic communication access will be available, and estimate a US contribution of $5M for needed improvements to accommodate PUMA. Additional funding for site improvements, if needed, may be provided by the host country.

Dish and feed

Available cost estimates from precursor projects (CHIME, HIRAX, CHORD, TIANLAI) were used to generate a per-dish cost for a notional non-tracking, 6m molded fiberglass dish.

On-dish electronics

We propose to include front end dual-polarization RF amplifier and filter chains, on-antenna digitizers operating in first Nyquist zone with F-engines implemented in FPGA, and fiberoptic serial IO, in thermally-stabilized enclosures. For these components we extrapolate from actual costs from HIRAX, CHIME, and BMX. Using historical industry pricing data, we applied 5%/year and 10%/year cost trends for the digitizer and FPGA/F-engine/SERDES, respectively.

Timing synchronization and distribution

Per-link cost adopted from SKA-mid estimate for a sub-picosecond optical synchronization link. Such timing systems are expected to be needed for many upcoming research and industrial applications; we assume 8%/year cost reduction factor. In PUMA, precision timing links will be installed to distribution boxes each serving a cluster of 6 antenna stations in close proximity. We estimate that this will be sufficient to maintain phase coherence over the entire array.

Correlator, corner turn, and back-end electronics facility

Cost is extrapolated from estimates for HIRAX-512 for an X-engine implemented in GPU, server farm and storage housed in an appropriately shielded facility with power and cooling. We assumed cost scales as N*log(N) and applied cost reduction factors of between 0 and 10% per year for the various components. If ASIC realizations are used in the correlator and corner turn, dramatic improvements in power efficiency may lead to even greater cost savings.

Control, calibration, and data management

Labor and non-labor costs for these subsystems were taken as a percentage of total project construction cost. Average of LSSTcam actual, and HERA-II, CMB-S4, and PICO proposed values was used.

Installation and commissioning

The average of LSSTcam, CMB-S4, and PICO percentages of total construction cost was used.

Project management

The average of LSSTcam, HERA-II, CMB-S4, and PICO percentages of total construction cost was used.

Operations phase

For each operations component (facility operations and maintenance, data management, and science) we took the annual cost as a percentage of construction cost, using the average of the available data from LSST, HERA-II, DESI, and CMB-S4:

Experiment	Construction cost	Facility Operations		Science + Data Mgt.	
		($M/yr)	(% of construction)	($M/yr)	(% of construction)
DESI	56.3	6.3	11%	2.3	4%
HERA-II	30	2.4	8%	5.8	19%
CMB-S4	506	8.5	2%	5.6	1%
LSST	641	31.1	5%	21.8	3%
AVERAGE	-	-	**6%**	-	**7%**

Table 2: operations costs from precursor survey experiments

Timeframe

The whitepaper assumes the start date of a 4-year construction phase (DOE-CD1/3a or NSF-FDR) in 2027, following a progression of R&D, prototyping, and technology maturation programs.

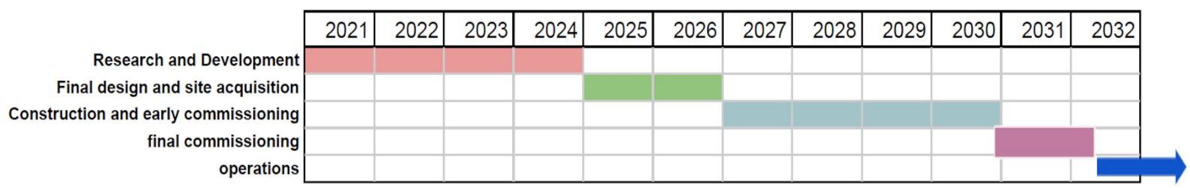

Figure 1: notional timeline for the PUMA-Petite array

Figure 2: notional timeline for the PUMA-Full array