	PUMA-5K				PUMA-32K			
Phase	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)	Years	U.S. Federal ($M)	Non-federal ($M)	Total ($M)
R&D	FY 21-24	15.0	5.0	30.0	FY 21-25	26.3	8.8	35.0
Final design and site acquisition	FY 25-26	8.0	2.0	10.0	FY 26-27	8.0	2.0	10.0
Construction and commissioning	FY 27-30	55.9	2.9	58.8	FY 28-33	354.7	18.7	373.4
Operations	FY 34-30	15.9	1.8	17.7	FY 34-38	100.8	11.2	112.0
Science	FY 31-35	12.4	4.1	16.5	FY35-38	78.4	26.1	104.5
TOTAL	FY 21-35	**107.1**	**15.8**	**133.0**	FY 21-38	**568.2**	**66.8**	**634.9**

Figure 16: Summary costs for PUMA-5K and PUMA-32K.

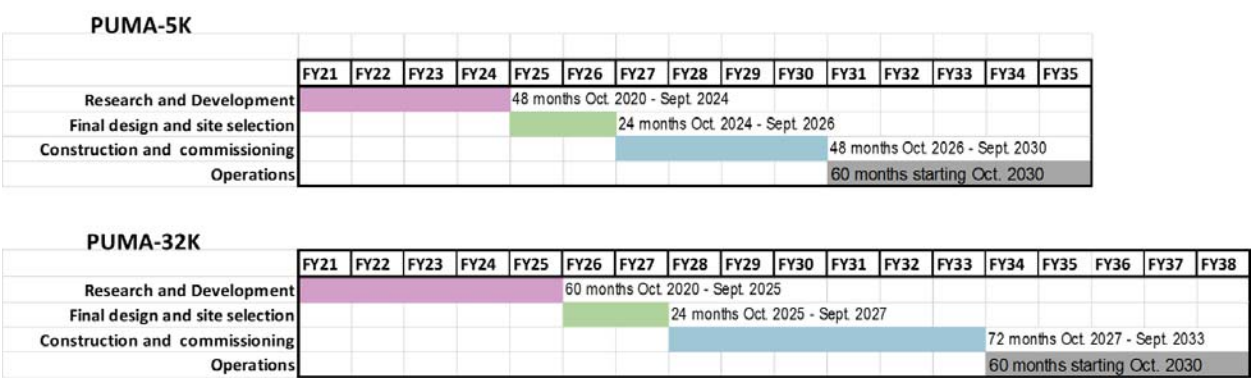

Figure 17: Summary timeline for PUMA project phases from R&D through Operations

10.2 Cost Estimate Detail

R&D Phase

We assume an aggressive R&D program lasting 4 or 5 years, addressing the most critical analysis issues and bringing key technologies to maturity. The focus will be on developing calibration and simulation methods that address the major risks. This is a notional estimate corresponding to roughly 20 scientists, engineers, postdocs, and students working full time on PUMA plus costs to construct pathfinder arrays. 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). If a site in the U.S. is selected the costs would be lower.

Construction Phase

Unlike other Cosmic Frontier projects, the PUMA 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-5K to require 4 years. A subsequent two-year build-out of P-32K could occur without completely disrupting the operation of P-5K, for instance by observing at night only.

The construction cost model is described below and details are given in

https://www.cosmo.bnl.gov/PUMACostingJul19.zip.

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 $(5,8)M for needed improvements to accommodate PUMA-(5,32)K. 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, altitude-adjustable 6m molded fiberglass dish.

Antenna and Receiver 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 (see 4.3). 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 Distribution and Synchronization 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

Parameter	CHIME/HIRAX	DSA-2000	Units
Number of Antennas N	512	2000	
Bandwidth B	400	1300	MHz
Total hardware cost	0.715	25	\$M
Cost/CMAC/bandwidth	3.41e-9	2.40e-9	\$/Hz

Table 8: FX correlator costs

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. If RFI considerations make it impractical to locate the digitizers and FPGAs on each antenna, they could alternatively be housed in the well-shielded per-cluster enclosures used for timing fanout.

Correlator The computational cost of a conventional FX correlator scales as

$$R = 2B(n_{ch}log_2N + N^2)$$

Where R represents the aggregate multiplication rate, B is the bandwidth, n_{ch} is the number of frequency channels processed, and N is the number of antennas [62]. The first and second terms correspond to the F- -and X-engines respectively. For large-N intensity mapping instruments, the X-engine term is dominant and $R \sim 2BN^2$. To verify this scaling model, we used data from CHIME/HIRAX [L. Newburg, 5/9/2019] and DSA-2000 [Astro2020 APC whitepaper](Table 8). We used the average of the two figures in the last row of Table 8 as a reasonable per-computation, per-bandwidth cost and based our overall PUMA-5K and PUMA-32K correlator cost estimate on this number.

As discussed in Section [FFT correlator] , a full N^2 correlator will be impractical from a cost and power standpoint even at the scale of PUMA-5K. Even with the most optimistic assumptions about technology advances PUMA-32K will need a direct-imaging, FFT correlator back end. The FFT correlator's computational cost will scale roughly as $N_slog_2N_s$, where N_s is the number of lattice sites taking into account padding, gridding, etc. ($N_s \sim 20N$). To account for periodic gain and phase calibrations, we assume the correlator will also perform full N^2 correlation on 1% of the baselines, resulting in a correlator cost of that scales by $(N_slog_2N_s + 0.01N^2)$. A cost deflator of 5%/year has been applied to this element.

As shown in [63], dramatic improvements in cost and power efficiency can be realized if key components are realized in ASIC technology. Our R&D activities will include exploration of optimal architectures using ASICs.

Control, calibration, and data management Labor and non-labor costs for these subsystems were taken as a percentage of total project construction cost. We used available data from comparable large agency-funded experiments, taking the average of LSSTcam actual, and HERA-II, CMB-S4, and PICO proposed values.

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.

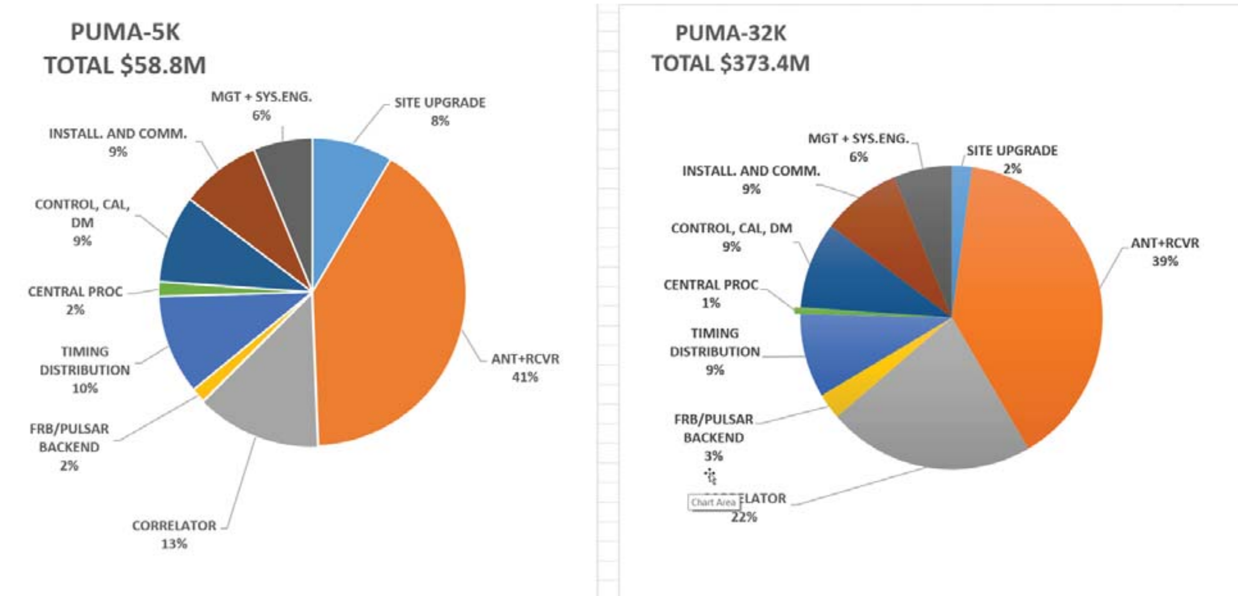

Figure 18: Breakdown of PUMA-5K and PUMA-32K construction costs.

Summary Construction Cost A breakdown of the PUMA-5K and PUMA-32K construction cost is given in Fig. 18.

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, each of which have similar needs for managing the extensive equipment and data volumes. See Fig. 19.

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%**

Figure 19: Cost of operations for other large surveys.