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## Program objectives and specifications for the Ultra-Fast Astronomy observatory

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# Program objectives and specifications for the Ultra-Fast Astronomy observatory

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## ABSTRACT

We present program objectives and specifications for the first generation Ultra-Fast Astronomy (UFA) observatory which will explore a new astrophysical phase space by characterizing the variability of the optical (320 nm - 650 nm) sky in the millisecond to nanosecond timescales. One of the first objectives of the UFA observatory will be to search for optical counterparts to fast radio bursts (FRB) that can be used to identify the origins of FRB and probe the epoch of reionization and baryonic matter in the interstellar and intergalactic mediums. The UFA camera will consist of two single-photon resolution fast-response detector 16x16 arrays operated in coincidence mounted on the 0.7 meter Nazarbayev University Transient Telescope at the Assy-Turgen Astrophysical Observatory (NUTTelA-TAO) located near Almaty, Kazakhstan. We are currently developing two readout systems that can measure down to the microsecond and nanosecond timescales and characterizing two silicon photomultipliers (SiPM) and one photomultiplier tube (PMT) to compare the detectors for the UFA observatory and astrophysical observations in general.

**Keywords:** instrumentation, silicon photomultiplier, photomultiplier tube, fast radio bursts, optical, telescope, astrophysical transients, nanosecond timescale

## 1. INTRODUCTION

Historically, searching in previously unexplored phase spaces has led to discoveries of new astrophysical phenomena. For instance, the discovery of fast radio bursts (FRB) occurred after archival data from the Parkes radio telescope was searched in the millisecond timescale.<sup>1</sup> While undiscovered sub-second optical phenomena may exist, few measurements have been conducted in the optical sub-second regime<sup>2-4</sup> due to the long read times and noise penalties of most standard array imagers such as charge coupled devices (CCD).

One example of a possible undiscovered sub-second optical transient is an optical counterpart to FRB. FRB are high energy millisecond duration radio transients of unknown astrophysical origin. To date, 82 FRB<sup>5</sup> with frequencies ranging from 400 MHz<sup>6</sup> to 8 GHz<sup>7</sup> have been discovered using large dish radio telescopes. Several theories on the origins of FRB have been proposed including white dwarf mergers,<sup>8</sup> neutron star collisions,<sup>9</sup> supergiant pulses from neutron stars,<sup>10</sup> giant magnetar flares,<sup>11,12</sup> neutron stars collapsing into black holes,<sup>13</sup> young pulsars in supernova remnants,<sup>14,15</sup> and coherent curvature radiation emitted from magnetars.<sup>16</sup> The discovery of repeating FRB<sup>17,18</sup> indicate that FRB, or at least a subclass of FRB, originate from non-cataclysmic origins. An observable optical counterpart would allow us to investigate and potentially identify the origins and

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emission mechanisms of FRB. In addition, as FRB exhibit high dispersion measures that point to an extragalactic origin, optical counterparts to FRB would also allow us to probe the epoch of reionization and baryonic matter in the interstellar and intergalactic mediums.

To date, searches for optical counterparts to FRB have been conducted down to the millisecond timescale. Hardy et al. searched for optical counterparts to FRB in the direction of the repeating FRB 121102 in coordination with the Arecibo Observatory and found no optical counterparts in their 70.7 millisecond timescale.<sup>19</sup> However, searches for optical counterpart emission would require much shorter integration times than in radio due to dispersion and pulse-broadening by electrons in the line of sight to the source. Searches for sub-millisecond duration flashes using millisecond duration cameras would be severely limited by the signal to noise ratio and would require the hardware needed to explore shorter timescales.

In this paper, we describe program objectives and specifications of the first generation Ultra-Fast Astronomy (UFA) observatory which will utilize single-photon counting detectors to characterize the sky and search for optical counterparts to FRB in the sub-second time domain.

## 2. PROGRAM OBJECTIVES

The UFA observatory will explore a new astrophysical phase space by characterizing the optical (320 nm - 650 nm) sky in the millisecond to nanosecond timescales using single-photon counting technology. Exploring the universe down to the nanosecond timescale will allow us to search for undiscovered sub-second astrophysical phenomena such as surface convection on white dwarfs, variability close to black holes, and interstellar laser communications from intelligent extraterrestrial civilizations.

One of our first objectives will be to search for and further constrain the limits of optical counterparts to FRB. We will search for millisecond to nanosecond optical signals in the direction of repeating FRBs. An observable optical counterpart would allow us to potentially identify the origins of FRB and probe the baryonic matter in the intergalactic medium and Epoch of Reionization. The UFA program will improve upon previous searches for optical counterparts to FRB by searching in a faster millisecond to nanosecond timescale with higher sensitivity.

## 3. INSTRUMENT

### 3.1 Telescope

The Nazarbayev University Transient Telescope at the Assy-Turgan Astrophysical Observatory (NUTTelA-TAO) is a Corrected Dall-Kirkham telescope from Planewave Instruments (CDK700) having an aperture of 700 mm and a focal ratio of 6.5. Installation of the NUTTelA-TAO at the Assy-Turgan Observatory completed in October 2018. The UFA instrument will share the NUTTelA-TAO with the Burst Simultaneous Three-channel Instrument (BSTI) camera which will use electron multiplied charge coupled devices (EMCCD) to measure optical prompt emission spectra from gamma ray bursts.<sup>20,21</sup> A plane mirror will redirect light to the UFA camera when the BSTI is not in use.

### 3.2 Camera

The UFA camera will consist of two single-photon resolution fast-response detector 16x16 arrays operated in coincidence using a 50/50 non-polarizing beamsplitter (Fig. 1). Only events occurring simultaneously within a coincidence window in both detectors will be recorded. This setup will help reduce the number of false alarms caused by both random sky background and internal detector noise such as dark current, crosstalk, and afterpulsing.

Photomultiplier tubes (PMT) and silicon photomultipliers (SiPM) are both particularly advantageous for the UFA camera due to their nanosecond duration timing resolutions. In comparison, CCD are limited by their read noise and the fastest EMCCDs currently are on the order of 0.1 s. In addition, both PMT and SiPM are capable of detecting faint single-photon events with a sky background. As pulses produced by these detectors have heights proportional to the number of detected photons high-flux photon events can be distinguished from random single or low-flux photon events by placing a threshold.

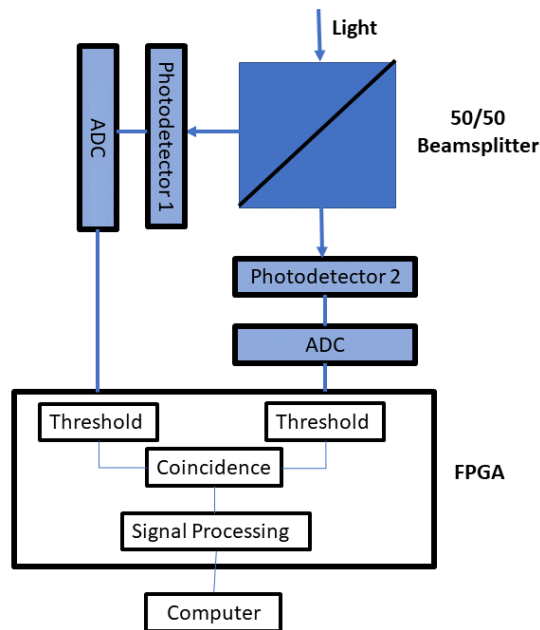


Figure 1. Coincidence scheme that will be used for the UFA camera. Two single-photon counting detectors will be placed at a 90°angle with a 50/50 non-polarizing beamsplitter. Events will be processed using coincidence logic.

The overall advantage of using either PMT or SiPM over the other for the UFA camera is not yet clear. Compared to PMT, SiPM have comparable gains and higher photon detection efficiencies, affordability, and durability. However, SiPMs also have higher dark count rates. We will first characterize each detector type before selecting an optimal detector for the UFA observatory. Although only one detector will be used for the UFA observatory, this study will also provide a reference for future observatories deciding between PMT and SiPM and searching for fast astrophysical transients.

Parameter	H9500 PMT	S13360 MPPC	S14161 MPPC
Spectral Range	300 nm - 650 nm	320 nm - 900 nm	270 nm - 900 nm
Recommended Operating Voltage	1000V	53V + 3V	38V + 2.7V
Channel Size	3.04 mm x 3.04 mm	3 mm x 3 mm	3 mm x 3mm
Gain	$1.5 \times 10^6$	$1.7 \times 10^6$	$2.5 \times 10^6$

Table 1. Typical detector parameters of the H9500 PMT, S13360 series MPPC, and S14161 series MPPC from Hamamatsu Photonics K. K..<sup>22–24</sup> The recommended operating voltage for MPPC is the breakdown voltage plus the recommended over voltage. Gain is given at the recommended operating voltage.

### 3.2.1 Photomultiplier Tube

PMT are vacuum tube photodetectors with single-photon counting capabilities that have traditionally been used for a variety of low-light applications in fields such particle physics, spectroscopy, microscopy, medical imaging, and astronomy. In astronomy, PMT have been used to search for astrophysical events such as cosmic ray showers,<sup>25</sup> gamma ray bursts,<sup>26</sup> and extraterrestrial technosignatures.<sup>27</sup>



Figure 2. H9500 PMT from Hamamatsu Photonics K. K.. This PMT will be characterized at Nazarbayev University.

Our candidate PMT is the H9500 multianode PMT 16x16 array from Hamamatsu Photonics K.K. (Fig. 2). Detector parameters can be seen in Table 1. We selected this PMT due to its large number of channels, high quantum efficiency (24% at 420 nm)<sup>24</sup> compared to similar PMTs, and convenient metal packaging configuration. To compare this PMT with our candidate SiPMs (section 3.2.2), we will characterize its breakdown voltage, gain, dark count rate, crosstalk probability, afterpulsing, photon detection efficiency, linearity, saturation, and photon detection efficiency inside a dark box test stand at Nazarbayev University.

### 3.2.2 Silicon Photomultiplier

The SiPM is a p-n junction solid state photodetector with single-photon counting capabilities consisting of single photon avalanche photodiodes (SPAD) connected in parallel. SiPM and SPAD are beginning to replace PMT in searches for astrophysical transients such as cosmic ray showers<sup>28,29</sup> and extraterrestrial technosignatures.<sup>30,31</sup>

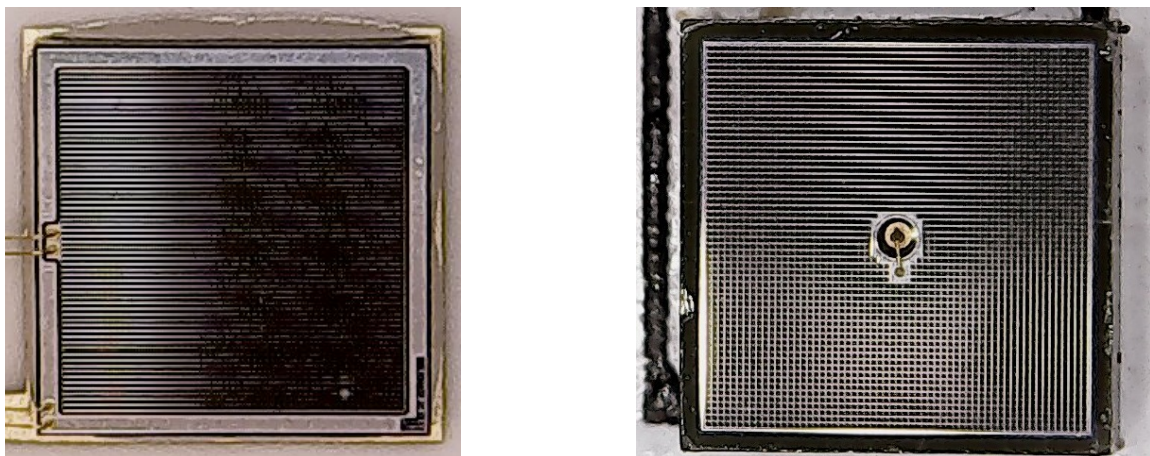


Figure 3. Both MPPC shown have 3mm x 3mm active areas and 50  $\mu\text{m}$  pixel pitches. LEFT: S13360-3050CS MPPC RIGHT: S14160-3050HS MPPC.



We have narrowed down our candidate SiPMs to two SiPM manufactured by Hamamatsu Photonics K. K.: the S13360 series Multi-Pixel Photon Counter (MPPC) and S14161 series MPPC. We selected these SiPMs due to their high photon detection efficiencies compared to SiPMs of similar microcell sizes and active areas from other companies. While the S14161 MPPC has a higher reported peak photon detection efficiency than the S13360 MPPC (50% at 2.7V over voltage vs. 40% at 3V over voltage, both at 450nm), it also has a higher reported dark count rate (1.1 Mcps at 2.7V over voltage vs. 500 kcps at 3V over voltage).<sup>22,23</sup> To compare these two detectors in further detail, we will characterize the dark count rate, crosstalk probability, photon detection efficiency, linear range, and saturation of the single channel versions of the S13360 series MPPC (S13360-3050CS)<sup>32</sup> and the S14160 series MPPC (S14160-3050HS) at the Hong Kong University of Science and Technology. Images of the S13360-3050CS MPPC and S14160-3050HS MPPC can be seen in Fig. 3. Because the largest arrays for the S13360 and S14160 series offered by Hamamatsu Photonics K. K. are limited to 8x8, we will tile four 8x8 arrays to create a 16x16 array for the UFA camera.

### 3.3 Readout

We are currently developing two readout systems to be capable of observing a wide range of sub-second signals. The first readout system consists of the 32-channel HTG-840 development platform with the VU440 field programmable gate array (FPGA) from Xilinx and FMC168 FPGA Mezzanine Card from Abaco systems (Fig. 7). Each FMC168 Mezzanine Card has eight 16-bit analog to digital converter (ADC) channels with a sampling rates of 250 Msps per channel allowing us to sample variations down to 8 ns. Each detector channel will be digitized using its own ADC channel (Fig. 4). We will use a 40 Gbps Peripheral Component Interconnect Express (PCIe) to transfer data from the FPGA to a computer.<sup>33,34</sup> The data processing flow can be seen in the left side of Fig. 6. This readout system will be operated in the pulse coincidence mode described in section 3.3.1.

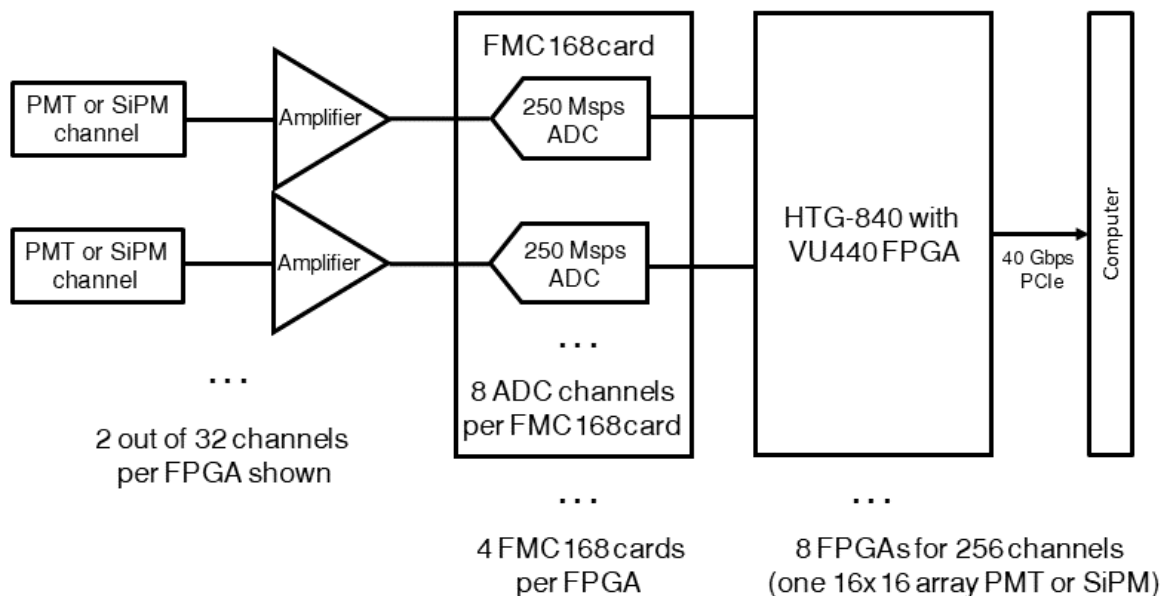


Figure 4. Schematic of the readout system using the HTG-840 development platform from Xilinx and FMC168 Mezzanine Card from Abaco Systems.

The second readout system consists of the 256-channel AFE2256EVM analog front end evaluation module from Texas Instruments (Fig. 7). The AFE2256EVM is an evaluation platform for AFE2256 chip-on-flex (COF) devices and was originally designed to read out digital X-ray flat panel detectors but has the capability of reading out other detectors such as SiPM as well. We will use a USB 2.0 to transfer data from the AFE2256EVM to a computer. The AFE2256EVM multiplexes using four 16-bit ADCs (Fig. 5) and has a minimum sampling period

of 12.8  $\mu$ s. The data processing flow can be seen in the right side of Fig. 6. The AFE2256EVM will be operated in the charge integration mode described in section 3.3.2.

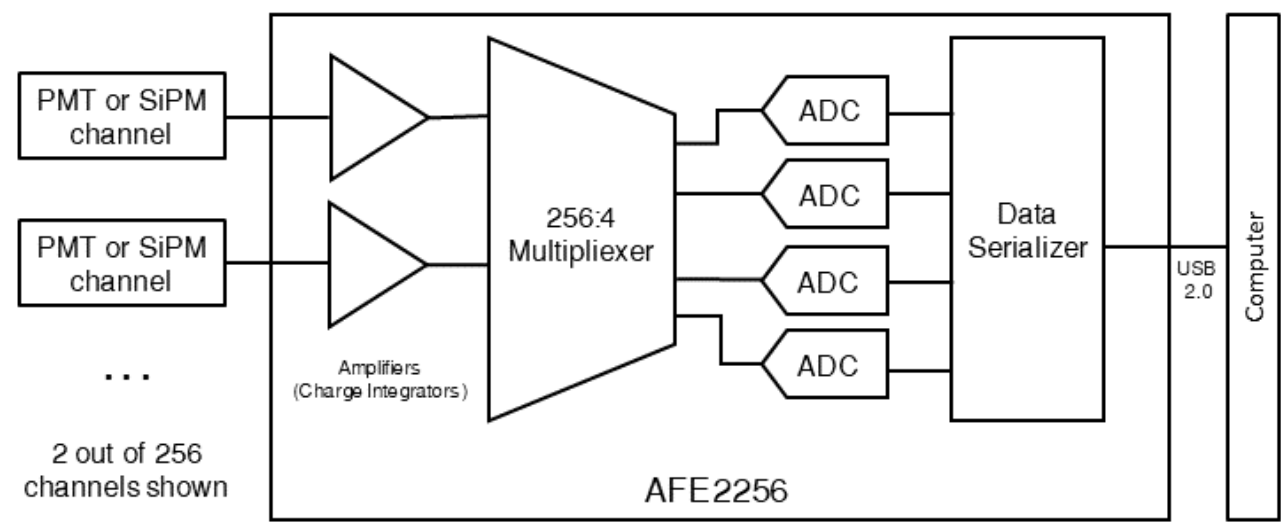


Figure 5. Schematic of the readout system using the AFE2256EVM evaluation module from Texas Instruments.

3.3.1 Pulse Coincidence Mode

Pulse coincidence mode is advantageous for detecting fast and bright transients with pulse durations on the order of the recovery time of the detector. Pulses produced by PMTs and SiPMs have heights proportional to the number of photons detected. As high photon-flux events will produce pulses that are higher than low photon-flux events, a threshold can be placed to filter out sky background. To decrease the number of false alarms caused by random internal noise, we operate two detectors in coincidence and set the coincidence window equal to the recovery interval. A signal that produces a pulse that exceeds a predetermined threshold and is detected by both detectors within the coincidence interval will be recorded as a candidate signal. The event will be time stamped, saved in a central computer for further analysis, and compared with other multi-messenger observatories to investigate its correlation with our target FRB. After a candidate signal is recorded, we will continue observation to look for repetition.

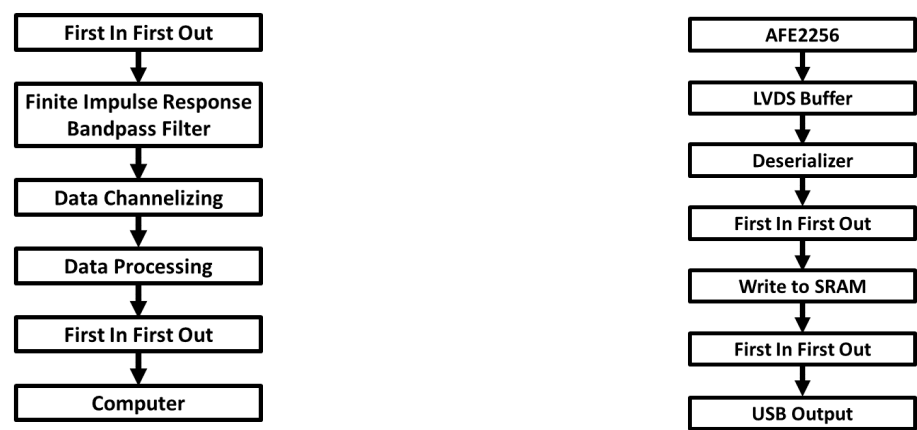


Figure 6. LEFT: Data processing flow that will be used with the HTG-840 and FMC168 readout system. RIGHT: Data processing flow that will be used with the AFE2256EVM readout system.

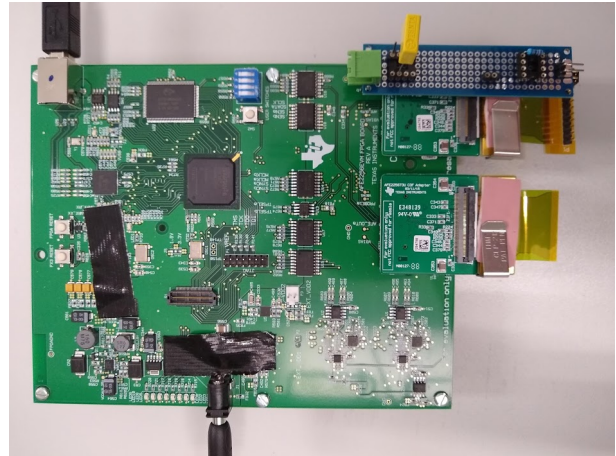
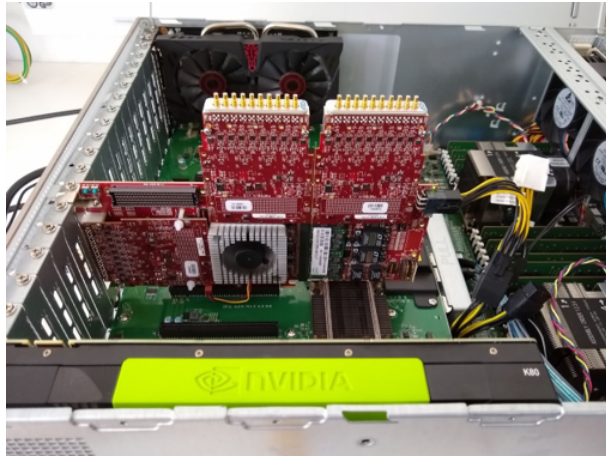


Figure 7. LEFT: Three out of four FMC168 FPGA Mezzanine Cards from Abaco Systems connected to a HTG-840 evaluation platform from Xilinx. This readout system will be operated in pulse coincidence mode. LEFT: The AFE2256EVM analog front end evaluation module from Texas Instruments. This readout system will be operated in charge integration mode.

### 3.3.2 Charge Integration Mode

Charge integration mode is advantageous for detecting weak signals with pulse durations much longer than the recovery time of the detector. The total charge output by the detector in a given time interval will be recorded and averaged to filter out light from the sky background. We look for significant increases in charge within each time interval and repetition. A candidate signal will be time stamped and transmitted to a central computer where it will be saved for further examination and compared with other multi-messenger observatories.

## 4. CONCLUSION

We are developing a first generation fast, single-photon resolution observatory capable of characterizing the optical (320 nm - 650 nm) sky from the millisecond to nanosecond timescales. Searching in this largely unexplored phase space opens up the possibility of discovering new astrophysical phenomena. While one of the first objectives of the UFA observatory will be to search for and further constrain the limits to optical counterparts to FRB, the UFA observatory will have the capability of discovering a wide range of astrophysical transients.

We are currently in the preliminary selection and design phase of the project. After performing detector characterization studies and selecting an optimal detector, we will build a prototype camera with two detector arrays and test the effectiveness of the coincidence scheme at lowering the false alarm rate. We will then commission the camera on the NUTTeLA-TAO to test and refine our system.

After completion of the first generation UFA observatory, we plan to upgrade our system with 1) larger detector arrays to give us higher spatial resolution, 2) a faster readout system that will increase our signal to noise ratio and allow us to explore faster timescales and 3) different detectors that will allow us to expand our search for counterparts to FRB to longer wavelengths.

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