Snowmass2021 – Letter of Interest

Packed Ultra-wideband Mapping Array (PUMA): Next generation facility for Sky Survey in Radio

Thematic Areas:

■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (IF2) Photon Detectors
■ (IF4) Trigger and DAQ
■ (IF7) Electronics/ASICs

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Abstract:

PUMA is a proposal for an ultra-wideband, low-resolution, transit interferometric telescope to perform a deep survey the radio sky from 200 – 1100MHz. We propose two array configurations composed of hexagonally close-packed 6-meter dishes with 50% fill factor. The initial 5,000 element PUMA-5K is scientifically compelling, and can act as a demonstrator and a stepping stone to the full 32,000 element PUMA-32K. This facility must be preceded by significant investment in the R&D required to establish the technical requirements and an accurate cost envelope. This research phase will involve design and laboratory characterization work as well as small test prototype systems. PUMA will require an exquisite radio-quite zone with similar properties to existing sites dedicated to radio astronomy. A location in the southern hemisphere will be beneficial for optimal cross-correlation opportunities with upcoming surveys in the optical (Vera C. Rubin Observatory/LSST, DESI) and cosmic microwave background (Simons Observatory and CMB-S4).

Context

Closely packed transit radio interferometers have recently become powerhouses of radio-sky survey science. Such telescopes, including the currently-operating CHIME [1], the under-construction HIRAX [2] and HERA [3], and the proposed CHORD [4], have orders of magnitude higher mapping speed than contemporaneous instruments. This high mapping speed enables a wide range of science, from cosmology to radio transients. The experiment presented in this letter, Packed Ultra-wideband Mapping Array (PUMA), constitutes the next generation of this type of instrument, with 2 orders of magnitude increased mapping speed compared to CHORD (3 orders of magnitude compared to CHIME), even in the reduced PUMA-5K configuration. In addition, PUMA will have exquisite control over systematic errors, enabled by an extensive pre-construction R&D phase, a staged series of small pathfinder experiments, and careful DOE-led management of the program. The resulting tight control over systematic errors will enable precision measurements as required for the most demanding cosmological science. The science opportunities of PUMA are presented in a companion Letter of Interest [5].

Instrument

PUMA [5–8] will be a transformative facility, enabling an extremely deep, wide-band and high resolution survey of the southern sky. The key science areas identified for PUMA are cosmology via 21-cm intensity mapping and radio transient science such as fast radio bursts (FRBs), and these motivate the following aspects of the reference design:

- **Large bandwidth** — to maximize science output and maximally leverage technology advances, PUMA's instantaneous bandwidth will be 200 – 1100 MHz;

- **Large element count transit array with quasi-fixed dishes** — to minimise costs and maximise stability and reproducibility, while at the same time maximizing their number. Dishes are re-pointable in altitude to achieve the overall survey area;

- **Compact array** — to maximise survey speed for scales of relevance;

- **FFT correlation** [15, 16] — to enable an array with a very large number of antennas by dramatically reducing the computational cost over traditional N^2 correlation;

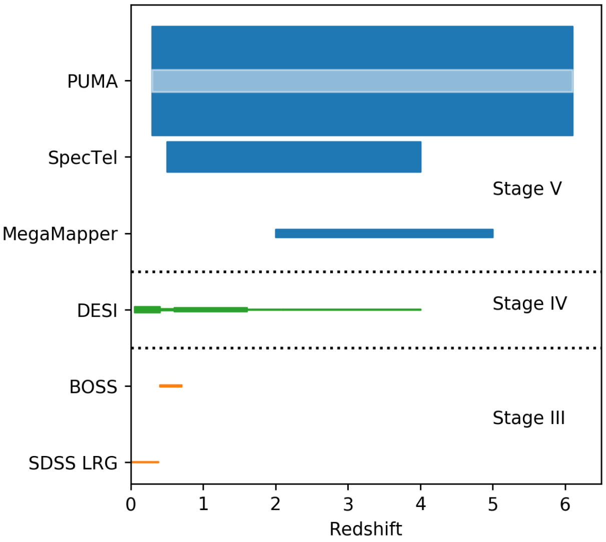

Figure 1: Comparison of Cosmic Surveys sorted by Department of Energy Stage, including completed (Stage III), upcoming (Stage IV) and proposed (Stage V surveys). For each survey, the x-axis represents the approximate span in redshift, while the width of the line is such that the total area scales as the effective number of galaxies. For PUMA the whole region corresponds to PUMA-32K and the light region is PUMA-5K. See [8] for discussion of assumptions and potential caveats.

- **Small dish antennas** — using 6 m dishes to balance the field of view and angular resolution (FoV of ~ 28 square degrees, and resolution of $1.1'$ at 650 MHz);

- **Systematics mitigation** — *early digitisation* to reduce analog chain systematics; *reproducible* manufacturing to lower the number of optical degrees we must measure.

PUMA will be built in two stages, a 5,000-dish array that will already achieve several key science goals, followed by a 32,000-dish array to achieve the remaining goals. In Table 1 we highlight some of the key properties of the PUMA design and the expected observational outputs.

Site Selection

Remote southern-hemisphere sites, which are known to have low levels of radio frequency interference (RFI) and which have existing infrastructures for large radio observatories, are strongly favored for PUMA. This includes the Karoo desert in South Africa and the Murchison site in Australia. Such sites would also have maximum sky overlap with major new facilities at other wavelengths, providing opportunities for cross-correlation science: **LSST** [9] is the main optical survey of the southern sky measuring 4 billion galaxies to redshift $z \sim 3$. DESI [10] and future optical spectroscopic survey using LSST for targeting will likewise overlap with PUMA; the upcoming **Simons Observatory** [11] and **CMB-S4** [12] are major CMB experiments that will cover significant fractions of the southern sky from the Atacama Desert in Chile and the South Pole; **SKA** will be a synergistic radio telescope that will observe at at high resolution and a wider band and enable pulsar science synergies. Finally, siting PUMA in the southern hemisphere, where it can observe the galactic centre, increases its reach for galactic science and increases the number of accessible pulsars.

Antenna Array		
Interferometer type	Transit array	
Element Distribution	Hexagonal close-packed	
Lattice Spacing	6 m	
Lattice Fill-factor	50% random lattice sites	
Frequency band	200–1100 MHz	
Receiver noise temperature	50 K	
	PUMA-5K	**PUMA-32K**
Array Diameter	630m	1500m
Number of Elements	5,000	32,000
Angular Resolution	1.5' - 8'	0.6' - 3.2'
$10\,\sigma$ Single Transit Sensitivity (at zenith)	8.7μJy	1.3μJy
Survey		
Observing Area	50% of the sky	
Observing Time	5 years on sky	
	PUMA-5K	**PUMA-32K**
Equivalent Source Density:		
At $z = 2, k = 0.2\,h\,\mathrm{Mpc}^{-1}$	2.0 $(h/\mathrm{Mpc})^3$	7.4 $(h/\mathrm{Mpc})^3$
Total at $k = 0.2\,h\,\mathrm{Mpc}^{-1}$	0.6 billion	2.9 billion
FRB rates (expected)	80/day	1300/day

Table 1: Basic parameters of the instrument and key science surveys.

Successful operation of PUMA will require certain infrastructure to be present at the observational site:

- **Connectivity** — to transfer data to a North American analysis and archival site.
- **Electricity** — the estimated power required is 250kW for PUMA-5K or 1.5MW for PUMA-32K.
- **Dish construction facility** — allowing for economical on-site production of large components

Recommendations for Snowmass 2021: Support for Research and Development

PUMA is enabled by two crucial technologies that did not exist two decades ago: high-performance radio-frequency electronics developed by the telecommunications industry, and high-throughput GPU computing. Current experiments using this technology like CHIME and HERA have demonstrated that, while building a telescope capable of astronomical observations is relatively straightforward, reaching the required dynamic range and stability is considerably more difficult than anticipated even a decade ago [13, 14]. This cautionary tale informs our approach to PUMA.

Our plan is thus to refine the design requirements and demonstrate all the necessary technologies before we commit to metal on the ground. This effort will be focused in four areas: **#1** laboratory validation and demonstration of the individual technology elements, such as clock distribution; **#2** extensive computer simulations of the entire system, including electromechanical properties of small clusters of individual receiving elements; **#3** detailed study into algorithms and performance of the real-time data reduction and calibration; and finally **#4** small-scale pathfinder arrays based in the US for prototyping and developing this technology. We argue that Snowmass should strongly endorse all aspects of R&D that will enable progress towards a next-generation intensity mapping experiment such as PUMA. Such novel technologies, while requiring significant initial investment, could have a transformative effect on the efficiency with which we map the universe and thus our understanding of the most fundamental physical phenomena governing it.

References

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