# Decadal Survey on Astronomy and Astrophysics 2020: RMS Questions for PUMA Collaboration

PUMA Collaboration

January 27, 2020

## Science:

***Q1*** *Science objective F on p9 of the RFI response refers to "daily monitoring of a significant subset of...pulsars discovered by the SKA." What exactly is meant by "a significant subset," and what level of time-of-arrival (ToA) precision can PUMA be expected to deliver?*

The claim on pulsar science is based on the fact that PUMA has significantly larger collecting area than the current SKA incarnations. In concrete numbers, the collecting area of PUMA is $0.14\,\mathrm{km}^2$ and $0.9\,\mathrm{km}^2$ for PUMA-5K and PUMA-32K, while the number of SKA-1 MID is $0.033\,\mathrm{km}^2$ and $\sim 0.1\,\mathrm{km}^2$ for SKA-LOW at 300 MHz (see Keane et al, 2017, arXiv:1711.01910). In addition, PUMA has larger bandwidth and roughly hour-long dwell times per transit. Therefore, as a first approximation we assume that if a pulsar is detectable with SKA, it should be within sensitivity reach of PUMA, even in the 5K configuration.

We then estimate the total number of pulsars in the PUMA field of view as follows: we take the existing list of pulsars from the ATNF pulsar catalog (`https://www.atnf.csiro.au/research/pulsar/psrcat/`) containing 2704 pulsars and add a list of SKA1-LOW simulated pulsars containing 3036 pulsars for a total list of 5704 pulsars. These were kindly provided by Shi Dai of Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). Note that SKA1-MID should find approximately 10,000 additional pulsars, many of which will be observable by PUMA, so our numbers are conservative.

We then assume PUMA to be observing from the latitude $-30^\circ$ (coinciding with the SKA observatory) and calculate the number of sources in the beam as a function of right ascension and offset from zenith pointing. This leads to the bottom right plot in Figure 2 of the APC Project submission, which we reproduce here for completeness (see Figure 1).

Depending on the declination, the number of pulsars that are observable in a sidereal day is 397, 512, 663, 731 and 769 for observing at altitudes -30°,-15°,0°,+15° and +30° from zenith for a total of 3072 pulsars or approximately half the total projected number of SKA pulsars. Of course, these numbers should be taken with appropriate uncertainties. For example, the size of the beam has been estimated at 500 MHz and no account has been taken for beam suppression, etc. However, it is nevertheless correct to say that an instrument like PUMA is in principle capable of observing approximately 10% of SKA pulsars daily with the total number surveyed over the nominal survey reaching to 50% of SKA pulsars.

In terms of ToA precision, our large collecting area, ultra-wide bandwidth, and long contiguous observations (roughly hour transits across the 15-degree beam, depending on observing frequency) will result in timing that is limited principally by pulsar intrinsic red-noise timing jitter, which can be better than 100 ns in a single epoch for certain millisecond pulsars. PUMA's wide band

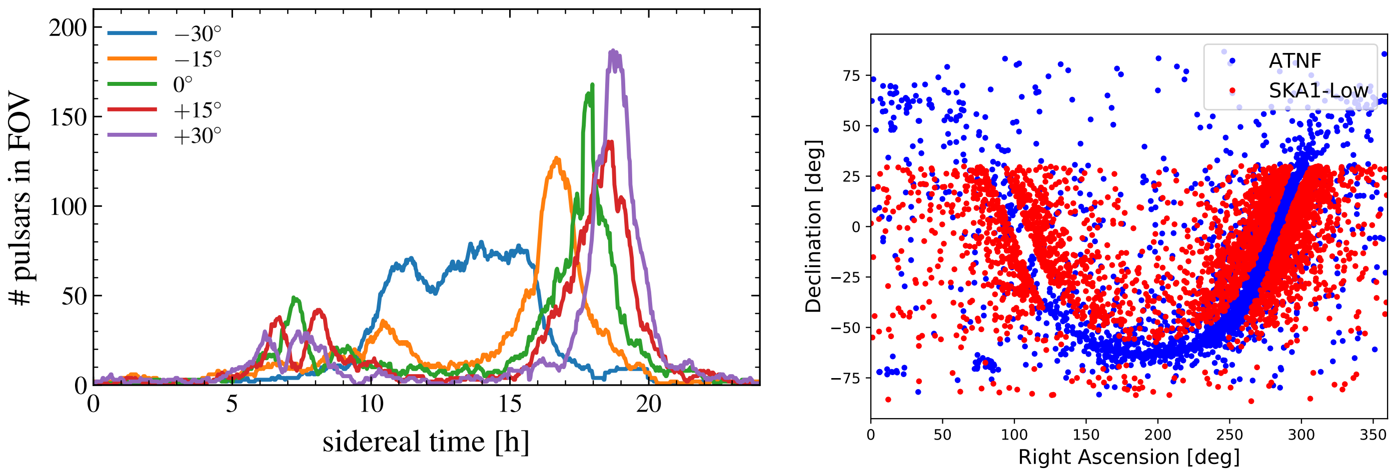


Figure 1: Left panels is a reproduction of bottom right plot from Fig. 2 of Decadal APC submission. It shows the number of instantaneously observable pulsars in our catalog that is a combination of the real ATNF catalog and synthetic catalog of SKA1-Low pulsars. The right figure shows the distribution of these sources on the sky. SKA1-Mid is expected to find around 10,000 pulsars which were not used in these forecasts.

will allow a precise measurement of pulsar dispersion at each observation, which is crucial since time-variability in the dispersion is a leading source of timing noise.

Another important consideration in pulsar timing is observing cadence, which is dictated by how often we repoint the array to different observing altitudes. While our detailed survey strategy has not yet been set, repointings will likely be in the range of weeks to months. As such, observing cadences for a given pulsar will around $\sim$1/hour/day for a month twice a year. In any case, there will be significant months longs periods missing in the timing campaign. The precise observing strategy is subject of further research. Regardless of these details, our high sensitivity, daily cadence during a given pointing, and a large number of monitored sources will make PUMA the leading timing telescope.

## Technical/Risk/Cost/Schedule/Management:

***Q2**** *Can the project team clarify the relationship between the federal funding request outlined in the APC white paper and the federal funding request outlined in the RFI response? It would be helpful for the panel to understand how and why (the federal shares of) construction and/or operations costs have increased above the rate of inflation.*

First a clarification: please be aware that the columns in the cost tables between the APC and RFI response are reversed; that is, the 5K configuration in the APC is shown in the right-hand columns and on the left in the RFI.

Both estimates were made in fixed 2019 dollars and do not contain contingency. The cost delta (+7%) between the APC and RFI estimates is a result of the following changes:

1. For PUMA-32K we increased the R&D period from 4 to 5 years;

2. We substantially revised the construction cost estimate for the correlator. First, we recalculated the number of operations/second based on the number of lattice sites needed in FFT

correlation mode and additionally developed a new per-operation cost from CHIME / HIRAX and DSA-2000 APC whitepaper numbers;

3. Costs for operations and science were scaled as percentages of the construction cost based on LSST/HERA-II/CMB-S4/DESI data, Fig. 18 in the RFI;

Since the PUMA proposal is still at a conceptual design level, it has not been appropriate to conduct a bottoms-up cost estimate following agency project guidelines. Instead, for the purposes of the Astro 2020 review we made this estimate based on a parametric costing model. This model relies, where possible, on available component costs (primarily computing, electronic hardware and dish construction) using data supplied by the current generation of experiments, and otherwise on extrapolations based on projects of comparable scope that the authors participate in. Where engineering judgement was required an attempt was made to be conservative. The full model is available at `http://puma.bnl.gov/doc/PUMACostingDec2019.zip` .

The costing model is a useful tool because it allows us to model the cost and the impact of assumptions on it in a systematic manner. Nevertheless, the cost tables in the RFI should be interpreted as nominal center values of ranges with substantial uncertainties. Several design choices under investigation have the considerable potential for dramatic cost savings, for example using FFT algorithms optimized for a hexagonal lattice, developing custom ASICs for correlator operations, lowering the cost of the clock distribution, etc. In other words, we emphasize that the true cost can be lower as well as higher compared to the numbers we propose.

As the proposal matures beyond the R&D phase, project oversight and support will be sought from an appropriate organization within the collaborating institutions, likely one of the DoE national laboratories with significant experience in costing and schedule development of high-value projects.

***Q3*** *What levels of funding is the project team expecting or seeking from NSF and DOE, respectively (for both the 5K and 32K configurations of PUMA)?*

DOE and NSF have collaborated in numerous project employing a variety of models of collaboration. At this stage it is difficult to predict what would be the most appropriate model for PUMA.

Based on previous and current dark energy experiments and their funding models, we expect that it might be possible that the PUMA-5K could be a DOE-led experiment scoped exclusively for the dark energy and early universe science (science goals A-D). In this case NSF could join as a partner to fund the science analysis and instrument features that will enable the FRB and pulsars analysis and to provide radio astronomy expertise.

The scale of PUMA-32K is such that DOE and NSF will both have to contribute as major participants and in addition funding from international collaborators becomes more important. This case would approximately follow the Vera Rubin Observatory LSST model.

In both cases, we expect considerable contribution from international partners, in line with the current generation of survey facilities.

***Q4*** *What is the required lifetime of PUMA, and what level of funding does the project team estimate will be needed for the eventual decommissioning of the array?*

As is often the case in astrophysics, decommissioning costs are not part of the project proposal and instruments often continue to take data years or decades after completion of the initial survey.

For examples, the Sloan Digital Sky Survey will enter its fifth iteration in the 2020s after being commissioned in the early 2000s. Similarly, VRO LSST has been designed as an integrated instrument/survey experiment that will in all likelihood continue observations at the end of its nominal 10 years. We anticipate that PUMA would follow a similar trajectory, perhaps with upgraded instrumentation.

We note that decommissioning should be straightforward, since there are no hazardous chemicals involved and the array does not present major hazards if decommissioned slowly over time. There is potential for equipment reuse for other research projects. Alternatively, PUMA equipment could be donated to the host country. In any case, the decommissioning should be a small fraction of the overall project cost.

***Q5*** *What is the status of the project team's negotiations with potential non-federal partners (described in the APC white paper as "private and international participants"?*

No formal negotiations with any non-federal partners have taken place. We think that this would be inappropriate for a proposal that is not endorsed by any of the potential funding agencies. Our nominal plan was to engage with potential foreign partners at a formal level once and if we receive sufficient endorsement by the Astro 2020 and Snowmass/P5 processes.

The costing model assumed fractions of foreign involvement that is different for different activities (construction, operations, etc.). These are based on typical level of foreign involvement in the current generation of dark energy experiments, rather than actual commitments.

***Q6*** *What is the forward-looking timescale for mitigating the risks associated with FFT correlation, and how does that timescale fit within the development timeline for PUMA?*

For projects of this scale, funding agency guidance would require a rigorous R&D program focused on mitigating and retiring major risks before proceeding to construction. We have currently proposed five years of R&D for PUMA-32K, where the dominant way of retiring the FFT correlation and real-time calibration is through extensive computer simulations. We note that the total system simulation effort at the proposed fidelity has not been performed for any of the Stage 1 low-redshift 21cm experiments and that the EoR community is only now embarking on a similar exercise. For PUMA, extensive simulations in advance of final design are crucial part of risk retirement strategy.

By comparing against results and measurements from our lab development (R&D prong #1) and smaller hardware prototypes (R&D prong #3), these full-system simulations should give confidence in algorithmic correctness and convergence of real-time calibration. There is already a good understanding of the level of foregrounds and likely incompleteness of current sky catalogs, and we stress that a precise model for the true signal is not needed to validate the approach. Therefore, with a carefully-constructed program of computer simulations we believe we can validate the system design.

CHIME is currently using real-time calibration and redundant-baseline co-addition, which is equivalent in terms of information content and calibration requirements to FFT correlation. This system is already deployed for transient detection and the work is in progress to demonstrate it for intensity mapping. Experience from CHIME will be folded into our simulations to better understand performance and requirements.

After a five-year R&D phase we will reevaluate its outcomes. This can result in construction, extension of the R&D phase or de-scope and change of the instrument design.