**RESEARCH CORPORATION FOR SCIENCE ADVANCEMENT**
**Cottrell Scholar Award Application**

*Please confine responses to this form, using one side only. Use Arial 11 point font.*


**Principal Investigator:** Jordan C Hanson

**Academic Rank:** Assistant Professor of Physics

**Department:** Department of Physics and Astronomy

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***EDUCATION AND EXPERIENCE:*** *(All academic degrees, postdoctoral appointments, PhD and postdoctoral mentors, previous employment dates and locations. Example: YYYY – Current Institution, Department, City, State, Position; YYYY – YYYY Institution, Department, City, State, Degree, Mentor.)*

2017 – Present:
Assistant Professor of Physics at Whittier College, Department of Physics and Astronomy, Whittier, California.
2015 – 2017:
Post-doctoral Fellowship at the Center for Cosmology and Astro-Particle Physics (CCAPP), The Ohio State University, Columbus, Ohio. Adviser: Dr. Amy Connolly
2013 – 2015:
Post-doctoral Fellowship at The University of Kansas, Department of Physics and Astronomy, Lawrence, Kansas. Adviser: Dr. Dave Besson
2007 – 2013:
Graduate Student Researcher and Doctoral Candidate at the University of California, Irvine (UCI) Department of Physics and Astronomy, Irvine, California. PhD Thesis Adviser: Dr. Steve Barwick
2003 – 2007:
Undergraduate Student at Yale University, New Haven, CT. Major: Physics (Intensive Track), Bachelors of Science. Mentors: Megan Urry and Daniel McKinsey
Summer 2006:
Researcher at Yale University, New Haven, Connecticut. Principal Investigator: Daniel McKinsey
Summer 2005:
NASA Undergraduate Student Researcher (USRP) at Los Alamos National Laboratory, Los Alamos, New Mexico. Mentor: Brenda Dingus

***PROPOSAL TITLE:*** *(Must fit on two lines and not exceed 130 characters.)*

Advanced Optimization of the Askaryan-class Ultra-High Energy Neutrino Detectors

***ABSTRACT:*** *(In the following space, provide a summary of your proposal plans. Please address both research and educational plans. Maximum 250 words.)*


The Antarctic Ross Ice Shelf Antenna Neutrino Array (ARIANNA) prototype is a neutrino and cosmic-ray detector in Antarctica. The objective is to observe the highest energy neutrinos in the universe, and open the window to ultra-high energy neutrino (UHE-nu) astronomy. UHE-nu could reveal the source of cosmic rays, shedding light on the most powerful particle accelerators in the universe. Antarctic ice shelves serve as the detection medium because the ice is transparent to the Askaryan radio-frequency (RF) pulses the neutrinos create, and because they form a giant target. Experience gained from ARIANNA is meant to inform the IceCube Gen2 upgrade, which will have a significant RF component. The RF designs for both must now be optimized and automated for large arrays. These upgrades include: developing RF phased array antennas synchronized in firmware for signal efficiency, optimizing firmware for noise rejection, and granting automation and machine learning capability to detectors. By completing these designs we will help detectors like ARIANNA-200 and IceCube Gen2 to become possible. Additionally, we plan to utilize the significant digital storytelling expertise at Whittier College to create digital education tools in which we illustrate the scientific concepts useful to introductory physics students, as well as neutrinos and cosmic-rays. These projects will open a window of understanding to a Hispanic and Spanish-speaking community that has traditionally not been exposed to this type of research. The digital products we create will be machine-learning driven, and will serve as bridge preparation between high-school and college for under-represented and first-generation students.

***PUBLICATIONS OF PRINCIPAL INVESTIGATOR.*** *List all within last five years (no abstracts, talks, or conference proceedings); include all authors and titles. For papers with more than 10 authors, list only the corresponding author(s) and your rank among all authors; e.g. 52 out of 200). Group separately and clearly indicate the publications that are independent of mentors and resulted from your work during a tenure-track appointment. Attach one additional page if necessary. Use Arial 11 point font.*

<ins>During tenure-track appointment at Whittier College, and/or independent from mentors:</ins>

The ARIANNA Collaboration. "A search for cosmogenic neutrinos with the ARIANNA test bed using 4.5 years of data." Journal of Cosmology and Astroparticle Physics, vol. 2020 no. 03 (2020) *(Author 10 of 25)*

The ARA Collaboration: "Constraints on the Diffuse Flux of Ultra-High Energy Neutrinos from Four Years of Askaryan Radio Array Data in Two Stations." *Accepted for publication in Phys. Rev. D. (2020) (arxiv:1912.00987) (Author 21 of 73)*

The ARIANNA Collaboration. "NuRadioMC: Simulating the radio emission of neutrinos from interaction to detector." The European Physical Journal C, vol. 80 no. 77 (2020). *(Author 11 of 27)*

The ARIANNA Collaboration. "Neutrino vertex reconstruction with in-ice radio detectors using surface reflections and implications for the neutrino energy resolution." Journal of Cosmology and Astroparticle Physics vol. 2019 no. 11 (2019) *(Author 10 of 27)*

The ARA Collaboration. "Measurement of the real dielectric permittivity $\varepsilon_r$ of glacial ice." Astroparticle Physics Journal, vol. 108 (March 2019) pp. 63-73 (*Author 20 of 70)*

J.C. Hanson et al. "Observation of classically 'forbidden' electromagnetic wave propagation and implications for neutrino detection." Journal of Cosmology and Astroparticle Physics, vol. 2018 (July 2018) *(Author 1 of 19)*

J.C. Hanson and A. Connolly. "Complex Analysis of Askaryan Radiation: A Fully Analytic Treatment including the LPM effect and Cascade Form Factor." Astroparticle Physics Journal, vol. 91 (2017) pp. 75-89

<ins>Papers published as a post-doctoral fellow or as a graduate student within last five years</ins>

The ARIANNA Collaboration. "Radio detection of air showers with the ARIANNA experiment on the Ross Ice Shelf", Astroparticle Physics Journal, vol. 90 (2017) pp. 50-68 *(Author 6 of 18)*

The TARA Collaboration. "First Upper Limits on the Radar Cross Section of Cosmic-Ray Induced Extensive Air Showers," Astroparticle Physics Journal vol. 87 (2017) pp. 1-17 *(Author 25 of 139)*

The ARIANNA Collaboration. "A First Search for Cosmogenic Neutrinos with the ARIANNA Hexagonal Radio Array." Astroparticle Physics Journal, vol. 70 (2015) pp. 12-36 *(Author 19 of 38)*

J.C. Hanson et al. "Time-Domain Response of the ARIANNA Detector." Astroparticle Physics Journal vol. 62 (2015) pp. 139-151

J.C. Hanson et al. "Radio-frequency Attenuation Length, Basal Reflectivity, Depth, and Polarization Measurements from Moore's Bay in the Ross Ice-Shelf." Journal of Glaciology vol. 61 no. 227, pp. 438-449

The ARIANNA Collaboration. "Design and Performance of the ARIANNA HRA-3 Neutrino Detector Systems." IEEE Transactions on Nuclear Science, vol. 62, no. 5 (2015) pp. 2202-2215

<ins>All other papers</ins>

The TARA Collaboration. "Telescope Array Radar (TARA) observatory for Ultra-High Energy Cosmic Rays." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment vol. 767 (2014) pp. 322 – 338. *(Author 12 of 22)*

S. Kleinfelder et al. "Design and Performance of the Autonomous Data Acquisition System for the ARIANNA High Energy Neutrino Detector." IEEE Transactions on Nuclear Science vol. 60 no. 2 (2013) pp. 612-618

L. Gerhardt, S. Klein, T. Stezelberger, S. Barwick, K. Dookayka, J.C. Hanson, and R. Nichol. "A prototype station for ARIANNA: A detector for cosmic neutrinos." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment vol. 624 no. 1 (2010)

W.G. Rellergert, S.B. Cahn, A. Garvan, J.C. Hanson, W.H. Lippincott, J.A. Nikkel, and D.N. McKinsey. "Detection and Imaging of He 2 Molecules in Superfluid Helium." Physical Review Letters vol. 100, no. 025301 (2008).

***FINANCIAL SUPPORT.*** *Include amounts for both internal and external direct support for this and any other projects since the start of your faculty position. List start-up funds, grants received (current and completed), and proposals under consideration. Include titles, period of support, and dollar amounts.*

Internal Grant Applications and Funding

Whittier College Startup Grant, Fall 2017 – Present …………………………..…… $30,000.00
*Startup funding received upon appointment at Whittier College. Currently $19,000.00 remains after installation of radio-frequency bench lab equipment, remote control drone construction and testing, and salary for undergraduate researcher to construct drone. The RF test-bench equipment can be used as part of the research meant to be covered by this proposal.*

Keck Foundation Undergraduate Fellowship, Summer 2018 (1) ……….………. $4,000.00 stipend for student
*This internal grant administered at Whittier College was for one undergraduate researcher to learn firmware programming for RF integrated circuits in support of ARIANNA technical development. This work is directly applicable to this grant proposal.*

Keck Foundation Undergraduate Fellowship, Summer 2018 (2) ……….………. $4,000.00 stipend for student
*This internal grant administered at Whittier College was for one undergraduate researcher to develop a RF propagation model in glacial ice with a changing index of refraction. This work is not applicable to the current proposal, but is connected to ARIANNA and IceCube Gen2. The work eventually led to the publication of one of the first-author papers above.*

Barbara Ondrasik '57 and David Groce Fellowship, Summer, Fall 2019 …...... $7500.00 stipend for student
*This internal grant administered at Whittier College was for one undergraduate researcher to continue the work began with the Keck Fellowship regarding firmware development for ARIANNA. We presented the results at the Southern California Conference for Undergraduate Research. The results are directly applicable to this proposal, as we will build on this students' accomplishments.*

Fletcher-Jones Foundation Research Fellowship, Summer 2020 ……………… $5000.00 stipend for student
*This internal grant administered at Whittier College is for one undergraduate researcher to update and enhance my time-domain model of the Askaryan electromagnetic field. This research is related to one of my first-author papers listed above, and will likely lead to a second paper along those lines.*

External Grant Applications, Pending

NSF 18-564. Collaborative Research, Windows on The Universe – Multi-Messenger Astronomy: Proposal to Construct the ARIANNA-200 high energy neutrino detector, 2020 – 2025 ……. $7,485,835.00
*I am listed as a co-principal investigator on this pending grant proposal, along with Dr. Steve Barwick (UC Irvine) who is the principal investigator. If awarded, my work will take the form of sub-contracting. The ARIANNA-200 project is an extension of the ARIANNA Hexagonal Radio Array (HRA). I am a founding member of the ARIANNA collaboration, and the collaboration is ready to scale up the prototype array to a large array. The larger array will allow us to probe the cosmogenic flux of ultra-high energy neutrinos. This effort will require technical research into the final station electronics design that solves problems which currently prevent our systems from operating an array large enough to probe cosmogenic neutrino fluxes (see research statement).*

## *RESEARCH PROPOSAL*

**STATEMENT OF THE PROBLEM, ITS SCIENTIFIC SIGNIFICANCE, AND YOUR PLAN OF PROCEDURE.** *State succinctly the problem that is to be addressed. Clearly outline the importance of the problem, the originality of the approach and the impact it may have on the field if successful. Give an overview of the broader significance as well as the immediate impact of this research. Then outline your approach to the problem and include preliminary results, if available. Point out innovative features, relate to previous work, including pertinent references, and indicate how this plan may contribute to the solution of the broader problem posed. Preliminary results can buttress your case, as can prior independent publications. Limit to four pages. Use Arial 11 point font.*

### The Problem: The Origin of Ultra-High Energy Cosmic Rays is Unknown

Three decades ago, scientists began to observe cosmic rays with extraordinary energies in excess of 100 EeV [1]. The origin of this radiation in the Universe and the relativistic acceleration processes responsible for acceleration remain unknown. Source identification is complicated by both the low flux of EeV cosmic rays, and the deflection of charged cosmic rays by galactic magnetic fields. Further, cosmic rays with energies in excess of 50 EeV lose energy to the GZK process when they interact with the cosmic microwave background (CMB) and are therefore confined to the local galactic super-cluster [2, 3]. Fortunately, the UHE-nu do not interact with the CMB themselves, and radiate from the GZK interactions. These UHE-nu become *cosmogenic* neutrinos. Most astrophysical models explaining the original UHE cosmic ray acceleration include ambient radiation, gas, or dust clouds where the UHE cosmic rays interact and produce *astrophysical* UHE-nu [4]. Therefore, UHE-nu detectors seek to identify events of both cosmogenic and astrophysical origin. Finally, cosmogenic and astrophysical UHE-nu may arrive at the Earth within a *diffuse* flux from a distribution of accelerators, or from *point-sources* that are either steadily emitting or briefly bursting UHE-nu into the cosmos. The detection of a UHE-nu diffuse flux would constrain models that explain diffuse gamma rays, cosmic rays, and neutrinos [5]. The detection of a UHE-nu point source would provide a concrete example of a UHE accelerator in the universe. Detecting either would likely provide critical clues as to the source of UHE cosmic rays.

Thus, UHE-nu astronomy seeks to unravel the origin of cosmic rays, and UHE-nu detectors must have versatile designs; diffuse and point-source flux, astrophysical and cosmogenic UHE-nu are all a possibility. Recently, the IceCube detector has presented the first data set of UHE-nu observations with reconstructed energies up to 10 PeV [6]. The flux appears diffuse, uncorrelated with the galactic plane. The flux decreases with increasing energy, and the IceCube design is most sensitive below 10 PeV. Although the spatial origin of the UHE-nu appears to be diffuse, there have also been some exciting potential point-source candidates and searches [7,8]. If the underlying flux in the IceCube data extends above 10 PeV, the UHE-nu will be entering the realm of cosmogenic sources that could solve the cosmic ray origin problem. Now is the time to extend beyond the capability of the first version of IceCube [9]. Over the past decade, a growing list of prototype and pathfinder projects have sought to raise the highest observable energy of UHE-nu: those based on the Askaryan effect.

### The Solution: Askaryan-based UHE-nu Detectors with the Lowest Possible Energy Threshold

The Askaryan effect occurs when UHE-nu, or other relativistic particles interact within a medium with an index of refraction. The initial interaction deposits enough energy to trigger a cascade of lower energy particles that have an excess negative charge [10]. The excess arises from multi-scattering effects (MSC), including Compton and inverse-Compton scattering, and the photo-electric effect. Atomic electrons in the medium are swept into the relativistic ($v > c/n$) cascade, leading to coherent radiation up to 500 MHz. The radiation is concentrated around the *Cherenkov angle* relative to the shower axis (about 60 degrees in ice). The Askaryan effect has been confirmed in linear accelerator laboratories for cascades [11,12], but never in the wild for UHE-nu. The medium must be RF-transparent for the signal to escape, and it must be large enough to capture a low flux of primary particles like UHE-nu. One of the best candidate materials in the world is natural ice. Antarctica has ice sheets and ice shelves with the necessary properties [13].

Projects like RICE, ANITA, ARIANNA, ARA, and RNO-G have endeavored therefore to create autonomous RF pulse detection systems in Antarctica and Greenland [14]. Throughout their prototype phases, these detectors have captured RF signals from cosmic rays, X-class solar flares, and even several tantalizing “mystery events” from ANITA that almost resemble UHE-nu candidates [15]. The IceCube collaboration has acknowledged that progress towards UHE-nu detection will come from the RF-style detectors in the conclusions of [16]. The originality of ARIANNA and RNO-G, for which this research is primarily directed, is that they are deployed *in situ*. That is, they are deployed inside the ice where the UHE-nu interactions are taking place. The ANITA 1-4 projects suffer from a higher energy threshold (requiring stronger Askaryan signal) and shorter livetimes because the detector flies on a weather balloon so as to observe dramatically larger effective volumes of ice [17]. The volume comes at the expense of being farther from the UHE-nu interaction, which requires a higher-energy neutrino to create a detectable signature at the balloon. Currently, ANITA balloons can fly for approximately one month, whereas the *in situ* detectors would last for several years, and be a factor of 50-100 closer to the UHE-nu vertex.

Each type of detector within the Askaryan class faces the same challenge: the RF detection threshold must be set as low as possible to be sensitive to the lowest energy UHE-nu capable of making an Askaryan pulse (the final voltage is proportional to energy). The reason is that the UHE-nu spectrum is most likely decreasing with energy [16]. Lowering the RF threshold increases the probability that this type of detector will record random RF thermal noise instead of signal. Thus, each detector program has to select an RF threshold that balances the need for fewer false-positive thermal noise events, and more UHE-nu sensitivity. *The research proposed herein strives to lower the threshold of Askaryan class detectors, without sacrificing UHE-nu signal efficiency due to RF thermal noise.*

For example, the output of radio antennas in ARIANNA is first sampled and digitized, and the detector records the data if a bipolar pulse has a positive amplitude larger than one threshold, and a negative amplitude lower than another threshold. This double-requirement is only rarely satisfied by the thermal spectrum, but is satisfied by 80% of simulated UHE-nu candidates [18]. The thresholds were set to $+4\sigma$ and $-4\sigma$, respectively, where $\sigma$ represents the rms voltage visible to the RF chain. The corresponding RF thermal rates (false positive rates) were 0.001 – 0.01 Hz. Though it's desirable to lower thresholds below $+/-4\sigma$, the exponential increase in false positive rate would consume limited disk space, and make it difficult to move the dataset through bandwidth-limited communications systems [19,20]. False-positive rates are also created by man-made RF pulses from equipment, including wind turbines, airborne balloons, aircraft, and communication systems. For a large array, manually re-tuning thresholds and offline false-positive rejection becomes impractical.

## Pathways to Advanced Optimization in Askaryan-based UHE-nu detectors

Selectively increasing the sensitivity to UHE-nu signals while decreasing it to thermal noise and other sources involves two paths forward on the side of *noise reduction*, and one path on the side of *signal enhancement*. For noise-reduction, we have begun to adopt **automation** and **machine-learning** techniques. For example, UHE-nu signals are broadband [50-1000 MHz], but the low portion of the band includes galactic emissions that vary with the rotation of the Earth [21]. Making thresholds time-dependent at the *firmware* level allows the detector to **automate** its threshold, keeping the RF background rate low and predictable. Without automation, manual readjustment to time-dependent backgrounds is required (as in [20]), and is impractical for a large array. We have solved this problem in our RF design lab at Whittier College, but have not had the opportunity to deploy it in the field due to COVID-19 [22]. We require resources to implement the component on deployed stations. Initial results presented at the undergraduate conference SCURR [22] are shown in Fig. 1. Thermal noise triggers the board with a predictable rate, and our firmware correctly measured this dependence.

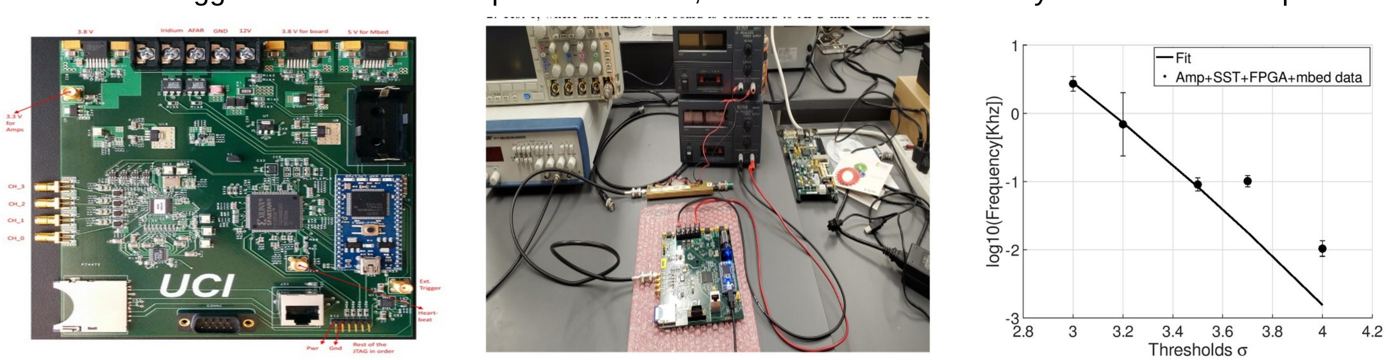


**Figure 1.** (Left) An example of an ARIANNA detector board, with RF front-end, digitization/sampling, FPGA, and microcontroller. (Center) The ARIANNA board under test with our custom firmware at Whittier College RF lab. (Right) The firmware component correctly measures the thermal trigger rate in the ARIANNA RF channel in coordination with all field software and firmware, below 3.5 σ. For data above 3.5 σ, the amplifier exhibited oscillation effects that dissipate with time. The black line is the theoretical trigger rate for RF white noise.

Noise rejection based on **machine-learning** is now being implemented in laboratory settings via convolution neural networks (CNNs) with RF waveforms as inputs. The goal is to reach thresholds of +/-3σ while keeping the thermal rate of +/-4σ. The networks are trained on samples of thermal data from the full RF chain, and then taught to exclude waveforms with features resembling thermal noise. Noise rejection factors of $10^{-5}$ are already being achieved. Initial results are displayed in Figure 2, performed in coordination with students at UC Irvine.

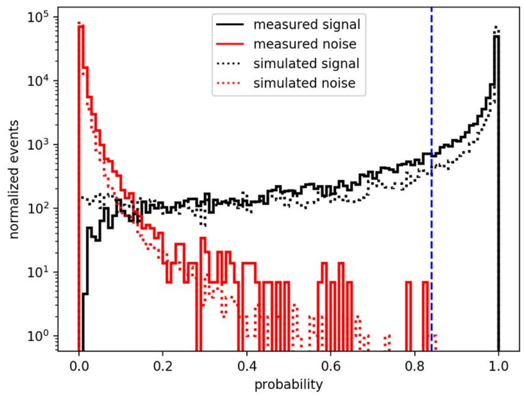


**Figure 2.** A convolution neural network was trained in an ARIANNA detector (at the software layer) to reject 100% of $10^5$ thermal triggers (red) while keeping 87% of input signals (black), and the results match simulations.

In addition, phased-array antenna triggers have been an important development in detector designs [23], but require additional cables, amplifiers, power, and antennas. A phased-array trigger will be part of the RNO-G project, with the objective of a UHE-nu minimum signal to noise ratio (SNR) of ~1.2. The phased-array coherent summing can actually be implemented in the firmware of Askaryan-based detectors. Firmware-based phased array triggers lower the minimum SNR in Askaryan-class detectors without additional cables or hardware. The preliminary work along these lines has already begun with collaborators at UC Irvine. Implementing the phased-array approach in *firmware only* rather than adding additional hardware would be a significant step forward for power and complexity reduction in Askaryan-based detectors deployed in harsh and unforgiving polar regions.

For *signal-enhancement*, significant theoretical work has been done to predict the Askaryan signature of the UHE-nu. These models fall into three categories: full Monte Carlo, semi-analytic, and fully analytic. Full Monte Carlo Askaryan simulations require tracking the Liénard-Wiechert field contribution of every simulated shower particle above a cutoff-energy of 0.5 – 1 MeV. For a cascade with total energy 1 PeV, this means tracking the radiation of ~$10^8$ particles. Typically, the fields for 100 TeV neutrinos are simulated, and then scaling laws are applied to obtain higher energy fields. The semi-analytic models solve Maxwell's equations in the Coulomb gauge while treating the cascade like a current density [24]. The charge excess *evolution* over time along the axis parallel to the UHE-nu initial momentum separates analytically from the instantaneous charge *distribution* (ICD) in 3D space: the "form factor." The charge evolution is simulated numerically, and the form factor is derived from the numerical results at the Cherenkov angle. Radiation at angles other than the Cherenkov angle is obtained by convolving the form factor with the simulated charge evolution.

In fully-analytic models, the charge evolution and the ICD are derived analytically, and the same factorization occurs as in the semi-analytic models [10,25]. The fully-analytic model treats the charge evolution like a normal distribution near the cascade maximum, which dominates the radiation. Thus, simple yet powerful equations are derived with well-understood parameters that can be evaluated at high-speed in any simulation. The trade-off with fully analytic models is that they do not capture the shower-fluctuations common in the highest energy UHE-nu events (>1 EeV). Cascades above this energy are prone to contain sub-showers that form additional Gaussian peaks in the charge evolution, leading to second-order features in the electric field. While semi-analytic models describe these features, they do not capture the effect of the viewing angle and near/far-field on the form-factor.

From the standpoint of detector optimization, the fully analytic models have two advantages to offer. The first advantage is that fully-analytic models offer the ability to scan *cascade* parameter space in a full simulation of the ARIANNA detector, rather than just *neutrino* parameter space. Pertinent examples include: deducing how the details of the ICD affect detection efficiencies, probing near-field effects that occur when the UHE-nu cascade is elongated or occurs closer than expected to a detector station, and developing a better analytic approximation for the LPM effect. At Whittier College we are already resuming work on a fully-analytic model begun at the Center for Cosmology and Astro-Particle Physics (CCAPP).

The second advantage is far more important that the first: fully-analytic Askaryan field models can be installed *on the detectors themselves*, forming signal templates for which the hardware can search. This strategy would be similar to implementing a matched-filter scheme, which are sensitive to very small SNR. Unlike the other model classes, fully analytic models can be evaluated in firmware at high speeds. The charge evolution convolution prescribed by semi-analytic models, for example, could not be done at high enough speeds to be useful for triggering detectors if shower fluctuations were taken into account. The most recent ARIANNA analysis used theoretically generated signal templates, but only offline after the data was triggered, saved, and uploaded from Antarctica to the USA [18]. Thus, the detector thresholds had to remain higher than if the trigger installed on the detectors themselves were more intelligent, searching for the templates in real-time.

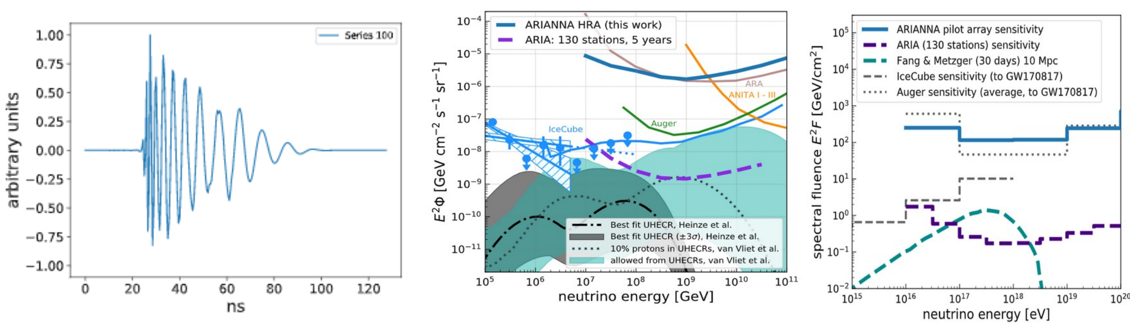


**Figure 3.** (Left) RF waveforms correspond to simulated analytic UHE-nu signals passed through the ARIANNA RF signal chain, for two different versions of the RF amplifier. These waveforms are therefore *signal templates* used to search the triggered data offline for UHE-nu events and filter thermal triggers. (Middle) The resulting UHE-nu diffuse flux limit and point-source fluence limit (Right) from the template analysis [18].

We can think of this strategy as a form of **machine learning**, since the detector is literally being "taught" to search for signals from a library of theoretical templates, similar to one initial LIGO strategy for gravitational waves (in addition to wavelet analysis). At Whittier College, we collaborate with our colleagues at UC Irvine to develop faster and more accurate templates. Connecting the theoretical work with firmware development is one final objective of this work. We will pay particular attention to the implementation of scans of *cascade parameter space* at trigger level in the detectors, so as to locate the most elusive UHE-nu signals.

## Conclusions

The research program being proposed here is targeted to deliver UHE-nu astronomy to the wider physics community by solving problems necessary for the deployment of large detector arrays in Antarctica and Greenland. For the last decade, prototype versions of *in situ* Askaryan-based detectors have learned key lessons and proven ready for long-term deployment in the rugged polar wildernesses. The ice has been shown to be of sufficient quality [13], and the IceCube collaboration has stated publicly that increased sensitivity to UHE-nu lies with the RF Askaryan-based class of detectors [16]. With one final push, detectors like ARIANNA-200 and RNO-G (Greenland) will launch a new window into the universe. These detectors will serve as crucial pathfinders for the expansion of IceCube: Generation 2 (Gen2).

We seek to deliver advanced optimization of these detectors with the goals of *noise reduction* and *signal enhancement*. **Noise reduction** priorities fall into two categories: **automation** and **machine learning**. Automation of trigger thresholds is an example of how thermal and man-made noise backgrounds would be reduced. Firmware-level enhancements falling under this category include neural networks and phased-array triggers. Once large arrays are built, operational personnel will need to rely on such strategies. Further, as detectors grow, communication bandwidth will remain constrained, requiring more stringent on-board background rejection. **Signal enhancement** will come from completing the fully-analytic model of Askaryan radiation and using it to implement signal templates on the detectors. This research seeks therefore to unlock the pathway to large UHE-nu detectors, with the ultimate goal of revealing an as-yet unexplored window on the universe.

***RESEARCH PROPOSAL*** *(continued)*

**Project Timeline.** We provide a project outline and timeline below, in order to clarify what milestones need to be reached as the project progresses. The project is separated into three phases, corresponding (approximately) to the three-year life cycle of the grant proposal. The overarching goals of each phase are: 1) completion of threshold automation and the completion of analytic Askaryan models, 2) advancement of the firmware-based phased-array trigger, and 3) exploration of the application of Askaryan models as templates installed in the detectors.

*Phase 1: Within the first phase of the project, there are several milestones that need to be reached within the first year of the project that correspond to projects already underway.*

**1. Completion of threshold automation firmware.**

During phase 1, we should be able to utilize work that has already been completed to satisfy this goal of the project. The thermal RF trigger rate of Askaryan-class detectors is controlled by the *threshold* relative to the random noise introduced by antennas and the low-noise amplifiers (LNAs). In order to adjust the threshold, one must first know the trigger rate in the firmware layer. This requires a firmware component to measure it, which we have already developed. The component, called the Mutli-Mode Frequency Counter (MMFC), accurately measures the trigger rate over five orders of magnitude [$10^2$ – $10^7$] Hz. We have additional firmware code that passes the rate information from the RF channels to the microcontroller, so that a decision can be made about the threshold. If the rates are too high, the threshold can be raised in real time based on individual channels. If rates are low, the threshold can be lowered. All that remains is to implement the specific threshold algorithm *in the microcontroller code*, since the firmware is complete.

Concrete goals:

a) Develop microcontroller code that demonstrates that the threshold responds to rate changes in real time. The LNAs used in ARIANNA, for example, give rms noise voltages that begin “hot” and cool off exponentially. The specifics of the microcontroller algorithm might reveal helpful changes to be made to the firmware.
b) We must test the full process, including firmware and microcontroller code, on a full ARIANNA prototype detector with broadband antennas. Ideally, this should take place in the field, but laboratory tests at cold temperatures are also informative and worthy of publication.
c) Prepare a rough draft of a publication for publication in either Astroparticle Physics Journal, Nuclear Instrumentation and Methods A, or Journal of Cosmology and Astroparticle Physics. The rough draft should be marked down by the ARIANNA collaboration.

**2. Completion of the fully analytic Askaryan model, including the cascade form factor and the full angular region around the Cherenkov angle.**

Currently, we have a fully analytic Askaryan model in the time domain that agrees with the form of the semi-analytic and fully Monte Carlo models, but only if the viewing angle is equal to the Cherenkov angle. Our current work includes extending it beyond this simple mathematical case, and to compare it to the semi-analytic models. Once complete, this model should be compared systematically to the output of the semi-analytic models, and key differences should be identified. Finally, we should install it as a module in the ubiquitous NuRadioMC Monte Carlo simulation package [41], which is used for all the *in situ* Askaryan-class detectors.

Concrete goals:

a) Complete the mathematical physics of Askaryan radiation away from the Cherenkov angle
b) Account for the cascade form factor and verify (as in our last paper) that the form factor agrees with the shower physics of full Monte Carlo simulations.
c) Compare our model to the semi-analytic models, and write a rough draft of a journal article for collaboration mark-down.
d) Installation of the model as a python module in NuRadioMC and comparing to other modules

*Phase 2: In this phase of the project, we move on to development of the phased-array coherent summing technique in Askaryan-class detector firmware. There are several milestones that need to be crossed before the products are implemented in detectors.*

**1. Performing correlation calculations on a field-programmable gate array (FPGA).**

In order to coherently sum RF antenna outputs, they must be cross-correlated to solve for the appropriate time-lag. It may be beneficial to simply check all possible causal timing combinations via a CPLD or AND-array, rather than perform fast Fourier transforms (FFTs). Our research will have to determine which approach is more efficient, given the format of the detector. These goals are more open ended than those in Phase 1. They require more planning and coordination with collaborators, like those at UC Irvine (see letter of collaboration). We aim to complete these objectives around the beginning of year 2 of the project. One advantage is that UC Irvine graduate students have already made progress in this area.

Concrete goals:

a) Determine the efficiency of performing signal correlations using FFTs.
b) Determine the efficiency of performing the correlations in the time-domain using an AND-array.

**2. Demonstrating prototype firmware functions in anechoic chamber, and in the field.**

The next step is an anechoic chamber test of the system, in which we demonstrate the RF trigger efficiency versus signal-to-noise ratio (SNR). The ultimate proof of concept would be an Antarctic field test, but it is difficult to plan future expeditions to modify detectors due to the logistics situation with the United States Antarctic Program (USAP).

Concrete goals:

a) Demonstrate a full phased-array system implemented in firmware only, complete with antennas connected to a detector RF front-end. Ideally, this trial should be conducted in an anechoic chamber. Researchers in our field have used the CReSIS anechoic chamber[1] in the past.
b) Demonstrate the full phased-array system in the Antarctic, provided the radio UHE-nu detectors are granted expeditions. In normal circumstances, there is one per year.

*Phase 3: In this phase, we seek to publish all the design results, and implement the firmware tools constructed in the lab in Antarctica. Our tools and results should be applicable to IceCube Gen-2, RNO-G, and ARIANNA-200. Regarding deployment, sometimes expeditions are delayed due to the logistical situation in USAP. However, this does not stop us from publishing by the beginning of year 3. Finally, we seek to study the feasibility of deploying the Askaryan model templates on the detectors themselves, and using them to trigger on RF impulses.*

**1. Publication of Threshold Automation, Phased-Array results, and Askaryan Model.**

By the beginning of year 3 of the project, we should have collaboration approval from ARIANNA and/or RNO-G to publish our results as they apply to the detectors.

Concrete goals:

a) Publish threshold automation algorithm, complete with firmware designs and associated microcontroller code design.
b) Publish phased-array firmware results, complete with analysis from the anechoic chamber.
c) Publish Askaryan model equations, complete with comparison analysis using NuRadioMC.

**2. Installation of Askaryan model as a template within detector firmware for an RF trigger.**

Currently, the only trigger used by ARIANNA-200 is the high/low example described in the research proposal (level 0 or L0), and a (continuous wave) CW filter called L1 (level 1). The trigger used by RNO-G is a separate phased-array. Templates are used to scan for signals in offline analyses that reject man-made signals and RF thermal noise. Installing signal templates in firmware could serve as an L2 (level 2) trigger that would further distinguish potential UHE-nu candidates from backgrounds. Level 1 represents the current RF trigger schemes in ARIANNA and RNO-G. This goal, if possible, should be completed by the end of year 3.

Concrete goals:

a) Using the knowledge gained from the correlation studies in firmware development, we implement the time-domain equations of the Askaryan model *within the firmware* to correlate in real-time with the RF front-end data. That way, the detector can choose to flag or trigger on only signals that resemble the UHE-nu theoretical signal.
b) Use NuRadioMC to simulate the effect of the L2 trigger on signals and background rejection.

**3. Deployment and utilization of Askaryan model templates as a true L2 trigger on the detectors.**

Once the simulation studies and laboratory tests are complete, we would like to deploy the firmware and software in detectors in the field. A follow-up analysis of the data collected after this point would reveal any UHE-nu candidates identified by the templates.

Concrete goals:

a) Work with USAP assess the time-line for future expeditions and when we can deploy.
b) Obtain collaboration approval from ARIANNA/ARA to attempt the level 2 trigger installations.
c) Send personnel to Antarctica to install these upgrades on ARIANNA and ARA detectors.
d) Participate in future data analyses to identify UHE-nu candidates.

1 https://chamber.ku.edu

***RESEARCH PROPOSAL*** *(continued)*

***RESEARCH PROPOSAL*** *(continued)*

**LETTERS OF COLLABORATION.** *If the research described above requires work from in-house or external collaborators, please insert letters of collaboration following the LIST OF REFERENCES. Please limit letter size to one page each.*

## *EDUCATIONAL PROPOSAL*

***STATEMENT OF THE PROBLEM, SIGNIFICANCE OF THE PROBLEM, AND YOUR PLAN OF PROCEDURE****. Describe identified educational priorities in your department and explicitly detail how your plan fits. State clearly the problems or issues you wish to address and how they relate to any ongoing work. Cite precedent. Carefully outline the importance of your plan and the impact it may have on your undergraduate and/or graduate students. A viable approach should be given, including examples from your own prior experience and/or from the literature. Indicate ways in which the completion of this work has a broader impact. Use Arial 11 point font. Limit to three pages.*

**Physics instruction at Whittier College brings a special opportunity**: to engage and inspire first-generation students and students of color to a wide variety of scientific, mathematical, and engineering principles. *We propose to create a digital-storytelling tool to aid in the preparation of our introductory students,* in line with our department objectives, and the nature of Whittier College. Whittier College is a liberal arts school classified as an Hispanic-Serving Institution (HSI). Seventy percent of our undergraduates are students of color[2], and forty percent of them are first-generation students[3]. The culture of the college is one that welcomes everyone, and we strive to serve these students as best we can, regardless of past preparation.

One of the core objectives of the Dept. of Physics and Astronomy connects directly to this proposal: we value the skill of *self-teaching*, and we show the students how to train themselves to think scientifically. Historically, we begin working on this objective once we have the students in class. We engage the students with self-designed laboratory experiments, group projects, and active-learning strategies. One area that would benefit from a new educational proposal is the engagement of our introductory students *before they begin the introductory courses*. We already collect data on student performance during the introductory courses, which informs us on how well students' conceptual understanding shifts during the semester [26]. Similar to bridge programs for first-year students [27], we seek to **prime** the students via self-taught digital modules, so that their conceptual understanding is sharpened before class and that problems are addressed sooner.

**What we propose is to enhance and accelerate the collection of data and the solutions it makes possible by creating an application that combines machine-learning and digital story-telling.** At Whittier College, we have expertise in both machine-learning and digital-storytelling. In the Digital Liberal Arts department of Wardman Library (www.diglibarts.whittier.edu), we have knowledgeable experts trained to help students and faculty create works of digital storytelling. In the Depts. of Physics and Astronomy, and Mathematics and Computer Science, we have expertise in machine-learning algorithms [28, 29]. Further, the literature on educational data mining (EDM) contains a plethora of examples in which clustering algorithms were used to understand undergraduate STEM learning patterns [30]. For example, when we observe bi-modal grade distributions early in courses it would have been better to identify the struggling sub-population in advance. The EDM literature also recognizes that the earlier struggling students are identified, the better [31]. Several examples of such digital tools have been created [32, 33]. Finally, it is our hypothesis that the digital-storytelling aspect will raise student engagement by relating the content to their own experiences.

Like all colleges, we have had to make adjustments to a digital/online educational platform due to the pandemic. Normally, our introductory curriculum is centered on an integrated laboratory and lecture approach, with concepts from workshop physics models and peer-instruction (PI) [34]. We strive to balance carefully-paced lecture content with active-learning strategies like PI techniques [35]. Each professor in our department regularly contributes to the liberal arts curriculum. We are accustomed to curriculum design and flexibility to meet our students' needs, so we were able to execute our online educational strategy in response to COVID-19. Now that the transition has happened, parts of our courses will remain online and asynchronous going forward. The use of digital tools online has become part of the normal curriculum, and the fact that the students used tools like Pivot Interactives lab content [36] has created precedent for the further use of digital tools.

**We encountered the idea for this type of digital tool originated in a novel entitled The Diamond Age, by Neal Stephenson** [37]. In the book, a digital tool called *The Primer* falls into the hands of a young orphan named Nell. Nell engages with the tool, which teaches her mathematics, design principles, physics, and how to be a leader. The key to her development is that The Primer (a reference to 19$^{th}$ century primers for children) *adapts* to her educational needs in real time, and provides a narrative for her growth in terms of conquering a land for her own. The MathBot project [32] already has achieved a conversational model to help students solve math problems in an SMS message format. We would add the narrative model of The Primer in the novel by incorporating digital-storytelling and graphic design from Whittier College. As the story progresses,

2 Defined as non-White, non-international, but does include students who list more than one race on application.

3 Defined as a student whose parent or guardian does not have a degree from a 4-year institution of higher education.

students would be required to solve progressively harder introductory physics and math problems in order to advance a chapter. Thus, the project would have a liberal arts component, and a software design and analytics component. First we describe the broad objectives of the software, followed by the advantages of the digital-storytelling, and finally describe the broader impacts. The *assessment plan* below provides more details regarding the function of each component.

Two essential actions would be performed by the software as the student progresses. First, data such as response rate and time, correct percentage, how often the student uses the app, and at what times, would be recorded and stored for further analysis. Machine-learning clustering algorithms (see below) would be run on trial data to establish any initial clusters to which the students belong, and insights derived would be taken into account in our courses. For example, if we find that a cluster of students regularly does not understand vector concepts, but *does* understand scalar kinematic variables, then covering vectors longer than kinematics would benefit those students. The second action performed by the code would be to establish the pace and intensity of the training. If we identify content with which a student struggles, we can *plan for that* and move the student through that content more slowly or on a different track. Thus, the story would contain an adaptive property meant to help individual students master the same set of basic example problems as their peers.

The storytelling aspect brings three advantages over simply copying other digital tools that collect data on the students. First, the Whittier College DigLibArts area already has the experience to help students tell their own stories. Students often engage in story-telling projects capturing the history of their family or neighborhood and share them through the DigLibArts Collaboratory (see Fig. 1). Further, the DigLibArts personnel at Whittier College have experience using digital-storytelling tools like Scalar (https://scalar.me/anvc) and Twine (https://twinery.org). Second, since we plan to create the tool with undergraduate students from the graphic design and Whittier Scholars Program (WSP) areas[4], the narrative themes should be recognizable to their peers and help them learn in an environment designed to be inclusive. Third, the story-telling format moves the data collection and analysis to the *back end*, so that the students do not feel that they are under examination and can immerse themselves in the story. The DigLibArts and WSP areas have introduced this project to students in the past, who developed character concepts (see Fig. 1).


**Figure 1.** (Left) Digital story-telling snapshots from Whittier College students. (Right) An example of a robotic main character design for The Primer, courtesy of Amy Trinh '19 and Brianna Estrada '19. These students were members of the Whittier College Program.

This project offers three broader impacts for STEM education: broad user base and data collection, sharing of the application, and EDM. First, creating a tool based on digital-storytelling implies it can be distributed to a broad audience. By developing the application for the Android OS, for example, there's no reason it cannot be shared with communities outside Whittier College via that platform. One such example of an Android OS/iOS app for STEM research, titled CRAYFIS (www.crayfis.io) seeks to locate cosmic-ray signals through broad distribution [38]. The second broader impact is that the application would be useful to understand students outside Whittier College, for comparison. Given the first broader impact, instructors and students from other schools could utilize the application to understand their learning patterns as well. The third broader impact is that all data could be made anonymous (to protect the students' privacy) and then made

4 The Whittier Scholars Program is our area in the college for students who want to design their own major. Students must apply to the program and submit educational proposals for courses and final projects. For more information, see https://www.whittier.edu/academics/whittierscholars

available for EDM to other physics education researchers. For the example of CRAYFIS, the data is analyzed primarily by the authors of the application, but they are willing to share the data and collaborate when approached. With an appropriate data-sharing policy in place, this broader impact has the potential to grow the analysis capability of the project by involving other machine-learning experts.

**The current programs at Whittier College already generate under-utilized data.** The college would benefit from almost any program oriented around the analysis of student data from a machine-learning perspective. There are many examples in the literature of EDM demonstrating how clustering and classification algorithms are used in STEM education. One example of clustering algorithms was [39], in which researchers identified patterns in self-regulated learning (SRL) in a large asynchronous online statistics course. A k-means clustering algorithm revealed three clusters of students after it was applied to student login information. First, there were students who self-regulated their learning by studying online content each day, and seeking help when they needed it. Second, there was a group who studied with regularity but did not often seek help. A third group did not self-regulate. Identifying these clusters was useful to instructors to create a plan of action. Another example was [40], in which student problem-solving clusters emerged from data generated in a physics MOOC (massive open online course). In this study, hierarchical clustering and self-organizing map algorithms were used in tandem to identify patterns in physics problem-solving. On occasion, EDM researchers develop educational protocols. One such study developed the HASbot system [33], in which a natural language processing (NLP) algorithm was deployed to respond to student-generated text answers. HASbot was shown statistically to boost student comprehension. We encounter a similar example in MathBot [32].

For Whittier College students, we collect Math Placement test scores for placement into introductory math courses, and the Force and Motion Concept Evaluation (FMCE) is recorded for introductory physics students in mechanics. Further, we collect data from students' high schools (GPA, SAT, etc.). These data inform our initial picture of the their skills. It is not difficult to write a simple clustering algorithm to identify clusters of students based on the initial data. However, we do not continue to record data that *re-informs* our picture of the students, nor do we systematically tailor content to the students as they evolve. Tools like MathBot base the next module on the performance of the student in real-time. We propose to include also this feedback in our project, so that students benefit from the experiences of failure and re-training on modules they did not understand the first time. No matter the background of the student, the adaptability the machine-learning ensures that students entering introductory STEM courses have a common foundation of physics skills.

**Equity and inclusion are core values of Whittier College.** The idea that each student could be given free access to a digital tool that helps train them in advance of introductory STEM courses fosters equity and inclusion at our institution. Regarding equity, we know that students arrive in these courses with uneven preparation. We must ensure that every student has a foundational skill set. It is our hope that by providing this tool free to all Whittier students, that those who feel fear when enrolling in introductory science and math courses overcome that fear with training before the course. Regarding inclusion, we know that three-fourths of our faculty are white, whereas seventy percent of our student body is not. By involving the students in the creation of the digital-storytelling, we will infuse it with narrative themes and imagery that feel familiar to the students. If the instructor is *digital*, there is literally no restriction on how the instructor looks and sounds. Another potential broader impact along these lines would be to translate the content into Spanish, which would serve the broader community in which Whittier College is embedded and as an HSI.

**The coronavirus pandemic of 2019-2020 has forced many learning communities to adapt to online instruction.** The ideas behind this project are in alignment and are complementary to this online transition. Students will need extra preparation to overcome delays or gaps in high-school preparation caused by school closures, so a new digital tool for our College is appropriate. If that tool takes advantage of machine-learning, then we have added value to our school. If it further adapts to the students' needs automatically, based on the results of the EDM, we would consider that a success. However, if the students come away from the experience more inspired to learn and master STEM subjects, it would make a great impact on our learning community. Currently, the experience of our introductory students is too often apprehension, followed by a course they are required to take from a person or group that does not always understand them. Embarking on a journey to create such a program at our school is therefore a worthy endeavor, with clearly defined broader impacts. These impacts are the ability to share the application with a broad audience, the ability to compare and contrast data sets from different communities, and the ability to make EDM data available to researchers who seek to understand introductory STEM educational patterns across communities.

***EDUCATIONAL PROPOSAL*** *(continued)*

***EDUCATIONAL PROPOSAL*** *(continued)*

***EDUCATIONAL PROPOSAL*** *(continued)*

**ASSESSMENT PLAN.** *Define expected outcomes of your educational plan. How will your evaluation design provide information to improve your project as it develops and progresses? How will you determine whether your stated project objectives are being met according to the proposed timeline?*

The assessment of the development of the digital-storytelling tool should be performed in three phases, corresponding (approximately) to the three-year life cycle of the grant proposal. The overarching themes of each phase are: 1) code development and digital design, 2) initial roll-out and data analysis, and 3) widespread adoption and presentation of the results. We describe the assessment design of each phase below.

*Phase 1: Within the code development and digital-design phase of this project, there are several initial project milestones, and several long-term goals, to be completed within 1 year.*

1. **Team recruitment, hiring, and planning stages**

Because we propose designing an app for either a mobile platform, or at least a web-based design, an initial goal is to recruit the right computer-science students and offer them the correct financial incentives. Further, the same is true for graphic design students and members of the Whittier Scholars Program (WSP). This recruitment phase should take no longer than 1 month. Members of WSP have shown interest in the past, and we have had good experience with recruiting summer students to perform research in our RF design lab at the college, as long as we can provide the right incentives. Finally, we need to choose the most appropriate software and acquire it so that the designers and coders can get started as soon as possible. We will adopt an Scrum/Agile approach to creating a working prototype as fast as possible, so that we have a starting point even if it is not perfect. Ideally, that should happen by the end of month 2 of year 1.

<u>Concrete objectives:</u>

a) Recruit 2 undergraduates to work on code development, including training on scikit-learn (scikit-learn.org) machine-learning modules in Python, and select software tools for project creation on Andoid OS.
b) Recruit 2 - 4 graphic-design or WSP students to develop color palettes, initial character designs, and storyboards/settings.
c) Work with the four students to create a simple app that records the data from a student answering one physics question, complete with digital artwork and background computations by the end of month 2.
d) Create a code repository that stores our work and tracks changes.

2. **Character creation, story development, and STEM content generation**

For 10 months of year 1, we assume that the digital story-telling side of this project will undergo refinement such that there is a workable story and set of digital designs that can be implemented as the visual content of the application. The portfolio should be broad, to account for students moving through it via multiple pathways. On the coding and analysis side, we must have the minimum ability to collect data from a device running the application in a central location, and separately run machine-learning algorithms on it. Optimally, we should determine how to execute machine-learning algorithms tools within the application. However, this is not a high priority in phase 1. Once the complete story and all the associated physics content are being executed well in the app, then we move on to infuse the app with the ability to adapt to the learner as he or she uses it.

<u>Concrete objectives:</u>

a) Completely determine the set of introductory physics concepts and questions to be added to the story, and where and when specifically they will appear.
b) Complete the digital artwork that goes with the physics concepts and questions.
c) Complete the first version of the code and beta-test it on a number of devices. Debug the code and determine ways to make it run faster and more efficiently.
d) Transmit data to a central location, and begin to run clustering algorithms on it. At first this will not require large amounts of student data, but raw data generated by the group. Eventually, this objective will require data gathered from a group of volunteers on campus.

*Phase 2: Within the roll-out and data analysis phase of this project, there are several milestones that must be reached by the end of year 2.*

1. **Machine-learning studies of data collected from Whittier College students**

For two semesters, we need to characterize the introductory physics student populations and the data they generate, using machine-learning techniques. Although clustering algorithms are suggested by the literature, this phase should be the time to investigate various strategies. The goal should be to train an algorithm to identify major clusters within the population. This phase of the project also includes refinement of the data pipeline.

<u>Concrete objectives:</u>

a) Recruit 1 - 2 additional integrated computer science (ICS) majors from Whittier College to assist with algorithm research (as necessary).
b) Embark on detailed studies of classification algorithms, genetic algorithms, hierarchical clustering, k-nearest neighbors clustering, self-organizing map clustering, random forest, and other machine-learning techniques that best identify sub-populations of students that struggle with various physics concepts.

c) *Demonstrate that, once we know a student struggles with a concept, re-training them or taking them down an alternate route through the content improves their scores. This is a key objective that will tell us whether or not the approach is working, and whether or not we should change the algorithmic design.*

2. **Refine the visual content, and begin to involve Whittier Scholars Program**

This stage of the project is ripe for input from a Whittier Scholars Program student who would like to study how the visual media affects student learning outcomes. We will seek advice and collaboration from the Whittier Scholars Program in order to improve the user experience, and if it's possible, have a WSP student contribute to the code/digital artwork. The following objectives should take place within the first semester of year 2.

Concrete objectives:

a) Hold a series of meetings designed to introduce the app to WSP members, and brainstorm for how such a student could enhance the project.

b) Work with the digital design and WSP students to update the visual design, and start to think about any audio components, voice recordings, and other media additions.

*Phase 3: Within the widespread adoption and presentation of the results phase of this project, there are several objectives. At this level of the project, we assume that we will be recruiting new student workers and researchers as the project grows.*

1. **Begin to collect large data sets from Whittier College volunteer students and determine if the learning gains match those found in the initial runs**

This phase 3 objective will be a turning point for the project, in that we will determine if our initial training sets for the machine-learning algorithms were robust enough to understand large groups of future students. If yes, the results would give the green light to allowing any Whittier College introductory STEM student to participate by contributing data through training with the application. If not, it will tell us that we need to rethink how the classification/clustering algorithms work and how students are directed through the story-line. This should happen within the first few weeks of semester 1 of year 3.

Concrete objectives:

a) Organize trials with larger groups of volunteer students.

b) Assess the results and determine if we need to make changes to the design of the application

2. **Give a colloquium to the Departments of Physics and Astronomy, and Mathematics and Computer Science**

Once the project has come together with code, digital design components, and analysis results, it is time to present the findings to the physics and math departments. At Whittier College, we have the Dept. of Physics and Astronomy, and the Dept. of Mathematics and Computer Science. This should happen within year 3.

Concrete objectives:

a) Give a colloquium to the departments

3. **Summarize research results in an article format, and select a journal for submission**

The list of references in this grant proposal contains several options for STEM educational research journals that might be suitable for publication. At this stage, we will begin the process of making the data available to other EDM researchers, as well as sharing the app with instructors at other schools. We suggest a phased approach here, before uploading the app to any potential user on the internet.

Concrete objectives:

a) Formulate journal article outline and produce a rough draft

b) Select journal for publication and submit

c) Build a simple website for sharing the data with other EDM researchers, ensuring student privacy is protected. Consult with the College regarding issues of privacy and data security, and ensure we are in compliance with Whittier College policy.

d) Bring in instructors/professors from other institutions for introduction to the app, and receive feedback on improvements.

*Identify departmental or institutional colleagues who might play a role in this educational endeavor (as mentors, collaborators, etc.) as appropriate and describe the role they will play.*

List of collaborators

Professor Andrea Rehn, Professor of English and Director of Whittier Scholars Program, Whittier College
Role: Mentoring and recruitment of Whittier Scholars Program students capable of helping out with the project, and organizational support. At Phase 3, helping to promote and share the results and to promote the use of the application.

Professor Frederick Park, Associate Professor of Mathematics, Whittier College
Role: Consultation for the use of machine-learning algorithms, since Prof. Park is an expert in machine-learning

Whittier College DigLibArts: Prof. Andrea Rehn (English), Prof. William Kronholm (Mathematics) and others
Role: Connecting graphic design students to the project, and helping to organize data and online presentation of the project to potential users

## ***EDUCATIONAL PROPOSAL*** *(continued)*

**COURSES TAUGHT.** *List all undergraduate and graduate courses you have taught since the beginning of your first faculty appointment. For each, indicate student enrollment, briefly describe content (up to 30 words) and highlight teaching methods/approaches. (For example, General Chemistry; Freshman level; 200 students; Measurements and Units, Description of Matter, Solutions, Stoichiometry, Thermochemistry, Equilibria, Electrochemistry, Kinetics, Atomic Structure, Chemical Bonding, Molecular Structure; Flipped Classroom)*

Physics 135A: Algebra-based mechanics, 1. 30 students. Units and approximation, kinematics of displacement, velocity, and acceleration. Newton's laws, energy conservation, work, uniform circular motion, linear momentum and momentum conservation, angular momentum. Peer-instruction techniques, workshop physics worksheets, traditional lecture format, self-designed final projects, integrated lab-lecture format.

Physics 150: Calculus-based mechanics, 1. 30 students. Calculus concepts, units and approximation, kinematics of displacement, velocity, and acceleration. Newton's laws, energy conservation, work, uniform circular motion, linear momentum and momentum conservation, angular momentum. Peer-instruction techniques, physics worksheets, traditional lecture format, self-designed final projects, integrated lab-lecture format.

Physics 135B: Algebra-based mechanics, 2. 30 students. Charge and electrostatics, current and DC circuits, magnetism, induction and qualitative introduction to Maxwell's equations and electromagnetic spectrum. Electricity in the human body and power consumption are special topics. Peer-instruction techniques, physics worksheets, traditional lecture format, self-designed final projects, integrated lab-lecture format.

Physics 180: Calculus-based mechanics, 2. 30 students. Vector calculus concepts, charge and electrostatics, current and DC circuits, magnetism, induction and Maxwell's equations. Peer-instruction techniques, workshop physics worksheets, traditional lecture format, self-designed final projects, integrated lab-lecture format.

Computer Science 330/Physics 306: Computer Logic and Digital Circuit Design. 10 students. Digital concepts, binary and hex number systems, boolean algebra, Karnaugh maps, logic gates and systems of gates, adders, comparators, multiplexing, encoders and decoders, timers, latches and flip-flops, digital memory, shift registers and finite state machines. Integrated lecture and digital design lab format. Training on PYNQ-Z1 SoC (system on a chip) with python, firmware control, and coding as part of understanding digital concepts.

Computer Science 390: Digital Signal Processing. 10 students. Statistics and Probability, Complex Numbers, Noise in Digital Systems, Linear time-invariant (LTI) systems and filtering, audio and image processing and filtering, Fourier and Laplace transforms in digital environments (FFT and z-transforms). Integrated lecture and MATLAB/octave code session format. Self-designed final projects.

INTD (interdisciplinary) 255: Safe Return Doubtful: A History and Current Status of Modern Science in Antarctica. 30 students. Adventures of Robert Falcon Scott, Ernest Shackleton, and Roald Amundsen. Initial discoveries and navigation of the Antarctic continent, and qualitative and quantitative details regarding landmark achievements in physics, astrophysics, geophysics, biology and climate science in Antarctica. Reading longer history texts, activities that simulate Antarctic survival, keeping a journal, evoking the concepts of exploration and personal reflection in undergraduate students.

INTD (interdisciplinary) 100: Freshman Writing. 20 students. Improving the writing skill of incoming students, focusing on scientific writing, technical descriptions, popular science, structuring different styles of essays and articles.

Physics 330: Electromagnetic Theory. 10 students. Traditional presentation of Maxwell's equations for physics majors, up to electrodynamics.

**LETTER OF SUPPORT.** *Include a letter of support from your Departmental Chair, Dean or Provost that endorses your educational proposal and indicates why you are the appropriate faculty member to undertake this project. Please insert the letter following the ACADEMIC CITIZENSHIP STATEMENT.*

**ACADEMIC CITIZENSHIP STATEMENT.** *Universities and colleges are complex institutions that rely on faculty to assume numerous and wide-ranging responsibilities. Faculty are directly responsible for making universities and colleges effective places for student learning, for advancing research, and for preserving and disseminating knowledge. Briefly indicate your plan to become a stronger academic citizen by gaining a deeper understanding of, and by participating in, the governance structure, policy setting, and decision making in your institution; by serving as a mentor, supervising student research projects, and collaborating with colleagues; and by taking time to consider institutional needs and opportunities, to develop and share creative ideas to enhance your university or college and advance its mission through meaningful service and (perhaps in the future) leadership positions. You may bolster your case by describing your past and/or current citizenship activities. Use Arial 11 point font. Limit to one page.*

**Whittier College has a unique heritage of consensus-based governance.** Whittier College was founded by the Religious Society of Friends in 1887 and named for abolitionist and poet John Greenleaf Whittier. From our founding, we have relied on egalitarian governance. Tenure-track faculty are expected to serve on committees just as tenured faculty do. I have taken that responsibility seriously, and have served on several faculty committees. One key example of my service work is described below, in which we identified an inequity in our financial aid distribution. I plan to diversify my service portfolio over the next few semesters. Further, I have mentored students in research projects from my very first day on the job, including one student in the Whittier Scholars Program. Finally, I have begun general advising to incoming freshmen. By mentoring these freshmen, I have made a positive impact on their path to graduation and career plans.

**On the Enrollment and Student Affairs Committee, I led an analysis of student admissions data.** We identified several minimum criteria that allowed us to carefully discern which students should not be admitted due to a high chance of drop-out. These analyses included financial aid information, high-school GPA, and standardized test scores. The issue of minimum standards was delicate, but we were able to come together after one year of discussion to a consensus and to pass a resolution. More interesting was a separate finding that came out of the data analysis. We quantify Financial Need (roughly) as the Whittier College cost, minus the sum of expected family contribution (EFC) and financial aid and grants. The distribution of Financial Need[5] was not distributed normally, but had two separate groups. Some students were receiving a net *positive,* and some a net *negative* Financial Need. This was a perplexing finding for a school that makes strong efforts to be egalitarian. I plan on continuing this analysis with fresh data in the Fall of 2020.

**In the near future, I plan on diversifying my committee service.** At Whittier College, our system encourages any professor who is willing to help with a committee. I have indicated to the administration that I would like to help in the following three areas in the future: Digital Liberal Arts (DigLibArts), the Whittier Scholars Program (WSP), and the Scholarship and Grants Committee. I have a vested interest in helping to maintain DigLibArts and WSP as indicated in my Educational Proposal. This will include working with my friend Prof. Andrea Rehn to create new opportunities for students. The Whittier Scholars Program is an institution within Whittier College with a proud history of guiding students through self-designed majors. I have helped one of my students, Nicolas Bakken-French (see below) design a major in Environmental Policy Analysis, with a Minor in Glaciology. Finally, I have had several students win internal grant fellowships (noted above). Serving on the Scholarship and Grants committee is my way of taking responsibility for the future of this program. These early experiences are valuable stepping stones in the formation of young scientists and engineers. Finally, I plan on serving on these committees sequentially so as not to experience burnout.

**I have had success as a mentor, and I am proud of my students and their accomplishments.** I helped Cassady Smith '20 (Physics) obtain an internship with LIGO after she worked for me for one summer via an internal Keck Foundation Grant. John-Paul Gómez-Reed '20, helped me complete the firmware-based research to date mentioned in the Research Proposal after winning both the Keck and the Ondrasik-Groce Fellowships. John-Paul will likely be one of the authors on journal publications that flow from this grant proposal, and he plans to become an engineer and then a professor. I will help him gain admission to graduate school, hopefully my alma mater UC Irvine. I advised Nick Clarizio '20 (Physics) as we built a DIY drone capable of automated flight. We plan on building self-charging drones capable of flying in Antarctica. Nicolas Bakken-French is my Whittier Scholars Program advisee, who completed an internship with ARIANNA at UC Irvine after learning some glaciology analysis from me. Finally, Raymond Hartig is my theoretical physics student, who I am advising on a double major in mathematics and physics. Raymond plans to go to graduate school, and I will help him land a position as well (again hoping for UC Irvine). I also advise typically 15 other freshmen in the selection of their classes, time-management and orientation in the Fall. We seek to build community in this way, so that all of our students feel welcome to campus.

5 Sometimes Financial Need is named Financial Aid Gap, although the terminology can differ by institution.

Letter of support for the Educational Proposal. 7/7/2020

Jordan Hanson was hired into the Physics department three years ago as a tenure-track Assistant Professor. His position was created to help service a new Integrated Computer Science program in which students can major in a combination of computer science and another discipline. Currently there are three majors available, namely COSC/Math, COSC/Physics and COSC/Economics. Since joining us he has created two courses specifically for the new program, Computer Logic and Circuit Design, and Digital Signal Processing.

Jordan's Educational Proposal, in which he plans to implement machine learning, is very much in line with the type of activities for which we hired him. He will be collaborating with other faculty members who contribute to the Computer Science program but in addition, he will have significant interactions with faculty outside of the sciences. This kind of interdisciplinarity is something that we value greatly at Whittier College. We also value the involvement of undergraduates in faculty projects and once again this proposal hits the mark. It is particularly exciting to us that we can involve non-majors in a physics project. Jordan has already had several physics majors involved in his research and with this project he will be able to inspire an even wider range of students.

Jordan has taught both algebra-based and calculus-based introductory physics courses here at Whittier and his three years have given him significant insight into the problems that students have with physics material. In particular, the algebra-based course is very challenging because many of the students have very weak backgrounds in math and science. Jordan has learned how to deal with this lack of preparation and so is in a great position to create a tool that addresses the weaknesses of such students.

Finally, I would point out that Whittier College embraces the Boyer categories of Scholarship (https://depts.washington.edu/gs630/Spring/Boyer.pdf). We therefore value the Scholarship of Teaching and, when applying for tenure and promotion, peer-reviewed scholarship aimed at improving pedagogy is valued in addition to the more usual Scholarship of Discovery. For this reason, the Physics department has no qualms about Jordan spending time on this educational project. This work can contribute to the body of work that he will put forward when he applies for tenure and promotion.

So, in summary, the Physics department is very supportive of this Educational Proposal (and of course his Research Proposal). The work is in line with our Computer Science program, our support for interdisciplinarity, our encouragement of undergraduate involvement and with the College's belief in the various forms of scholarship delineated by Boyer.

Seamus Lagan

Professor Seamus Lagan

Chair of the Dept. of Physics and Astronomy

Whittier College

***LIST OF REFERENCES****. Annotate the proposal with a list of references from the primary literature. Include all authors and titles. If more space is required, attach a maximum of one additional page. Use Arial 10 or 11 point font.*

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June 25, 2020

To Whom It May Concern,

It is with great pleasure that I write a letter of collaboration for Prof. Jordan Hanson, who is applying to the Cottrell Scholars Program with a proposal entitled ”Advanced Optimization of the ARIANNA Ultra-High Energy Neutrino Detector. “

First a little background to the ARIANNA project: The goal of ARIANNA is to measure the flux of ultra high energy neutrinos produced by the collision of cosmic rays with cosmic microwave background radiation, and to perform a search for sources of extragalactic cosmic rays. Just like the recent detection of gravity waves by the LIGO facility, we hope to observe high energy neutrinos, an entirely new messenger, to complement traditional telescopes that detect light (of one form or another). This is part of a larger revolution in astrophysics called “multi-messenger “ astrophysics which has been highlighted by NSF as a priority for future support.

The ARIANNA detection method is based on the observation of a brief pulse of radio emission from the neutrino interaction in the Antarctic ice. The basic operational robustness was established with a 10 station pilot array of detectors during the past half decade, and in November of 2019, the collaboration (including Jordan) submitted a proposal to NSF to construct 200 additional stations, called ARIANNA-200. It serves as a pathfinder mission for a much more ambitious detector called IceCube-Gen2 which is now in the planning stages. The ARIANNA collaboration has partnered with the IceCube collaboration to form a joint working group to develop a radio-based concept for the next generation of the IceCube neutrino detector at the South Pole. This is where Jordan and his team at Whittier College come in. He is proposing to dramatically improve the peformance of the ARIANNA concept and help us apply it to ARIANNA-200 and IceCube-Gen2.

I have no doubt that Jordan will be a strong asset and positive role model. He has attracted capable and enthusiastic undergraduate students to his research group. Collaboration between Whittier and UCI is particularly straightaforward since the two are only separated by 32 miles. He is exactly the type of young STEM faculty in liberal arts colleges we should encourage, I urge you to support his application.

Sincerely,

Steven W. Barwick

Steven W. Barwick
PI, ARIANNA

***LIST OF REVIEWERS.*** *The reviewer list should include at least eight "outsiders," individuals with whom you have had no substantive contact, who are experts in your area of research. At least four of the outside reviewers should be from US academic institutions. List at least two "insiders," preferably former mentors. We may also select reviewers of our choice. Please include complete names (initials are not enough), titles, institutions, mailing addresses, phone and fax numbers, and email addresses. Use Arial 10 or 11 point font.* ***You must note briefly the nature and extent of your interactions with each of the outside reviewers; e.g., met at a meeting, interviewed with, no interaction, never met, etc.*** *Limit to one page.*

Outside reviewers

1) Francis Halzen, Gregory Breit and Hilldale Professor of Physics at the University of Wisconsin, Madison. Phone: (608) 262-2667 Email: francis.halzen@icecube.wisc.edu. Mailing address: 2320 Chamberlin Hall, 1150 University Avenue, Madison, Wisconsin 53706-1390. Interactions: I have seen Prof. Halzen speak at conferences, and he is well-respected.

2) Peter Gorham, Department Chair and Professor of Physics at the University of Hawai'i, Manoa. Phone: (808) 956-9157. Mailing address: Watanabe 416, 2505 Correa Road, Honolulu, Hawai'i 96822 Email address: gorham@hawaii.edu. Interactions: I have seen Prof. Gorham speak at conferences, and met once at a conference.

3) Michael DuVernois, Senior Scientist, Wisconsin IceCube Particle Astrophysics Center (WIPAC), Phone: (608) 263-9461. Email address: duvernois@icecube.wisc.edu. Mailing address: 222 West Washington Ave., Suite 500, Madison, WI 53703. Interactions: We talked over coffee at a conference and I learned he works on IceCube. I also hear him on conference calls occasionally.

4) John Beacom, College of Arts and Sciences Distinguished Professor of Physics and Astronomy, Henry L. Cox Professor of Physics and Astronomy, Director of the Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University. Phone: (614) 247-8102. Email Address: beacom.7@osu.edu. Mailing Address: 191 West Woodruff Avenue, Columbus, Ohio 43210. Prof. Beacom is the director of CCAPP where I used to work, and was the supervisor for all the post-doctoral fellows.

5) Manoj Kaplinghat, Professor of Physics and Astronomy, University of California at Irvine. Phone: (949) 824-8541. Email: mkapling@uci.edu. Mailing address: University of California, Irvine, Department of Physics & Astronomy, 4129 Frederick Reines Hall, Irvine, CA 92697-4575. Interactions: Prof. Kaplinghat is a professor at UCI where I was a graduate student, so I know of his work. However, we have never really interacted.

6) John Ralston, Professor of Physics, University of Kansas. Phone: (785) 864-4020. Email: ralston@ku.edu. Mailing address: Department of Physics & Astronomy, 1082 Malott,1251 Wescoe Hall Dr., Lawrence, KS 66045. Interactions: One of my first-author papers involves a result from one of his papers, so we have exchanged several emails answering questions.

7) Michael G. Anderson, Associate Professor in Physics Instruction, University of California, Riverside. Phone: (951) 827-5370. Email: michaelg.anderson@ucr.edu. Mailing address: 900 University Avenue, Riverside, California, 92521. Interactions: I have never met Prof. Anderson, but he is an expert in Physics Education Research, and is in Southern California.

8) Daniel Whiteson, Professor of Physics at the University of California, Irvine. Phone: (949) 824-2108. Email: daniel@uci.edu. Mailing address: University of California, Irvine, Department of Physics & Astronomy, 4129 Frederick Reines Hall, Irvine, CA 92697-4575. Interactions: Daniel is qualified to review both the research and educational side of the proposal, as he works in both high-energy physics and science communications. He and I interacted when I was a graduate student at UC Irvine.

Inside Reviewers

1) Dave Besson, Professor of Physics at the University of Kansas. Phone: 785-864-4741. Email: dzbesson@gmail.com, zedlam@ku.edu. Mailing address: Department of Physics & Astronomy, 1082 Malott,1251 Wescoe Hall Dr., Lawrence, KS 66045. Interactions: Dave was an excellent mentor and he is an astute researcher. He is also a Fulbright Scholar, with an excellent track record of research in our field and mentorship.

2) David Seckel, Professor of Physics at the University of Delaware. Phone: (302) 831-1846. Email: dseckel@udel.edu, seckel@bartol.udel.edu. Mailing address: 217 Sharp Lab, Newark, Delaware, 19716. Interactions: David is a member of the ARA and RNO-G collaborations, so I interact with him regularly at conferences and conference calls. He is a respected theorist in my field.

RESEARCH CORPORATION FOR SCIENCE ADVANCEMENT
Cottrell Scholar Award Application

## ENDORSEMENT PAGE

### Conditions of Research Corporation for Science Advancement's Cottrell Scholar Award

A RESEARCH CORPORATION FOR SCIENCE ADVANCEMENT (RCSA) AWARD is a contribution to the scientific and academic program of the institution and is to be used for support of work described in the application prepared by the principal investigator and adopted by the institution.

Since research by its very nature is unpredictable and may require adaptations in order to exploit promising leads, the principal investigator should feel free to make changes in the emphasis or direction of the work as it progresses. If major changes are contemplated, prior approval should be obtained.

Details of program allowances and restrictions can be found on our website, www.rescorp.org.

Financial and scientific reports prepared on the foundation's forms are absolutely required. The first report is due within 30 calendar days of the 12-month anniversary of the award start date. The final report is due within 30 calendar days of the 36-month anniversary of the award start date. Failure to provide the first annual report may result in suspension of the award and a request to return unspent funds. Failure to provide the final report will result in suspension of the institution from participation in RCSA programs.

The principal investigator is urged to publish the findings in the appropriate scientific journals, acknowledging the support of Research Corporation for Science Advancement.

RCSA awards are true awards to the institution, not contracts for research with the institution or the principal investigator, and RCSA disclaims any rights in the results of the research.

APPLICANT NAME: Jordan C. Hanson

PROJECT TITLE: Advanced Optimization of the Askaryan-class Ultra-High Energy Neutrino Dectectors

SUBMITTED BY: (INSTITUTION) Whittier College

Name of institution adopting and assuming responsibility for the above project, believing the principal investigator is qualified to conduct the project, and accepting the Conditions of Award, if an award is approved.

NAME, POSITION AND E-MAIL ADDRESS OF AUTHORIZED FINANCIAL OFFICER: Jim Dunkelman, Vice President for Finance & Administration
jdunkelman@whittier.edu
13406 Philadelphia Street, Whittier, CA 90608

SIGNATURE OF FINANCIAL OFFICER: [signature] DATE 7/17/20

NAME OF CHIEF EXECUTIVE OFFICER (CEO) Linda S. Oubre

TITLE OF CEO (President or Chancellor) President

SIGNATURE OF PRINCIPAL INVESTIGATOR: Jordan C. Hanson DATE 7/17/20

**SCAN THIS SIGNED ENDORSEMENT PAGE AS THE LAST PAGE OF YOUR PDF FILE**