PROJECT SUMMARY

Overview:

This project will support the deployment of an Advanced Cryogenic L-Band Phased Array Camera for Arecibo (ALPACA) for the Arecibo 305 m radio telescope. The 7-horn L-band ALFA instrument installed on the Arecibo telescope in 2004 and the subsequent surveys have demonstrated the advantages of multi-pixel systems for surveys with a very large telescope aperture. By increasing the field of view to 40 beams, the proposed ALPACA instrument will have approximately five times the survey speed of ALFA. Phased array feeds (PAFs) have been installed in Australia and The Netherlands, but these are uncooled systems that do not achieve a system temperature competitive with state-of-the-art cryogenic feeds. Unlike all other deployed PAFs, the ALPACA instrument will be cryogenically cooled. The design is based on the successful development at Cornell University and testing on the Arecibo telescope of a prototype 19 dual polarization dipole cryogenic PAF. Brigham Young University (BYU) participated in these tests by providing a narrowband digital beamformer back end and is developing a 150 MHz beamformer to be used with a 7-beam L-band PAF on the Green Bank 100m telescope. The ALPACA instrument will build on these development efforts to dramatically increase the survey speed of the Arecibo telescope. Major scientific objectives will be new pulsars, especially millisecond pulsars (MSPs) with stable periods suitable for inclusion in the program to detect gravitation radiation (NANOGrav), searches for extra-terrestrial intelligence (SETI), the detection and study of more of the enigmatic Fast Radio Bursts (FRBs), and a census of gas bearing low mass dark matter haloes hosting galaxies in the local universe to test the validity of the [Lambda]CDM cosmological model on small scales.

Intellectual Merit :

ALPACA will be the first decimeter wavelength PAF with tens of beams built in the United States and the first full sized cryogenically cooled PAF worldwide. This receiver will break new ground in instrumentation development for radio astronomy and could be the forerunner for large PAFs for other radio telescopes such as the 100 m Green Bank Telescope. ALPACA will be used to discover new MSPs contributing to the NANOGrav project's objective of detecting gravitational waves and will help unravel the mystery of fast radio bursts (FRBs). Successful SETI searches enabled by a wide-field radio camera would, of course, have a tremendous intellectual impact. The census of gas bearing low mass dark matter haloes to test the validity of the [Lambda]CDM cosmological model on small scales will clearly be of major importance in furthering our understanding of the evolution of the Universe.

Broader Impacts :

Three graduate students will be involved in the construction and commissioning of the ALPACA instrument and there will be opportunities for undergraduate involvement. Large scale surveys are a tremendous way to involve graduate and, especially, undergraduate students. Several hundred undergraduate students, about one third of them women, have been involved with the extragalactic HI ALFALFA survey with the ALFA system at Arecibo and many tens with the PALFA pulsar search survey. New surveys with ALPACA have the potential to engage similar numbers of students. Surveys are also a great vehicle for engaging interested people in the community, citizen science, with two examples utilizing Arecibo data being Einstein at Home, searching large data sets to find pulsars, and SETI at Home. These programs will continue with data from the ALPACA system.

As its major research facility, the Arecibo Observatory is tremendously important to Puerto Rico for student training, community engagement, tourism and the jobs provided to the local community. The ALPACA instrument coupled with Arecibo's enormous collecting area will keep Arecibo pre-eminent in many areas of survey science at radio wavelengths. The 7-beam ALFA system revitalized the radio astronomy program at Arecibo after its installation in 2004 and the ALPACA instrument's potential for ground breaking results will repeat this process to the long term benefit of our understanding of the universe, the Observatory and Puerto Rico.

1 Introduction

This proposal falls under Category 4a of the MSIP solicitation (NSF 15-580), "open access capabilities: new instruments for existing telescopes, both national and private, in return for US community access." Brigham Young University, in partnership with Cornell University and the Arecibo Observatory, is proposing to build, install and test the *Advanced L-Band Phased Array Camera for Arecibo* (ALPACA) as a user provided facility instrument on the Arecibo 305 m radio telescope.

Over the past twenty years large scale surveys have become major contributors to knowledge of our own galaxy and the local and distant universe. Radio surveys at decimeter wavelengths with both single dish telescopes and interferometers have been inefficient due to limited fields of view because of the lack of multi-pixel radio cameras. Multi-horn systems at L-band on the 64 m Parkes, Australia, telescope and on the Arecibo 305 m telescope have demonstrated the advantages of multi-pixel systems in reducing survey times to practical levels. However, horn systems at these wavelengths have the disadvantage that the beams are well separated on the sky, thus limiting the number of pixels within the field of view. Phased array feed (PAF) systems alleviate this issue as the beamformer can place the synthesized beams at any spacing within the field-of-view. PAF systems have been developed recently for the Australian ASKAP interferometer array [1] and for the Dutch Westerbork array (APERTIF), and plans are being developed for installing ASKAP PAF's on the Parkes 64 m and Effelsberg 100 m single dish telescopes. These are all uncooled systems with system noise temperatures in the $\sim$52K (ASKAP) to 70K (APERTIF) range. Survey speed is proportional to the inverse square of the system temperature, so survey speed can be significantly improved by cooling the front end feed and amplifiers to give a system temperature of 30K or less. This temperature is comparable with that of the 7-beam ALFA system on Arecibo so a 40-beam ALPACA system is expected to have close to five times the survey speed of ALFA.

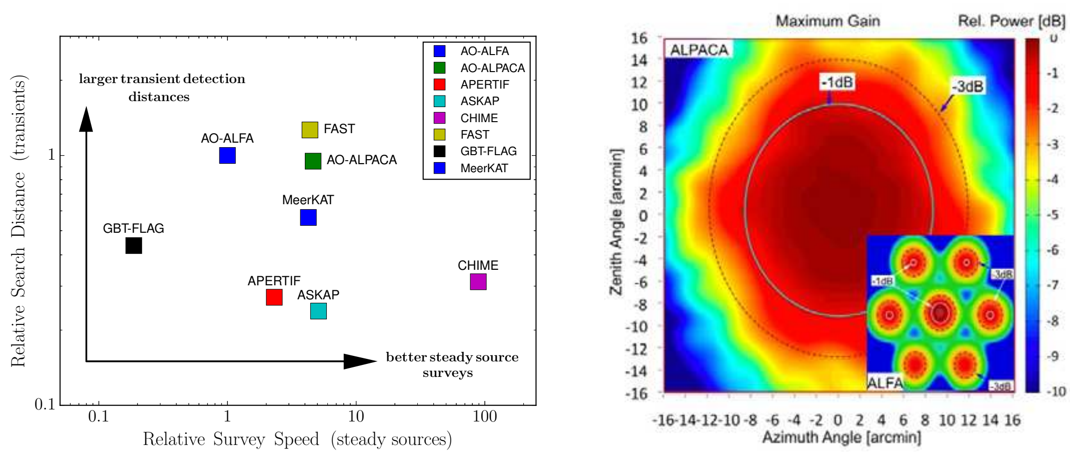


Figure 1: Left: Characterization of ALPACA and other telescope/receiver combinations using the standard survey speed appropriate for steady sources (x axis) and search distance or "reach" of a given telescope (y axis) which is important for surveys for transients, such as fast radio bursts (FRBs), intermittent pulsars, and ETI sources. All are L-band ($\sim$ 1.5 GHz) systems except for CHIME, which operates from 0.4 to 0.8 GHz and is a transit instrument. Right: Gain vs. azimuth and zenith angles for ALPACA, showing its footprint in comparison with ALFA.

With a cryogenic receiver providing 40 dual polarization beams on the sky, ALPACA's survey speed on Arecibo will be comparable to that of the ASKAP, MeerKAT (South Africa) and Westerbork arrays and the Chinese single dish FAST telescope currently under construction. For a fixed bandwidth (all the systems with the possible exception of MeerKAT have 300 MHz bandwidth and for spectral line measurements the bandwidth is the spectral resolution) the survey speed is given by

$$\text{Survey speed} = N_b \Omega_b \left(\frac{A_\text{e}}{T_\text{sys}}\right)^2 \tag{1}$$

where N_b is the number of formed beams, Ω_b is the field of view area per beam, A_e is the antenna effective area, and $T_{\rm sys}$ is the system noise temperature. Another metric, the relative search distance or "reach" is important for transient surveys; it scales as $\sqrt{A_{\rm e}/T_{\rm sys}}$ without any dependence on survey dwell time because integration times depend on burst durations. This is discussed further in the science section.

Table 1 has our best estimate of the parameters of the major array and single dish survey instruments all of which except ALFA are still in the development/construction phase. The 7-beam L-band PAF FLAG system being developed for the 100 m Green Bank Telescope is also included. Within about a factor of two, it is very difficult to do a detailed comparison as it depends on the spacing of the formed beams and unknown factors such as the formed beam's sensitivity as a function of angular distance from the central beam.

Table 1: Relative L-band survey speeds (normalized to unity for AO ALFA) of the major array and single antenna systems based on our best knowledge of the relevant system parameters ($T_{\rm sys}$). We have assumed a 30K $T_{\rm sys}$ for ALPACA, which is the goal. For ASKAP the assumption of a $T_{\rm sys}$ of 52K combined with an antenna efficiency of 0.60 is consistent with their published $T_{\rm sys}$/antenna efficiency of <95K over ASKAP's frequency band. Based on a statement by the FAST group, its effective area will be only 1.6 times Arecibo's due to a less efficient illumination.

Telescope	Dia (m)	#Ant	# Beams	Beam Area (deg^2)	Eff Area (m^2)	$T_{\rm sys}$ (K)	Rel SrvSpd
GBT FLAG	100	1	7	0.014	5,890	27	0.19
AO ALFA	225	1	7	0.0027	31,013	27	1
ALPACA	225	1	40	0.0027	31,013	30	4.6
ASKAP	12	30	36	0.83	3,393	52	5.1
APERTIF	25	12	37	0.22	5,890	70	2.3
MeerKAT	13.5	64	1	0.79	7,329	20	4.2
FAST	300	1	19	0.0017	49,621	27	4.3

Within the uncertainties in their performance parameters, the ASKAP, MeerKAT, FAST and ALPACA systems have projected survey speeds (Figure 1, left, x-axis) that are very close to each other. The Westerbork APERTIF system is about a factor of two slower but, again, this difference is not large given the uncertainties. While very competitive in terms of effective area and number of beams on the sky, the Canadian CHIME system covers 400 MHz to 800 MHz (z of 0.8 to 2.5) so would not be available for HI studies at low redshifts that are planned for ALPACA. However, as discussed below it does have potential for pulsar and Fast Radio Burst (FRB) searches in its frequency range within its northern sky coverage although the high multipath pulse broadening at these frequencies may be an issue especially for FRBs.

The ALPACA receiver will be the only U.S. system comparable with the array feeds being installed worldwide, and will have the key technological advantage over all other deployed systems with the exception of the GBT FLAG system of cryogenic cooling, which, when coupled with the largest total aperture, will make it the consummate instrument for high sensitivity pulsar searches, observations of the transient radio sky, neutral hydrogen surveys of the local universe and SETI. ALPACA will be an open access instrument available, via reviewed proposals, to the entire astronomical community.

The R&D required to field this system has been done by the Cornell University group in collaboration with the BYU PIs. Under German Cortes-Medellin, Cornell/NAIC began in 2010 the planning for a L-band phased array feed for the Arecibo telescope. The first task was to measure the field-of-view (FoV) of the Gregorian optics at L-band. BYU provided a 19 dipole element array and backend receiver system. NAIC procured an adjustable mount that could move the array in two dimensions. Source measurements gave a FoV to the -1 db in sensitivity level of $\sim$ 15×20 arc minutes (Figure 1, right), large enough for a 40-pixel PAF camera with the beams at approximately the Nyquist spacing. Funding, initially through NAIC and then via an NSF ATI grant and some Cornell provided funds, was used to design and fabricate a fully cryogenically cooled 19-dual polarization element PAF system (AO-19). BYU provided the post dewar RF stages and a narrow bandwidth digital beamformer, and the integrated system was successfully tested on the Arecibo telescope in 2013 [2]. In parallel, the BYU group is developing a 150 MHz bandwidth digital beamformer as a back-end for a cooled 19-dual polarization element PAF for the Green Bank 100 m telescope (GBT). The ALPACA system will build on significant prior work by the PIs [1–11] and on the key risk retirement and experience gained with the Cornell developed AO-19 prototype cryogenic front-end and the BYU 150 MHz digital beamformer.

2 Scientific Justification

Deep and fast surveys are central to the exploration of the astronomical frontier at all electromagnetic wavelengths and also in gravitational waves. ALPACA will provide the means for discovering rare energetic events and extreme, exotic objects in the radio band. Science drivers include topics in extreme gravity, gravitational waves, extragalactic bursts of unknown origin, mini halos in ΛCDM cosmology, and the search for extraterrestrial intelligence (SETI). Major surveys in these areas can be conducted commensally; all benefit from the unique combination of wide field of view and high sensitivity that Arecibo will provide with ALPACA. The two metrics shown in Figure 1 (left) — survey speed plotted against relative detection distance or reach that a transient source with given luminosity and duration can be detected — indicate that ALPACA gives a large survey speed surpassed significantly only by CHIME (Canada), the very wide-field telescope designed as a cosmology telescope with pulsars and transients as secondary science. However, Arecibo's reach (via ALFA or ALPACA) is far larger than CHIME's and other high survey-speed telescopes, including APERTIF, ASKAP, and MeerKAT. Reach is especially important for fast radio bursts (FRBs) that are now known to originate from extragalactic sources but from uncertain distances. A possible disadvantage of CHIME for FRB studies is that pulse broadening from multipath scattering seen in some FRBs is much larger (by a factor $\propto \nu^{-4.4}$ of 250 to 12) in its ν =0.4-0.8 GHz band than the 1.4 GHz band of all the other telescopes shown, which could render FRBs undetectable. In addition, CHIME does not allow deep probing of the local universe in HI. FAST (China), when outfitted with the planned 19-beam feed array, may surpass ALPACA in reach, but not in survey speed. Sensitivity goals with FAST require adequate implementation of its active surface, which may take some time to achieve after first light observations later in 2016 (D. Li, FAST Project Scientist, private communication).

Extreme Gravity and Fundamental Physics: Pulsar science has been driven by surveys and followup pulse-timing observations. Neutron stars (NSs) in exotic binaries, particularly those involving strong gravity, allow measurement of relativistic effects important for neutron star mass measurements, tests of specific gravity theories, and advanced studies of the nature of gravitational radiation. A pulsar/black-hole binary would allow precise measurements of black hole mass and spin [12, 13] and possibly precise tests of general relativity's no-hair theorem [14]. Surveys provide local (i.e. Galactic) estimates of the merger rate of NS-NS binaries needed for cosmological projections for gravitational wave (GW) detection in the kHz band with LIGO and other laser interferometers. The recent announcement by the LIGO Science Collaboration that a $29 + 36\ M_\odot$ black hole binary merger has been detected in GWs [15] also adds impetus to searches for pulsars with massive black-hole companions. Their evident rarity demands a large-scale survey and large companion masses require a wider range of accelerations than has been done in pulsar survey analyses. Comprehensive surveys are also critical for finding new, high-quality millisecond pulsars (MSPs) as elements of a Galactic-scale detector for nanohertz GWs in NANOGrav's pulsar timing array (PTA).

Fundamental tests of General Relativity (GR) have been made with double neutron star (DNS) binaries and millisecond pulsars (MSPs) with white-dwarf companions. The first DNS system was discovered at Arecibo [16] and led to the demonstration that GWs exist in accordance with GR [17, 18], leading to the 1993 Nobel Prize in physics. It also emboldened the community to construct ground-based interferometers that have now culminated in the direct detection of GWs with LIGO.

In the last 40 years almost 20 new DNS systems have been discovered, providing ever-improving tests of GR, such as the double-pulsar system with a 2.4 hr orbital period that provides five independent GR tests [19, 20], with almost two orders of magnitude greater precision than for the first DNS (M. Kramer, private communication). Because DNS systems ultimately merge, even more spectacular systems with sub-hour orbital periods should exist; they and pulsars with black-hole companions remain to be discovered, providing much greater testing power for gravitational theories.

MSPs with periods as short as 1.4 ms were first discovered at Arecibo [21] and gave impetus to the notion [22] that pulsars could be used as *detectors* of low-frequency (nanohertz) GWs. More than 200 MSPs have now been discovered, many with Arecibo. Their short periods, proportionately narrow pulses, and greater spin stabilities than standard pulsars combine to make them the best known natural clocks. They form the basis for the high timing precision (sub-μs) required for higher-order studies of gravity and for the detection of GWs.

Tests of alternative theories of gravity from the timing of MSP-white dwarf (WD) systems are the most stringent to date [23, 24] and cannot be matched by current or forseeable gravitational wave detectors [23]. Measurements of GR effects, such as orbital precession and decay, test gravitational interactions that depend on binding energy and have placed tight limits on changes in the gravitational constant (G), demonstrated that there is no dipolar component to gravitational radiation, and shown that the strong equivalence principle (SEP) is consistent to high precision. The triple system PSR J0337+1715 [25] promises several orders of magnitude improvement in tests of the SEP.

NS mass measurements are a byproduct of binary pulsar timing. They inform us about the equation of state of dense nuclear matter [26], which is important for understanding the strong nuclear force. The masses of two pulsars, J1614−2230 ($M_p = 1.97 \pm 0.04\, M_\odot$) [27] and J0348+0432 ($M_p = 2.01 \pm 0.04\, M_\odot$) [28], exclude many possible equations of state for the cores of neutron stars, in particular those that were considered to be the most physically plausible (e.g. neutron matter with hyperons), and strongly constrain the surviving models [29].

GR tests and mass measurements result from exploiting particularly advantageous discoveries among the pulsars found in surveys. Yet-more extreme DNS and MSP-WD binaries than found to date remain to be discovered, along with the prospect of the first pulsar-blackhole binary. These can only be found through large-scale surveys such as those enabled by ALPACA.

Gravitational Wave Detection Using Pulsar Timing Arrays (PTAs): MSPs provide a unique opportunity for detecting low frequency GWs in the nanohertz band, about as far in frequency from LIGO's kHz band as radio waves are from gamma-rays. Monitoring multiple MSPs allows detection of the coherent 'Earth term' of the GW perturbation that affects all lines of sight.

Currently, the NANOGrav collaboration [30] analyzes timing data on fifty MSPs with RMS precisions ranging from 30 ns to 1 μs. NANOGrav has placed astrophysically constraining bounds on the stochastic GW background [31, 32] generated by inspiraling, supermassive $\sim 10^9$-10^{10} $M_\odot$ black-hole binaries (SMBHBs) produced in galaxy mergers at redshifts ~ 1. Detection in the nHz band benefits from averaging over multiple MSPs to reduce noise that is uncorrelated between objects (arrival time estimation errors, NS spin noise, and interstellar plasma effects) to build up the detection significance of the coherent Earth-term signal. NANOGrav data also allow detection of continuous waves from individual SMBHBs [33] and from bursts produced at the time of coalescence. So far, significant limits have been placed on CW sources and bursts with memory [34, 35].

NANOGrav projects a plausible detection of the GW background within five to ten years [36, 37], *subject to finding additional high-quality MSPs for inclusion in the PTA*. A detailed analysis of NANOGrav's timing measurements [38] and the European PTA group's data [39] shows that the error budget on arrival times is well understood. For MSPs that are visible from Arecibo, no other telescope can approach the achievable timing precisions due to its unparalleled sensitivity. Arrival-time precision is better for MSPs with narrow pulses and low spin noise [40] and recent surveys show that MSPs important for pulsar timing arrays remain to be discovered [41, 42]. Wide-angle surveys for MSPs with ALPACA are therefore central to the success of NANOGrav in its goal to open up the nanohertz GW window through an initial GW detection. Analysis of spin noise in pulsars [43] indicates that about 20% of MSPs have spin stabilities like those (or better than) in the current NANOGrav portfolio. Combined with the need for wide coverage of the sky by MSP direction, which test for the presence of the quadrupolar GW signature, finding a large sample of new MSPs in the Arecibo sky is essential.

Extrapolating from the PALFA and Parkes Pulsar Surveys: All of the above science areas are enabled by discovery of pulsars in large-scale surveys; the same surveys also yield transient objects including RRATs (rotating radio transients) [44] and FRBs (discussed below). The PALFA survey has been one of the most important such surveys: it has been enormously successful in spite of the presence of problematic radio frequency interference (RFI). Of the seven known NS-NS binaries that will merge in less than a Hubble time, five have been discovered at Arecibo, including the Hulse-Taylor pulsar; two of them (J1906+0746 and J1913+1002) are recent discoveries from the PALFA survey. Also, five of the 26 MSPs discovered by PALFA have been added to the NANOGrav PTA and more are being evaluated.

ALPACA Pulsar Yield: ALPACA can be deployed for deeper Galactic-plane surveys to search for massive binaries, including the possibility of the first known pulsar/black-hole binary, and for surveys at higher latitudes to find MSPs and FRBs. To assess the pulsar yield, we carried out Monte Carlo simulations based on the current sample of over 2500 pulsars [45]. Using the `psrpop` simulation package, originally developed to replicate the results of the Parkes multibeam pulsar survey [46], we created a snapshot of the normal (i.e. non-recycled) pulsar population and consider an all-Arecibo sky survey with ALPACA assuming 300 s dwell times. Such a survey would detect 3100 normal pulsars - well in excess of the sample of 470 currently known in the Arecibo sky. The same simulations reproduce the number of pulsars currently seen in PALFA surveys [47]. For MSPs, we adopted a recently determined log-normal period distribution based on the Parkes multibeam survey [48] and created a population consistent with both the Parkes and PALFA surveys. For ALPACA, we predict that an all-AO sky survey will detect 270 MSPs, of which 60 are currently known. We also predict that one DNS binary will be found per 1000 hr of survey time.

Unidentified Millisecond Bursts of Extragalactic Origin: The origin of FRBs from well outside the Milky Way is now fully established. Figure 2 (right) shows the distributions of FRBs in "dispersion measure" space along with other objects that can be sampled in ALPACA surveys. Though small in number so far (16 published as of 2016 Feb 1), FRBs appear to represent the tail of a high-rate, isotropic source population that produces $\sim 10^3$–10^4 bursts per day over the entire sky [49, 50]. The underlying sources are presently unidentified and could be due to exotic phenomena occurring at cosmological distances or to less exotic but still extreme objects, such as NSs in star-formation regions or in the centers of relatively nearby galaxies. The number of detections to date is limited by the inherent small fields of view of large telescopes. A larger number will allow a better understanding of the burst amplitude distribution and increase the prospects for better localization by using Arecibo detections to trigger imaging telescopes (e.g. the VLA and possibly low-frequency arrays). FRB121102, discovered in the PALFA survey, was the first event from a telescope other than Parkes [51]. More importantly, recent reobservations of FRB121102 using the ALFA receiver have revealed more than ten new bursts from the same source [52]. The sensitivity of Arecibo reveals individual spectra that show an astonishing variability relative to the initial detection [Figure 2 (left)] that is intrinsic to the source. This re-discovery has ruled out models for this FRB that involve cataclysmic events such as supernovae or γ-ray bursts. Other recent work [53] has demonstrated that one FRB came from a region with magnetoionic properties (dispersion and Faraday rotation) like those of a galaxy disk, suggesting association with star-forming regions. These empirical results are consistent with a picture where FRBs generally are emitted sporadically from the large population of extragalactic NSs, but multiple source classes may be involved.

Despite its discovery of FRB121102 in the Galactic anticenter direction, the PALFA survey is suboptimal for FRB detection because it has concentrated on inner Galaxy directions where bursts are heavily broadened by interstellar scattering. Large samples of FRBs with a large-reach instrument are needed to elucidate their spatial and luminosity distributions. The FRB detection rate scales as the product of exposure time, solid angle, and the cube of the "reach" along with a sensitivity factor dependent on the scattering broadening of pulses. ALPACA's survey speed makes practical a high latitude survey where Galactic scattering is minimal. ALPACA will have nearly uniform gain across its field of view, making reobservations of FRBs much more robust, not having to work around gaps and sidelobes of an ALFA type system (Fig. 1).

ALPACA FRB Yield: Depending on the unknown luminosity and spatial distributions of FRB sources, an ALPACA survey could detect a large number of FRBs. We calculate this number by scaling from the empirical burst rate $\Gamma_b(>\ 1\ \mathrm{Jy}) = 6^{+4}_{-3} \times 10^3$ sky^{-1} day^{-1} [54, 55] and a power-law flux-density (S) distribution $\propto S^{-\alpha}$ with indices $\alpha = 2.5$ to 3.5, which encompass that expected for a uniform population in Euclidean space (3.5) and, alternatively, the distributions seen for giant pulses from the Crab pulsar [56]. For ALPACA's aggregate solid angle (0.065 deg^2) and a 10σ detection threshold of 70 mJy, numbers range from 20 to 300 FRBs per 1000 hr of survey time for $\alpha = 2.5$ and 3.5, respectively. Since ALPACA surveys are likely to comprise several thousand hours, including a good fraction at Galactic latitudes $\gtrsim 10^\circ$, a conservative sample of more than 100 FRBs may result. ALPACA will provide information crucial for understanding the nature of FRBs and for utilizing them as tools for studying ionized gas and magnetic fields (using ALPACA's polarimetry capability) along their propagation paths [57], which likely include the intergalactic medium and any host or intervening galaxy.

Near-Field HI 21 cm Line Cosmology: Over the last decade, the HI 21-cm line surveys undertaken with

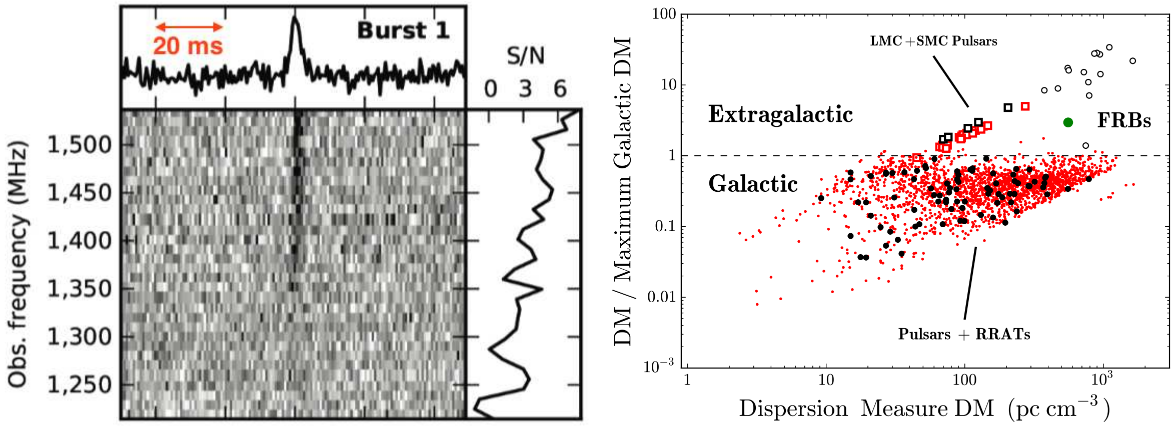


Figure 2: Left: Frequency-time plot for FRB121102 discovered at Arecibo in the PALFA survey [51] shows the averaged time series in the top panel and the spectrum in the right subpanel. Subsequent redetections show that the spectral shape is highly dynamic. Right: Dispersion measure of Galactic and extragalactic objects relative to the maximum possible DM in each source direction (from the NE2001 Galactic electron density model [58]). Pulsars (red points), RRATs (rotating radio transients, black circles), and FRBs (open circles) are labeled. The green circle denotes the FRB discovered in the PALFA survey and recently found to be the first repeating FRB. ALPACA surveys can detect large numbers of Galactic pulsars (with gems such as NS-NS and NS-BH binaries), MSPs for GW detection, and potentially 100 or more FRBs.

the ALFA receiver have greatly advanced our understanding of the HI-bearing extragalactic population. Over the next years, the SKA pathfinder interferometric arrays ASKAP, MEERKAT and WSRT/APERTIF, will begin conducting their planned HI surveys [59]. As shown by [60], the large collecting area of Arecibo continues to offer the best advantage for detecting significant numbers of low mass systems in the *local* Universe, where confusion is not important and the lack of resolution is actually an advantage: the full flux detection and superior column density sensitivity of a large single dish make straightforward the statistical corrections needed to measure the faint-end slope of the HI mass function and the discovery of the low surface brightness, low metallicity, star-forming galaxies which dominate the extragalactic population.

According to the ΛCDM paradigm, dark matter mini-halos with masses less than $10^9\ M_\odot$ should exist in large numbers in the local Universe. While the ΛCDM cosmology is extremely successful in describing the overall evolution of cosmic structure, the failure of current observational results to detect its predicted large numbers of “satellites” remains a challenge. Although the number of known satellites of both Andromeda and the Milky Way has increased dramatically in recent years, the number with circular velocities of 20 km s^{-1} or smaller remains too low, and in fact, has led to recognition of the “Too Big To Fail” problem [61]. While environmental processes can explain the dearth of stars and gas in small halos by their interaction with a large galaxy’s hot corona, it is much harder to explain the kinematic mismatch between the smallest galaxies and their host halos in the field [62–64]. In fact, the occupation of low mass ($< 10^9\ M_\odot$) halos by visible galaxies is poorly constrained [65], and the observed luminosity and velocity functions fall well below the predictions of ΛCDM. Because accurate distances to nearby systems cannot be derived from the HI data alone, an optimal approach is to derive and then compare the faint end slope of the HI mass function in other very nearby local volumes. At distances of 5-10 Mpc, dwarf systems can be differentiated kinematically from galactic and perigalactic phenomena, thereby allowing a direct estimate of distance without the detection of stellar counterparts. A future deep ALPACA HI survey can test the ΛCDM galaxy formation paradigm in predicting large numbers of small halos in both galaxy groups and in voids [66]. If they exist, are they detectable through the emission of their remaining neutral gas baryons? And can we trace the predicted impact of local environment on the ability of a galaxy to retain its baryons?

In addition to providing direct measures of the HI gas mass and recessional velocity, HI line surveys yield velocity widths which, in combination with optical/IR imaging, allow construction of the baryonic Tully-

Fisher relation (BTFR). Since disk rotation is intimately linked to the host dark matter halo, the BTFR places strong constraints on galaxy formation models and serves as a valuable tool for measuring distances and peculiar velocities in the local Universe. A wide area, deep HI survey which samples the volume needed to look for the lowest mass halos will also provide a rich dataset to explore other important cosmological suggestions:

- At intermediate masses ($\sim 10^{8-9}\ M_{\odot}$), preliminary results from ALFALFA [67, 68] suggest a steepening of the HI mass function along the filamentary cosmic web that is not simply a reflection of the overdensity of galaxies or of their location in groups. There is also a suggestion that filaments may host a population of modest baryonic mass but optically "almost-dark" [69, 70]. A deep sampling of galaxies along the prominent Coma-A1367 (z = 0.025) and Pisces-Perseus (z = 0.018) supercluster ridges would provide the needed observational challenge to numerical simulations which incorporate astrophysics to map galaxies onto their dark matter halos.
- A vastly improved BTFR dataset centered on those same supercluster ridges, both of which are nearly in the plane of the sky and delineated by foreground and background voids, would permit a definitive measurement of the mass overdensity along the two filaments [71], yielding an observational constraint to simulations of local large scale structure [72, 73].

The three scientific aims — (1) to discover the HI population at the lowest masses, (2) to establish the imprint of the cosmic web on galaxy evolution and (3) to measure the mass density along the Coma-A1367 and Pisces-Perseus filaments — can be accomplished through a *single legacy ALPACA HI survey*. Because of its combination of Arecibo's huge instantaneous sensitivity with the mapping speed of ALPACA, such a survey would reach greater depths and cover substantially more volume at the lowest masses than any proposed SKA pathfinder HI survey. Based on the success of the ALFALFA extragalactic HI survey in its achievement of observing efficiency, data quality, community engagement and scientific productivity, a legacy ALPACA HI survey would be undertaken as a broad community open-collaboration effort and would exploit a similar meridian drift scan technique (delivering $> 97\%$ "open shutter" time). An allocation of some 4000 hours over 4 years would yield a survey of $>$1200 square degrees (split equally between the fields of the two superclusters) to a sensitivity of 0.5 mJy (about a factor of 5 better than ALFALFA) at 10 $\mathrm{km\,s^{-1}}$ resolution plus a deeper survey to $\sim$0.3 mJy over a smaller sub-field of $\sim$100 square degrees centered on a known very nearby overdensity ($<$ 10 Mpc) such as the NGC 672/784 cloud [74–76].

The Search for Extraterrestrial Intelligence (SETI): Advanced technologies exhibiting large physical extent, large energy usage, or large inherent luminosity, have been shown to be detectable at interstellar distances, and can thus be used as a proxy for determining the prevalence of intelligent species in the Universe [77]. Radio emission from communication technology is a particularly attractive signature of intelligent life for several reasons, including the relative transparency of interstellar space to cm-wavelength electromagnetic radiation, the ubiquity of radio emission associated with terrestrial technologies, and the sparsity of natural sources of radio emission that are very narrow band ($\sim$ 1 Hz) or regularly modulated.

SETI programs have a long history at the Arecibo Observatory, extending at least as far back as the early 1970s [78]. More recently, the dominant paradigm for SETI observations at Arecibo has been commensal observing, in which SETI signal processing systems receive a duplicate of the analog IF output from an in-focus receiver, along with a stream of metadata describing the telescope state, and perform a SETI search independently from and without interference of the primary observer [79]. Commensal SETI observations using ALPACA will be accomplished in a similar manner, with digital copies of calibrated beams replacing the analog IF output. The SETI digital backend will be built and operated separately, in order to provide the very high time and frequency resolutions necessary to search for signals of interest. SETI observations will be conducted commensally with virtually all other ALPACA users. Data products produced by SETI observations with ALPACA will be amenable to citizen science projects such as SETI@Home.

The Breakthrough Listen Initiative funded through the Breakthrough Prize Foundation has produced great interest in a comprehensive SETI survey program. While nominally involving the Green Bank Telescope and the Parkes telescope in Australia, along with an optical program, a parallel program at Arecibo also is of great interest. SETI observations conducted commensally with ALPACA surveys would be highly complementary to the Breakthrough Listen surveys with the Parkes and Green Bank telescopes. Like transient astrophysical sources, any ETI source will vary, if not intrinsically, then by modulations from interstellar scintillation [80, 81] so multiple passes over objects and sky regions are needed to reach targeted sensitivities and probe for intermittency. SETI searches thus operate very effectively as commensal projects, covering much of the sky several times while operating alongside many different primary observers. To ensure that this scientific goal is well served in the ALPACA project, Dan Werthimer and Andrew Siemion, Co-Directors of the U. C. Berkely SETI Research Center and recipients of the Breakthrough Listen Prize, are included on the project team as advisors.

3 Instrument Description

The ALPACA instrument consists of two main components, a front-end cryogenic phased array feed (PAF) camera and the back-end digital beam forming receiver. ALPACA's operational specifications are presented in Table 2.

The overall architecture design of the ALPACA system is shown in Fig. 3. The main components include: the cryostat front-end camera, a room-temperature post-amp section, a 0.610 km RF-over-fiber optics link, an analog down-conversion section and the digital receiver back-end. There are 160 channels (from 80 dual-polarization dipoles) at the output of the camera. Each dipole/LNA package includes provisions for multiplexed noise injection signals for calibration of individual elements. We also foresee having signal injection points at the post-amp and down-conversion sections for signal path integrity test and channel phase equalization prior to digital conversion. The front end bandwidth is 440 MHz at L-band, of which only a bandwidth 312 MHz will be selected in the down-conversion section for analog-to-digital conversion.

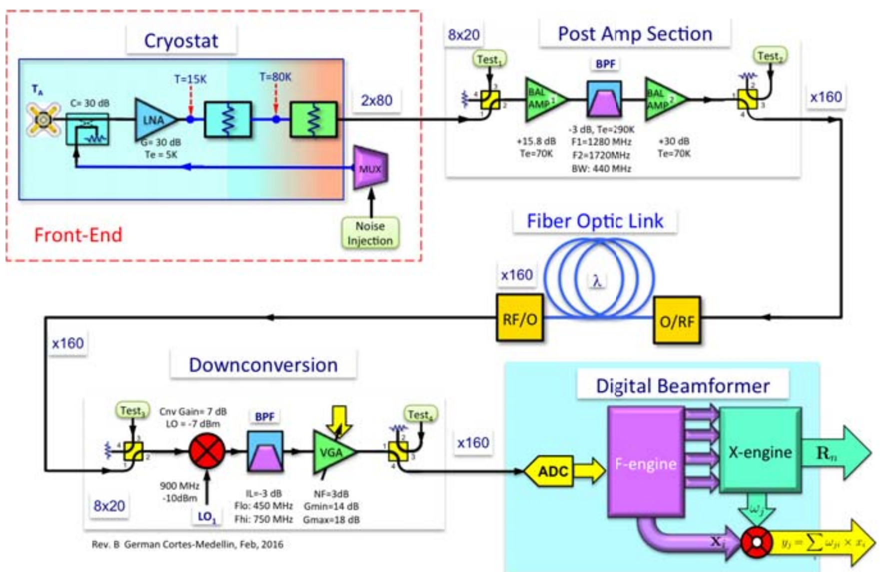


Figure 3: The overall architecture of the proposed ALPACA instrument.

Front-end System: The ALPACA cryo-PAF camera consists of 80 dual polarized dipole array elements (160 channels total) [3], with associated low noise amplifiers and noise calibration injection system, all housed inside a 1.42 m diameter $\times$ 0.6 m height cryostat, (Fig. 4, *Left*). The array will have four times the number of elements of our initial prototype [2], which was successfully designed and deployed from 2011 to 2013. The cryostat has a radio-transparent high density polyethylene (HDPE) vacuum window with a unique top-hat dome design, with 5 mm thick walls. The dome structure is internally supported by three layers of Rohacell foam, which are also transparent at L-band. Four CTI 1050 cold heads provide the thermal load lift in two stages: a 80 K thermal sink for the ground plane, and a 15 K thermal sink for the dipole/LNA modules inside the cryostat (Fig. 4, *Center*). A quarter-section view of the conceptual design for the cryostat that will house the array is shown in Fig. 4, *Right*. The lower foam layer, surrounding but thermally isolated from the 15 K dipoles, rests on the 80 K ground plane. When under vacuum, the 15 metric ton atmospheric load is transferred from the front window through the foam and the 80K first stage structure and to the back

Table 2: ALPACA instrument operational specifications.

Number of dual polarization beams	40
Rotator	± 15 deg specification
System temperature	specification < 35 K, goal < 30 K
Beam spacing	2 arcmin, close to Nyquist spacing but selectable within FOV
Frequency range	1280 MHz to 1720 MHz (determined by RFI issues)
Total bandwidth	440 MHz
Input BW to beam former	312.5 MHz (selectable within the 440 MHz band)
Coarse channels per polarization	800
Coarse channel BW	$\sim$390.6 kHz (dictated by fast burst searches)
Fine individual channel BW	12.2 kHz for HI in external galaxies
Fine channel overall bandwidth	150 MHz max, scalable for channel bandwidths finer than 12.2 kHz
Sample rate (coarse spectrometer)	64 usec (for pulsars and FRBs)
Sample rate (fine spectrometer)	> 0.1 sec (for spectroscopy)

of the cryostat via G10 support tabs.

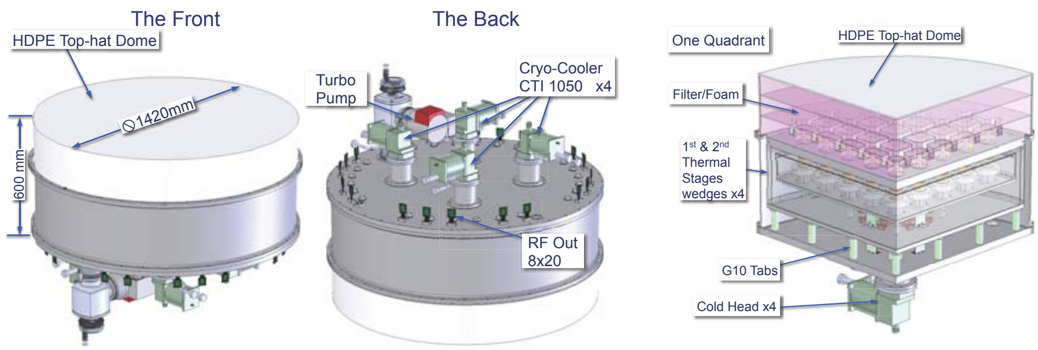


Figure 4: *Left*: Front perspective view of ALPACA cryostat with HDPE top-hat dome vacuum window. *Center:* Back perspective view of ALPACA with the four CTI 1050 cold head needed to provide the 80 K and 15 K thermal sinks. *Right*: A cutaway schematic of one quadrant of the ALPACA cryostat showing the inner structure of the top-hat dome, the Rohacell foam layers, the dipoles (20 out of 80), the 80 K and 15 K (quadrant) independent thermal stages and the G10 thermal isolating tabs supporting the frame of the 80 K first stage.

Figure 5: *Left*: Successfully tested shield-modified AO-19 cryo-PAF with the HDPE top hat over the three layers of Rohacell foam. *Center*: Shield-modified AO-19 cryo-PAF after removing the three layers of foam above the dipoles and the HDPE top-hat dome. *Right*: Manufactured Top-hat dome made of fused HDPE, shown here filled with ROHACELL foam. Lower layer shows the dipole's cut-outs.

This technique for supporting a very large window without any metallic dewar walls (which otherwise would distort the dipole radiation patterns) down to the ground plane of the dipoles, was successfully demonstrated with a 70 cm diameter window of identical design on the AO-19 prototype phased array feed shown in

Fig. 5. On the *Left* we show the modified AO-19 prototype completely assembled; in the *Center* panel we show the cryostat after removing the top-hat dome and three layers of foam, and on the *Right* we show the HDPE top-hat dome filled with the three layers of Rohacell foam, and the dipole's cut-outs in the foam.

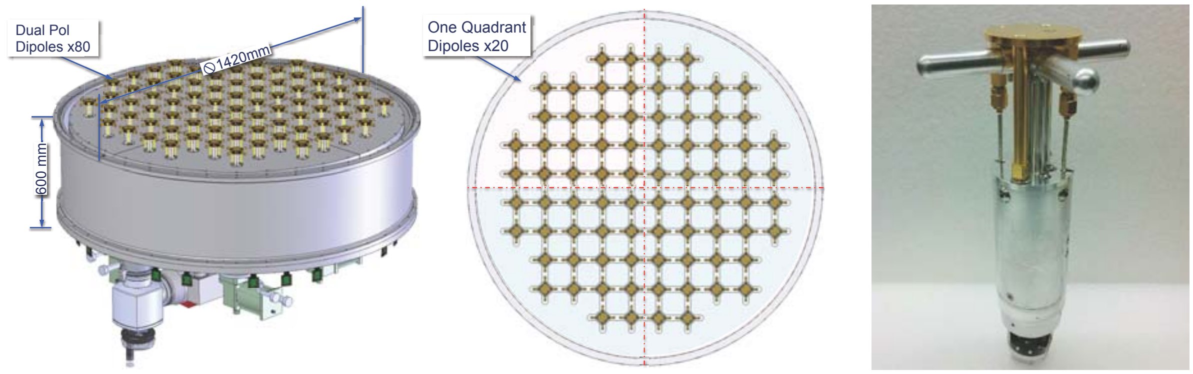


Figure 6: *Left*: View of ALPACA's 80 dipole array over the 142 cm diameter ground plane. *Center*: Front view of the 80 dipoles indicating the 4-fold symmetric square grid layout 20 dipoles per quadrant, fully sampling Arecibo's available FoV. *Right*: Dipole/LNA re-insertable package, each cylinder contains two LNAs. The press fit connectors are at its base.

The heart of the instrument is the 80 dual-polarization dipole element array and the cryo-LNA (low noise amplifiers) cylinders in close thermal contact with the 15 K second stage (Fig. 6, *Left*). The dipoles are distributed on a 4-fold symmetric square grid (Fig. 6, *Center*) inside a 122 cm diameter circle, allowing full sampling of the entire available FoV of the Arecibo telescope at L-band. The dipole/LNA assemblies (Fig. 6, *Right*) have press fit connectors at their base allowing them to be relatively easily replaced from the front of the camera by removing the top hat dome and foam layers after warming the cryostat.

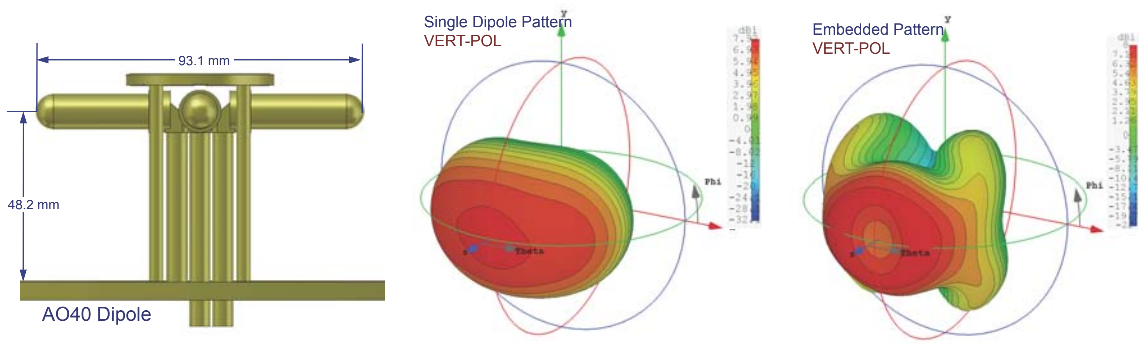


Figure 7: *Left*: Modified Sleeve Dipole dimensions. *Center*: Far Field pattern of a single dipole over a ground plane (VERT Pol, 1.4 GHz). *Right*: Far field radiation pattern of the dipole embedded in the array (calculated here with a 20 dipole-array on a square grid layout, at 1.4 GHz, VERT Pol).

The array elements are modified sleeve dipoles specially designed for cryogenic operation with dual polarization and a balun to connect directly to a 50 Ω SMA connector. The dipole dimensions (Fig. 7, *Left*). are tailored to have an input match better than -12 dB at the target band of operation from 1.28 GHz to 1.72 GHz. In Fig. 7-*Center* we show the calculated far field radiation pattern of a single dipole over a ground plane at 1.4 GHz, for vertical polarization, with a directivity of 7.9 dBi (over isotropic). When the dipole radiates within the array, the pattern is modified by the neighboring elements, and is then called the element embedded pattern. Fig. 7-*Right* shows the calculated embedded far field pattern of the ALPACA dipole on a square grid layout, with a calculated directivity of 8.0 dBi at 1.4 GHz and vertical polarization.

The high sensitivity of the instrument we are proposing depends on the operation of the dipole/LNA assembly at very low cryogenic temperatures. Extensive and detailed FEA thermal modeling of the top-hat dome and Rohacell foam vacuum window and dipole assembly has been implemented. The conduction through

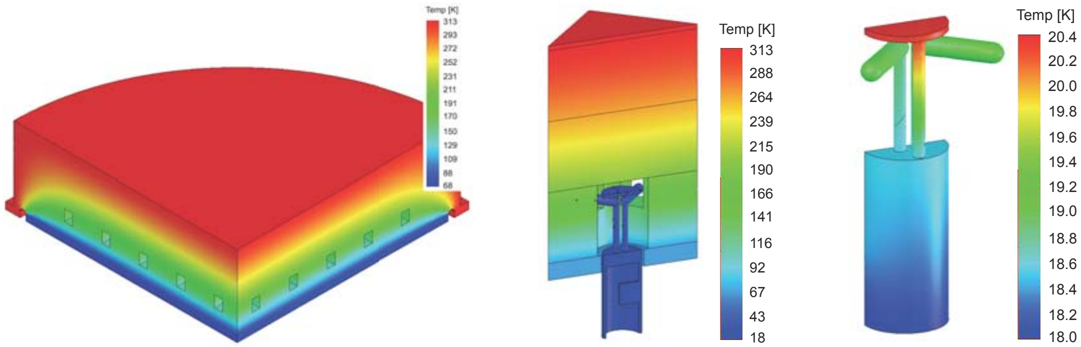


Figure 8: *Left*: FEA Thermal model for the front section of one quadrant of ALPACA. *Center*: FEA Thermal model for a 1/2 dipole-cell, including ground plane, foam, HDPE top, dipole, dipole cylinder and LNA mounting block. *Right*: The LNA heat load and radiative coupling between the dipole and the foam cavity results in heat flow to the 2nd stage, and a small temperature gradient along the dipole. Boundary conditions are outside 313 K, ground plane 68 K, and dipole sink 18 K. Maximum dipole temperature is equal to 20.4 K.

the foam dominates the first stage heat load, but given the size of the dewar window, the magnitude of the heat transferred is relatively low, Fig. 8, *Left*. Although there is no conductive load from the foam to the dipoles, the radiative load is a significant fraction of the total load on the second stage, exceeding even the waste heat from the LNAs by nearly 20%, Fig. 8, *Center*. However, due to its careful design, the dipole temperature does not rise significantly above its sink temperature, ensuring the LNAs function at or below their operating temperature (Fig. 8, *Right*). Preliminary results predict the variation in LNA base temperature will not vary by more than ± 0.2 K across the entire ALPACA instrument.

The cryostat is supported on the rotary floor of the receiver room of the Gregorian dome of the 305 m Arecibo telescope (Fig.9), with the dipole's ground plane at the focal plane of the telescope. The instrument is the maximum size that will fit within the radial support members of the rotary floor. Fig. 9, *Left* shows a simulation of the ALPACA instrument mounted under the rotary floor of the Arecibo radio telescope, indicating the relative position of the I-beams that constrain the instrument envelope. The instrument will include a mechanical rotator with $\pm 15^o$ range to track the changing parallactic angle during typical observations. Fig. 9, *Right* shows a view from the top of a concept for mounting the cryostat on the Arecibo rotary floor with an integrated rotator. The mount is a truss structure that provides a stiff, light-weight support for the instrument. The slew ring, an off-the-shelf component, is a self-lubricating, low- friction sliding element capable of handling very high loads in all directions. Two motor-gearbox units are used to take out system backlash and drive the slew ring gear.

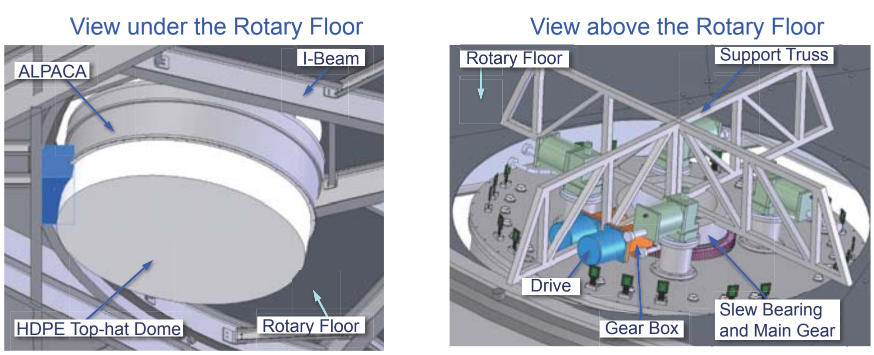


Figure 9: *Left*: View (under) of ALPACA mounted on the rotary floor. *Right*: ALPACA mount concept shown installed on the rotary floor. For proper focus, the cryostat must sit almost entirely below the floor plate surface. A truss structure transfers the instrument weight directly to the rotary floor I-beams. A $\pm 15^o$ instrument rotator couples the cryostat to the truss. Drive motors are blue, gearboxes orange, and slew bearing with integrated gear is purple.

3.1 Digital Receiver Back End

The ALPACA digital back end system incorporates the following processing functions [82]:

1. *Multi-port frequency channelization:* For each of the 160 antennas in the array, the full bandwidth signal is processed with an FFT-based polyphase filter bank into many separate frequency channels.
2. *Array covariance estimation:* This critical real-time function estimates the inter-element array covariance matrix for each frequency channel, and captures phase and gain relationships including mutual coupling across all pairs of antennas for response to signal of interest, noise, and RFI.
3. *Array beamforming calibraion:* Re-calibration must occur periodically to account for relative electronic drift across the $N = 160$ (80 dual pol.) antennas, direction dependent ionospheric effects (particularly at low frequenceis), and elevation dependent changes in the noise field for sensitivity optimization [1,10]. Calibration uses the array covariance estimates formed on a regular grid of pointing positions toward a strong deep space calibration source. A calibration pointing is needed in each direction a beam is to be steered.
4. *Real-time beamforming:* Individual antenna signals are linearly combined per frequency channel to form a set of simultaneous on-sky beam response patterns as determined by the beamformer weights. Calibration data and beam response constraint criteria are used to calculate weights for each channel.
5. *Imaging:* With the ability to form grids of simultaneous beams on the sky, new modalities of snapshot imaging beyond conventional interferometric imaging are enabled. This includes single dish or station radio camera imaging. We have shown that these new approaches require special attention to field flattening, wide field effects, and mosaiccing [83, 84], which will be areas of focus.

Basic operation for each of these functions has been demonstrated for PAF arrays on ASKAP, Westerbork Apertif, and BYU's experimental single-dish platforms. Proposal team members and collaborators BYU, Cornell, and UC Berkeley CASPER have been leaders in developing PAF antenna arrays and large-N array processing hardware and algorithms for each of the above functions.

Existing correlators are not only inflexible, but also require long development lead times. For example, the ALMA correlator development spanned over ten years from conception to commissioning. More recently, extremely powerful but much more flexible radio telescope signal processing back ends are being built with a combination of FPGAs, 40Gb Ethernet switches, and high performance multi-core CPU/GPU workstations, an approach pioneered by the CASPER collaboration led by ALPACA team members Werthimer and Siemion. ALPACA PIs Jeffs and Warnick have used this CASPER development paradigm for the GBT FLAG and Arecibo AO19 PAF array projects. As an example of the flexibility of this approach, the GBT VEGAS pulsar search backend can switch between pulsar searching, coherent dedispersion pulsar timing or spectral line modes by reloading FPGA personalities and GPU software.

Functional Description:

High sensitivity PAF beams are formed by linearly combining outputs from all 80 dual polarization array elements in real time. This requires a digital back end with significant throughput and processing capability. BYU has previously developed a narrowband 20 MHz field programmable gate array (FPGA)-based real-time beamformer for engineering tests of PAFs on the GBT and Arecibo Telescope. The BYU – Cornell collaboration on this project began in 2010 and has involved two on-telescope field experiments at Arecibo with room temperature and cryogenic 19 element arrays, and two generations of digital back end acquisition systems. Fig. 10 [Left] shows the second of these, installed in the Arecibo receiver and feed cabin for data acquisition and beamforming tests which demonstrated the great potential of an Arecibo radio camera. These experiments showed that a PAF could operate very effectively in the radar RFI environment at Arecibo. PAFs are capable of forming adaptive spatial nulls to cancel RFI, a capability which has been studied extensively by the PIs, as discussed in Section 3.2 below (see e.g. [11].)

Currently, BYU is developing a 150 MHz BW L-band back end based on hybrid FPGA – GPU (graphical processor unit) real-time correlator and beamformer architecture to support a wideband 19 dual polarization element array feed for the GBT (FLAG, NSF award AST 1309832.) FLAG will have seven beams on the sky. Also in October 2015 BYU completed an observation campaign on the GBT with the World's first mm-wave phased array feed developed by U. Massachusetts. The BYU team provided the digital back-end

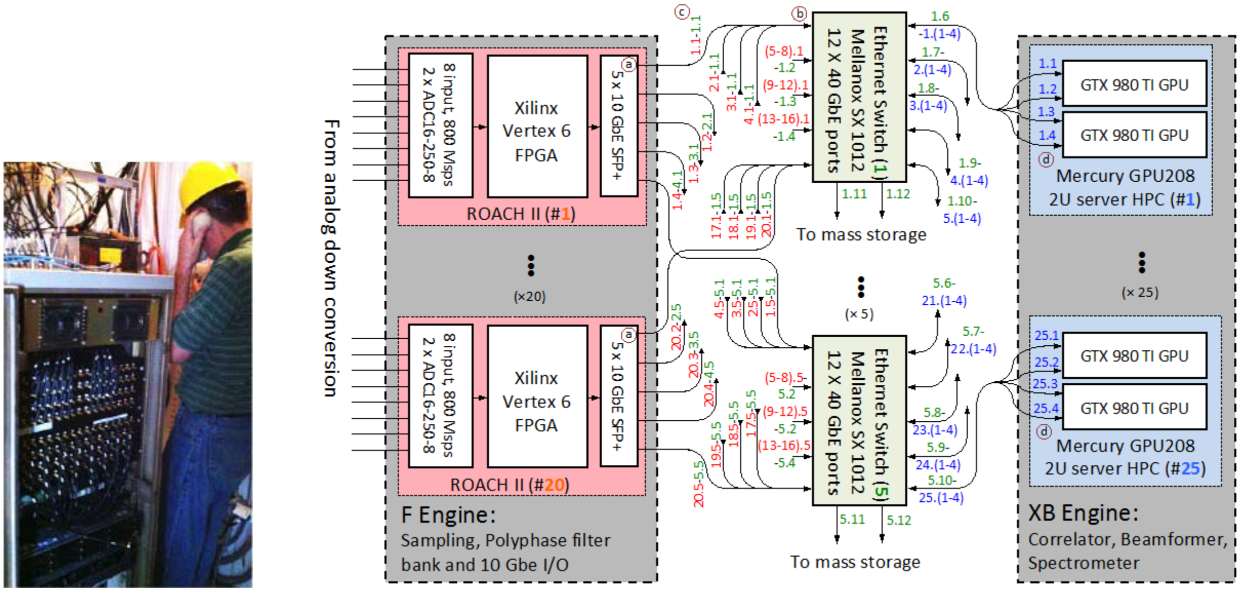


Figure 10: Left: AO19 digital receiver in the Arecibo receiver cabin dome, with PI Jeffs. Right: ALPACA Digital receiver back end hardware configuration.

system and post-processing correlator and beamformer (NSF award AST 1106218.) This prior work has thoroughly vetted and demonstrated critical functionality for the proposed ALPACA digital receiver design architecture, mitigates project risks, and places the current proposal on a strong foundation.

The full ALPACA LNA output bandwidth of 1280 MHz to 1720 MHz for *each* of the 160 antenna ports is transported after second stage amplification and filtering from the telescope's Gregorian receiver room to the control room via analog RF over equalized fiber links. There the RF signal is mixed to a lower IF frequency and bandpass filtered to 312 MHz BW by the analog down converter system, and routed to the digital receiver.

The digital receiver back end consists of two main subsystems: the sampler / frequency channelizer (or F-engine), and the correlator / beamformer (or XB-engine). Fig. 10 [Right] illustrates the hardware configuration for these subsystems, which both constitute large scale massively parallel digital signal processing units. Processing in the F-engine operates identically and independently per antenna input, across all frequencies. The XB- Engine operates identically and independently per frequency channel, across all antenna inputs. Data paths in each engine are ordered accordingly. Signal paths from the F-engine to the XB-engine pass through a 10 GbE network switch array which performs a large corner turn operation to re-order data packets from per-input antenna parallel ordering to per-frequency channel order for the XB-engine.

The F-Engine hardware architecture of Fig. 10 [right] employs 20 high-end ROACH II FPGA processors from the UC Berkeley Center for Astronomy Signal Processing and Electronics Research (CASPER) for sampling and frequency channelization. ALPACA team member Dan Werthimer is the director of this center, and he and team member Andrew Siemion have been the driving forces behind the development and wide adoption of the CASPER approach for astronomical signal processing.

The XB-engine includes 50 NVIDEA GPU parallel processors hosted in 25 high performance PCs. This architecture utilizes entirely off-the-shelf hardware components for development risk reduction. The hybrid FPGA/GPU approach to astronomical array signal processing has been used with great success in a number of new large-scale instruments, including the LEDA correlator, PAPER, CHIME, VEGAS Spectrometer, GUPPI, PUPPI, and BYU's current project for the FLAG PAF for the GBT. A significant existing body of both FPGA firmware and GPU code is available for the development effort, again reducing risk.

Figure 11 (left) illustrates the processing functions and signal flow for the XB-Engine, including real-time beamforming, coarse and fine frequency resolution spectrometers, and real-time array correlator. This processing flow is repeated for each of the 800 coarse frequency channels (each 391 kHz BW), indexed here by

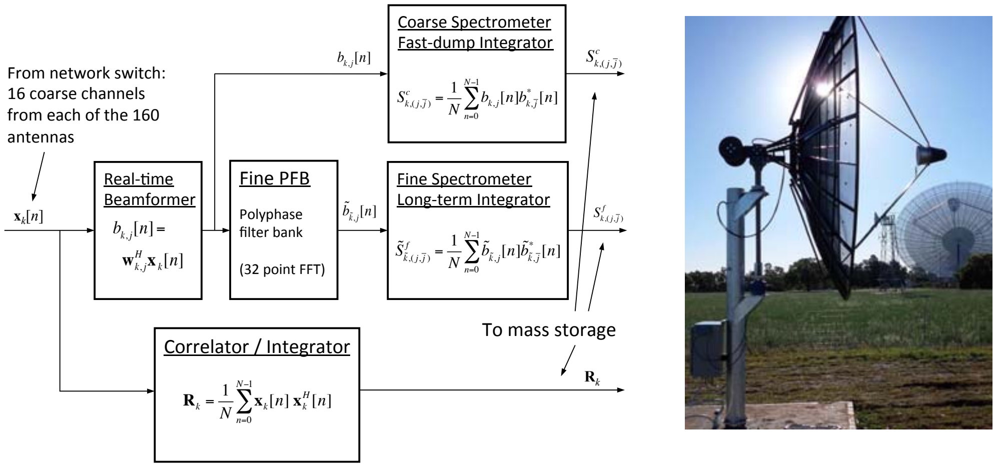


Figure 11: Left: Functional block diagram for the FB Engine, corrrelator, beamformer, spectrometer. Right: 3.7m auxiliary antenna at the Australian Parkes Observatory used for satellite tracking to produce deep beamformer nulls on moving RFI with an ASKAP BETA PAF array.

k. This architecture represents significant innovations in PAF back end processing:

i. The coarse channel and fine channel spectrometers can operate simultaneously with different integration dump times. This enables commensal high resolution spectral line studies (e.g. HI observations) and transient searches (e.g. FRBs.) The latter requires short integration times (order 100 μsec) for dispersion measure searching, while the former demands much deeper integration and a fine resolution second PFB stage for detection sensitivity.

ii. The correlator is used to compute array covariance matrices during periodic (e.g. every few weeks) re-calibration scans to update beamformer weights [5, 10]. Unique among existing PAF back ends, the ALPACA design can dump covariance matrices at a 10 msec rate. This enables rapid recalculation of weights using adaptive beamformer algorithms for null tracking of moving RFI sources (see Section 3.2.)

iii. Covariance matrices can be stored along with spectrometer outputs as standard data products. This enables after-the-fact post-processing beamforming. In this way, the observation data can be re-analyzed with new beamformer pattern shapes to study detailed object structures, correct a pattern defect, or suppress other dominant astronomical or RFI sources *after* the observation is made.

3.2 Radio Frequency Interference mitigation with the ALPACA PAF

In this section we will show how the ALPACA design enables new powerful modalities of RFI mitigation to mange the environment at Arecibo Observatory. The ALPACA team has long been a leader in developing RFI mitigation for PAFs [5, 82, 85–94].

RFI mitigation must be considered as an integral part of new astronomical instrument designs to maintain access to the radio spectrum for evolving scientific needs. This is particularly true at the Arecibo observatory where this world-class telescope does not have an effective radio quiet zone and must contend with a challenging RFI environment. The ALPACA design will provide advanced RFI mitigation capabilities which previously have simply been unavailable at other multibeam and PAF wide field of view search instruments.

3.2.1 RFI at Arecibo

The L-band RFI environment at the Arecibo Observatory (AO), like that at many other telescopes, can be challenging. We will discuss existing methods for managing RFI, and the new spatial canceling capabilities of the proposed ALPACA PAF instrument.

In addition to the typical RFI sources seen at all observatories (satellite downlink, DME aircraft navigation, etc.), Arecibo must cope with four L-band radar systems on the island: *i*. the FAA San Juan International Airport Common Air Route Surveillance Radar (CARSR) radar, 106 km from AO; *ii*. the Punta Salinas frequency agile military radar, 62 km from AO; *iii*. the Punta Borinquen CARSR radar, model ARSR-4, at the Ramey airport, 44 km from AO; *iv*. and the aerostat balloon platform radar at Lajas which is used for drug interdiction, approximately 45 km from AO.

These radars collectively operate on 17 frequencies ranging from 1228.5 to 1349.6 MHz, with pulse lengths ranging from 160 to 410 μsec, pulse repetition periods between 1.3 and 3.7 msec, and bandwidths from 1.0 to 1.7 MHz. The nature of this RFI is understood in detail and well documented at AO.

Current mitigation measures for the L-band ALFA multibeam receiver at AO include regular RFI monitoring and logging, data flagging, and a number of cooperative arrangements with radar operators. For example, the most commonly used pulse carrier frequencies are 1280 MHz and below. ALPACA is designed with a lower frequency range limit of 1280 MHz to avoid these. Also, the Punta Salinas radar uses agile frequency hopped waveforms over a wider spectrum, but there is a cooperative arrangement with AO. Coordination schedules specify when to limit operations to "mode A" waveforms, which keep carriers below 1280 MHz. And each of these radars operates cooperatively with AO by blanking transmissions over an angular sector of the periodic (typically 12 sec.) antenna sweep corresponding to the direction of the observatory. This blanking wedge significantly reduces peak direct path signal power.

However, often the strongest RFI signals at Arecibo and other observatories are actually from indirect aircraft echoes rather than the direct path from the transmitter. This problem is also seen at Green Bank, even in the radio quiet zone. An ASR-4 air navigation radar located 104 km from the GBT regularly causes problematic aircraft echoes in L-band. Such echoes are difficult for a conventional flagging algorithm because they are irregular moving sources which may be hard to flag when levels are below detection thresholds, but are yet strong enough to corrupt observations. We note that even with these RFI challenges, the ALFA multibeam receiver at AO has been very successful in the same band intended for ALPACA.

For pulsar and burst searches, analysis has typically relied on excision of RFI in processing pipelines. That will remain the case, but such surveys will benefit greatly from the dynamic range of ALPACA and on real-time mitigation measures, with due attention paid to the time scales of the astrophysical signals in comparison with RFI time scales.

To improve performance in this RFI environment, ALPACA will include three new capabilities which are not available on ALFA or most other telescopes:

i. Predictive Kalman tracking and Bayesian detection of aircraft radar echoes: When strong direct path and fixed clutter echoes are removed by data flagging, there are still undetected weaker aircraft echoes present which can corrupt the data. In [87] we presented an algorithm to improve real-time echo blanking by forming a Kalman filter tracker to follow the path of a sequence of bistatic radar echoes observed on successive sweeps, and predict the location of upcoming echoes. In [88] we introduced a Bayesian detection algorithm which uses this prediction to enable more sensitive weak pulse acquisition. Track information is used to form a spatial prior probability distribution for the presence of the next radar antenna sweep's echoes. Regions with higher probability are processed with a lower detection threshold to pull out low level pulses without increasing the overall probability of false alarm detection. The result is more complete removal of radar corruption in astronomical observations, as we demonstrated with real GBT data. Figure 12 illustrates improved echo detection performance.

ii. Increased dynamic range: In the presence of strong RFI, some stages in the receiver chain can be driven into non-linearity. This typically occurs in the first stage low noise amplifiers (LNAs), at the analog to digital converters (ADCs), or in the re-quantized digital network communications link between frequency channelization (F-Engine) and beamforming (XB-Engine.) This issue leads to a requirement for wide system dynamic range to pass both weak astronomical signals and strong RFI without saturation. Otherwise, intermodulation products, harmonics of out-of-band RFI, and distortion of the calibrated beamformer array response, can introduce what appears as new RFI spectral lines.

The ALPACA design carefully incorporates wide dynamic range principles throughout. Individual array element LNAs have excellent dynamic range for a cryogenic design, with 5K noise temperature, 0 dBm 1dB compression point, and 30 dB gain. The current ALPACA design uses 8-bit ADCs. With proper noise floor level setting, this should provide more than adequate dynamic range. However, by the end of 2016 we will have data from our GBT FLAG PAF back end which incorporates a similar F-Engine 8-bit ADC. With this

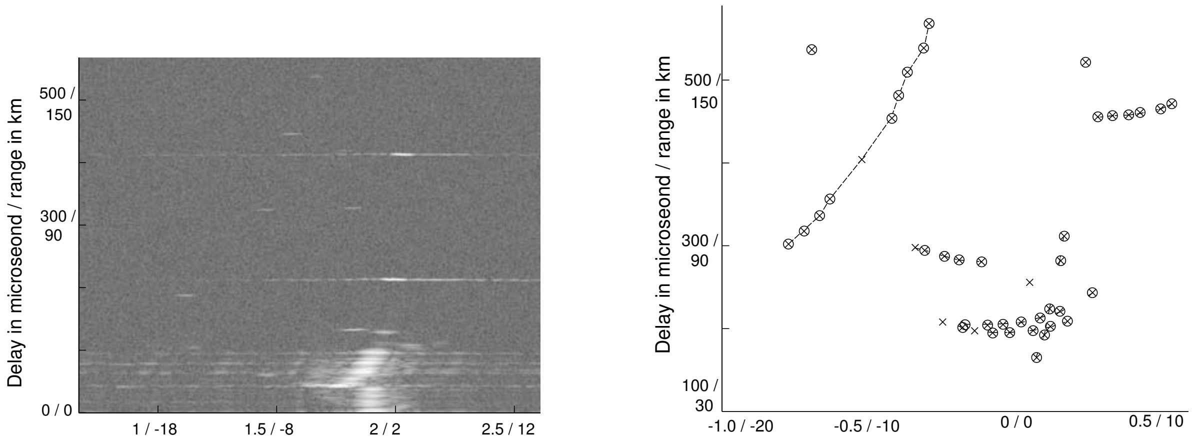


Figure 12: [Left] 1,292 MHz GBT data with ASR-4 radar echo RFI for a single transmit sweep. Windows of data corresponding to the pulse repetition rate are stacked in columns. Short range echoes are mountains surrounding GBT. All others are aircraft. Horizontal axis is (transmit antenna sweep time, sec.) / (azimuth angle, deg.) [Right] Corresponding Kalman filter tracks of aircraft echo detections. Conventional detections are marked $\circ$, and Bayesian detections are $\times$, which recovered 4 missed echoes.

real-world experience from FLAG we will make a determination whether we need to move to 10 or 12 bit ADCs on ALPACA. These components are currently being evaluated and will be incorporated as needed in the ALPACA design. Also, in most existing astronomical FPGA / GPU digital back end systems, the F-Engine to XB-Engine transport of frequency channelized data uses 8 bit complex quantization. In order to better handle RFI, the ALPACA design uses 16-bit complex quantization.

There is an inherent quantization and dynamic range advantage in a multi-sensor beamformer like ALPACA, as compared to a single antenna feed, even if both use the same ADCs. This principle was demonstrated in the early 1960s with DIMUS, the first digital sonar beamformer [95]. DIMUS used 1-bit ADCs, i.e. a simple saturating threshold circuit per array element. However, it performed with only a 1 dB SNR penalty as compared to theoretical full range continuous amplitude calculations in the beamformer. The magic is that it was essentially trading off bits of ADC quantization for a large number of sensor inputs for the beamformer. This effect is the mathematical dual of delta-sigma quantization methods used widely in high fidelity digital audio recording. The Super Audio Compact Disc (SACD) Direct Stream Digital format is an example of this. A 1-bit ADC is used, but the sample frequency is 2.82 MHz vs 44.1 kHz for CD. A high dynamic range (120 dB) is achieved by low-pass filtering ("spectral shaping") the 1-bit ADC stream and decimating [96]. The ALPACA beamformer will enhance dynamic range in the same way by "high frequency" spatial sampling with 160 closely space antennas rather than 1 horn feed, and narrowband directional filtering of the spatial wavenumber with the beamformer weighted linear sum.

Also, an active research area for PIs Jeffs and Warnick is adaptive beamformer performance in the presence of strong RFI which induces nonlinearities across the array. Our early results indicate that even in the challenging scenario where this causes out-of-band RFI to appear as harmonics and intermodulations in band, the adaptive beamforming methods described in Section 3.2.2 can still effectively null the RFI [90].

iii. Spatial nulling of RFI with array signal processing: The following Section develops the proposed ALPACA approach to provide this capability.

3.2.2 Adaptive Beamforming

With 160 elements in the PAF array, ALPCA is a consummate system for RFI spatial filtering, or adaptive canceling beamforming. The PAF digital receiver design in Section 3.1 will be the first large scale astronomical receiver of its kind with rapid array covariance dumps and beamformer weight update calculations. No other PAF (including ASKAP and Apertif) has this capability, but it is inherent in the ALPACA design. Since the dominant RFI sources are moving (e.g. aircraft echoes, navigation satellite downlinks) a canceling beamformer must be able to simultaneously form all beams in real time while: a) computing short–time–integrated (STI) covariance matrix estimates $\mathbf{R}_i$ for every ith STI, b) using $\mathbf{R}_i$ to compute updated beamformer weight vectors $\mathbf{w}_i$ to form tracking nulls, and c) uploading these new weights to the beamformer. All this must be done with a latency of about 100 ms. No existing PAF system can do this.

Unlike a fixed horn feed telescope, with a PAF, beamformer weights can be recomputed at any time to e.g. maximize sensitivity given the current noise environment or directly specify and control beam mainlobe and sidelobe patterns [10,83,97]. A set of these weights, one for each of the M array elements, are arranged into a vector $\mathbf{w} = [w_1, \cdots, w_M]^T$. Likewise the array complex baseband PAF output voltage vector is formed from the individual element voltages v_m as $\mathbf{v} = [v_1, \cdots, v_M]^T$ for each coarse frequency channel. The single channel beamformer output voltage sample v is given by

$$v = \mathbf{w}^H \mathbf{v}, \ \text{ where e.g. } \ \mathbf{w} = \mathbf{R}_\mathrm{n}^{-1}\mathbf{d} \tag{2}$$

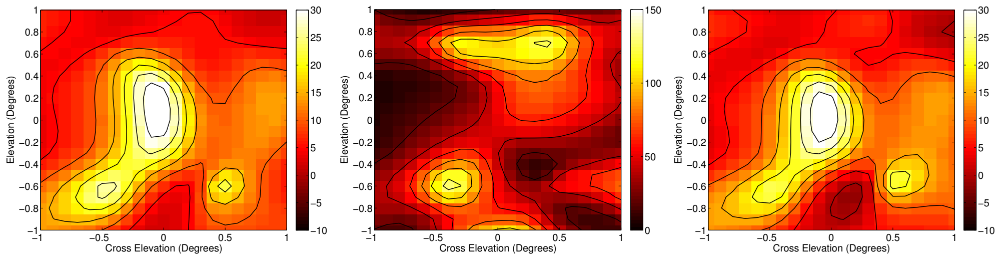
and $(\cdot)^H$ denotes vector complex conjugate transpose. The expression in (2) for $\mathbf{w}$ is the most commonly used basic narrowband maximum sensitivity beamformer. $\mathbf{R}_\mathrm{n}$ is the noise voltage covariance matrix as estimated by the real-time correlator during a previous beamformer calibration session, and $\mathbf{d}$ is the calibrated array response, or steering vector for a plane wave signal arriving at the dish from the desired beam pointing direction. A distinct weight vector, $\mathbf{w}$, is computed for each direction a beam is to be steered. These simultaneous multiple beam outputs can be combined to produce a radio camera snapshot image over the array field of view, with one beam per pixel (see Fig. 13.)

With PAFs one may use array signal processing algorithms to compute $\mathbf{w}$ so as to place nulls on interfering sources. The most fundamental challenge is that even relatively weak interferers, tens of dB below a receiver's noise floor, can destroy sensitive passive observations, yet are beyond the reach of classical variance minimization adaptive techniques such as LCMV and MVDR beamformers [98]. The "deep null" requirement for astronomical observations in the presence of RFI can be addressed using spatial filtering algorithms at the beamformer which are based on zero forcing subspace projection (e.g., [86, 89, 99].) An orthogonal projection matrix, $\mathbf{P}$, is formed such that it spans the vector subspace orthogonal to the estimated interference array spacial response vector, $\mathbf{d}$. If the interference is strong, $\mathbf{d}$ can be estimated as the dominant eigenvector, $\mathbf{u}_1$, of array covariance matrix $\mathbf{R} = E\{\mathbf{v}\mathbf{v}^H\}$, where $E\{\cdot\}$ denotes expected value and $(\cdot)^H$ is conjugate transpose. Beamformer equation (2) is then modified to

$$v = (\mathbf{P}\mathbf{w})^H \mathbf{v}, \ \text{ where } \mathbf{P} = \left(\mathbf{I} - \mathbf{u}_1\mathbf{u}_1^H\right). \tag{3}$$

This cancelation approach has been shown to be effective even when the RFI signal arrives at the PAF through the dish's deep sidelobes, with many multipath components, or as a scattered or diffracted signal. Interferer motion, weaker RFI source power, and system gain drift limit the achievable null depth. To overcome these issues, recent enhancements to orthogonal subspace projection include a bias correction algorithm [99] to restore the original beampattern on average, oblique projection which insures the SOI is not attenuated by projection operator $\mathbf{P}$ [100, 101], and cross subspace projection, which uses a smaller "auxiliary" antenna to track the interferer [86, 93, 94]. Figure 11 [Right] shows a 3.7m auxiliary antenna installed by PI Jeffs at the Parkes Observatory for experiments to track interfering Galileo satellites to improve beamformer canceling performance with the ASKAP 12m BETA PAF test platform telescope.

We have demonstrated the feasibility and exciting potential of array spatial filtering RFI mitigation with a 19 element PAF on the Green Bank 20 meter telescope. While observing the OH maser source W3(OH) at 1665 MHz, we created a moving FM-modulated RFI source by hand carrying a signal generator and antenna. The RFI bandwidth and power level were sufficient to entirely overlap and obscure the OH spectral line. RFI was effectively canceled using the subspace projection algorithm [99]. Images of the source with and without RFI mitigation are shown in Figure 13. The source which was completely obscured by interference is clearly visible when using subspace projection. By implementing the above techniques, we will significantly improve our ability to perform the fundamental science of this proposal and take advantage of the World's largest available single aperture, even in the challenging RFI environment at Arecibo.



(a) No RFI (b) With RFI (c) RFI canceled

Figure 13: W3(OH) image with and without RFI. The color scale is equivalent antenna temperature (K). The figures are "snapshot" PAF radio camera images made from a single dish pointing. A grid of 21 by 21 beams is formed from the PAF data, with each image pixel value being the signal power output of the beam steered in the corresponding direction.

4 Broader Impacts

The building of the ALPACA instrument and its availability on the Arecibo telescope will provide research opportunities for undergraduate and graduate students and have a significant beneficial impact within Puerto Rico.

Technology: The ALPACA instrument will be the world's first large fully cryogenic phased array feed system. Its success will represent a major technical advance that can be applied to a wide range of similar instruments for both single dish radio telescopes and interferometer arrays.

Student involvement: Three graduate students, two at Brigham Young University (BYU) and one at Cornell will be involved with the construction and testing of the ALPACA instrument with the one at Cornell also involved in pilot observations for RFI assessment and excision and pulsar and FRB surveys. Throughout the project, there will be opportunities for undergraduate involvement with the instrument construction, and each institution will continue practices aimed at involving a diverse group of students in the project:

The ALFALFA legacy extragalactic HI survey will be undertaken by a broad community collaboration, in the style of the previous surveys of HI with ALFA. The Arecibo ALFALFA survey of HI in external galaxies (PIs Riccardo Giovanelli and Martha Haynes, Cornell) utilizing the 7-horn ALFA system installed in 2004, involves about 40 universities and colleges including many undergraduate institutions. Much of the undergraduate involvement is through the 19-institution Undergraduate ALFALFA Team (UAT), separately funded by the NSF (PI Becky Koopman, Union College). Almost 500 undergraduate students, 33% women, have had the opportunity to visit and/or observe with the Arecibo telescope or to conduct research projects centered on the ALFALFA survey. The UAT program also includes professional and career training sessions as well as tutorials in common-use software packages and environments and has had proven success (through its assessment program) in steering students, particularly at smaller and/or less research-oriented institutions, into STEM careers and graduate education.

The UAT collaboration continues to educate, train and engage students and faculty in research and technical development which will lead naturally to the ALPACA HI survey. Current activities include a group pilot program to detect infall into the Pisces-Perseus supercluster using the single pixel L-band wide system. Undergraduate students and their faculty mentors are engaged in selecting targets from public photometric databases, conducting the observations (both at Arecibo and remotely from their home institutions), reducing the HI spectra, writing software, and performing the analysis. As ALPACA is developed, the UAT program will develop modules, activities, software and databases relevant to undergraduate participation and understanding of the ALPACA PAF system and strategic design of the next generation HI survey with it.

Similarly, the pulsar and FRB searches with ALPACA will build upon the involvement of many graduate and undergraduate students with the PALFA Consortium that conducts a large scale pulsar and transients survey (PI Vicky Kaspi, McGill, Co-PI James Cordes, Cornell) which is laying the foundation for the ALPACA pulsar and FRB surveys. Many of the undergraduate students were involved through the Arecibo Remote Command Centers (ARCCs) at the University of Texas at Brownsville, the University of Wisconsin at Milwaukee, and Franklin and Marshall College. Other ARCCs are in the planning stage.

Citizen science: Two programs with the Arecibo telescope involve the larger community in research, Einstein at Home, where anyone can participate in the search for pulsars with data from Arecibo, and SETI at Home, where anyone can be involved with SETI searches utilizing data from Arecibo. Both of these programs will benefit from the use of the ALPACA instrument on the Arecibo telescope.

Puerto Rico: The Arecibo Observatory is the major research center in Puerto Rico, a resource for student training and community education through its Visitor Center, and a source of jobs in the local community. Like any research facility, the observatory's longevity is dependent on remaining at the forefront of its research areas and this can only be achieved by continual improvement of its instrumentation. The 7-horn ALFA system installed in 2004 and used for many large scale surveys revitalized the observatory's radio astronomy program. The ALPACA instrument with almost 5 times the sensitivity of ALFA will do the same to the long term benefit of astronomy, the Observatory and the people of Puerto Rico.

4.1 Student Training and Workforce Diversity

Student training, both undergraduate and graduate, have been central to research in the Cornell pulsar and transients group and the NANOGrav and PALFA collaborations that Cornell is part of. Undergraduates have developed quicklook software tools for investigating raw data and data products relevant to assess data integrity and to compute initial science-format data products. Undergraduate have also developed algorithms and software for excising radio frequency interference (RFI) and for detecting astrophysical transient sources. In the ALPACA project, we will continue this modus operandi by engaging undergraduates (through work study, independent research with course credit, and summer research) to work on commissioning data from ALPACA for RFI mitigation for ALPACA's specific situation along with characterization of data integrity and early detections of test pulsars. Cornell will also work with our partners, in particular the ARCC (Arecibo Remote Command Center) programs at NANOGrav member institutions that organize observations of pulsars by undergraduates.

The BYU group will continue a mentored research environment structure that involves senior graduate students advising undergraduate research assistants on the project. Undergraduates will also receive advisement on applying to graduate school and help in preparing applications for prestigious national fellowships. The radio astronomy application is a strong draw for students with diverse gender and ethnic backgrounds.

Students have also been a key part of the HI surveys at Arecibo, through the Undergraduate ALFALFA Team (UAT) and the Research Experience for Undergraduates program at the Observatory. The UAT has involved over 250 undergraduate students, more than a third women, in HI research projects, including a number of Hispanic students from the University of Puerto Rico. The ALPACA extragalactic HI survey will give an opportunity to continue this student engagement in the future.

4.2 Benefits to the Community

The ALPACA instrument will be an open user access instrument on the 305 m Arecibo telescope and available to the entire astronomical community based on the Arecibo Observatory's normal proposal and review procedures. Within its usable frequency range, Arecibo is still by far the most sensitive single dish radio telescope in the world and its collecting area far exceeds that of any existing interferometer system. The 7-horn L-band ALFA instrument installed on Arecibo in 2004 and the subsequent surveys demonstrated the advantages of multi-pixel systems for surveys especially when coupled with a very large telescope aperture (e.g. The ALFALFA extragalactic HI survey (86 published or submitted papers to date) and the PALFA pulsar survey (163 new pulsars discovered)). With its 40 beams, the ALPACA instrument will have almost five times the survey speed of ALFA. The Scientific Justification section highlights several areas of high impact survey science of specific interest to the proposers but many other surveys will also be of great interest to the community (e.g. galactic OH, high redshift HI and OH).

5 Results from Prior NSF Support

Warnick and Jeffs (BYU) "Collaborative Research: Wide-Field L-band Focal Plane Array Beamformer for Pulsar, Diffuse Hydrogen, and Fast Transient Surveys on the GBT" AST-1309832, 09/01/2013 - 08/31/2016,

$453,656. **Intellectual merit:** This project is creating the first cryogenic phased–array feed for the Green Bank Telescope, as well as developments in RFI spatial filtering and beamforming for PAFs. **Broader impacts:** phased-array feeds offer the possibility of radio frequency interference cancellation using adaptive spatial filtering, which will allow more efficient use of the radio spectrum and enable better integration of passive and active radio services. Research results are incorporated in coursework material and students with diverse backgrounds have been involved. The PIs are collaborating with Cornell University to extend the results of this project to a PAF receiver for Arecibo. **Products** include [1, 83, 93, 102–106].

Cordes: "Collaborative Research: Einstein@Home," NSF PHYS-1104617, 10/01/2011–09/30/2016, $470,430. The project is a collaboration between Cornell (Cordes), UC Berkeley (Anderson), and UW Milwaukee (Allen, Siemens) to provide and process data for the Einstein@Home project from the Pulsar ALFA Consortium. This citizen science project contributes data and software to volunteers from around the world who provide local computer resources for analyzing LIGO and Arecibo pulsar data to search for gravitational waves and radio pulsars. The Cornell portion of the project manages data obtained at Arecibo for the Pulsar-ALFA project that is surveying the Galactic plane for new pulsars. For Einstein@Home they are transported by 10 Gb/s network to the Albert Einstein Institute in Hannover, Germany for dissemination to volunteers. The PALFA project has discovered 163 new pulsars including 22 millisecond pulsars (MSPs) and three double neutron star binaries. **Intellectual Merit**: Einstein@Home volunteers have discovered 31 new pulsars, including several binary pulsars that have warranted sustained followup observations. One of these is an MSP with a white dwarf companion in an orbit with sizable eccentricity, indicative of an unusual formation mechanism compared to the bulk of MSP binaries with highly circular orbits. **Broader Impacts:** The project is a portal to the astrophysics of neutron stars and their importance as objects in and of themselves as well as for testing general relativity and understanding late-stage stellar evolution. The citizen science project exposes worldwide volunteers to radio astronomy, gravitational wave astronomy, compact stellar objects and signal processing. Volunteers' results provide important research input to the gravtia-tional and radio astronomy communities working in forefront areas of astrophysics. The project illustrates the utility of distributed, volunteer computing to basic research and serves as a model for future data ana lysis on large aggregate data volumes from future radio telescope arrays. **Products:** New discoveries are listed at http://www.naic.edu/ palfa/newpulsars/. Publications include [41, 107–117].

Campbell was Co-PI on NSF AST/ATI award 1207727 in the amount $394,546 and covering the period 07/15/2012 to 06/30/2014. The project title was "Phased Array Feed: Development of a Cryogenic 19 Element System for Radio Astronomy" (PI: German Cortes-Medellin). Under the award a prototype 19-element cryogenically cooled L-band phased array feed (PAF) system was completed and successfully tested on the Arecibo 305 m telescope. **Intellectual Merit:** This was the first fully cryogenically cooled PAF and, as described in the proposal, the techniques developed, especially the very large 70 cm diameter vacuum window, are the basis for the 80 dual polarization element ALPACA instrument being proposed. ALPACA will significantly improve on the survey speed of the 7-beam ALFA system opening up possibilities for additional high impact surveys. **Broader Impacts:** The techniques developed in building the AO-19 cryogenic system will be transferrable to radio cameras at other wavelengths. New surveys enabled by ALPACA will involve large numbers of undergraduate and graduate students, continue "citizen science" activities through the SETI@Home and Einstein@Home programs, and revitalize the astronomy program at Arecibo to the benefit of science, the Observatory and Puerto Rico. **Products:** [2, 3].

Minchin is co-PI of the NSF-funded Arecibo REU program (AST-1262974, 04/01/2013-03/31/2016). **Intellectual Merit:** Based on observations at the Arecibo Observatory, students presented their work at conferences and four refereed papers (so far) draw on student research. **Broader Impacts:** 69% of students employed on the grant were from underrepresented groups (48% from underrepresented minorities, 35% women). Over 60% were from colleges and universities not classified as having high or very high research activity in the Carnegie Classification of Institutes of Higher Education, and over 70% came from public universities or colleges. **Products** include [118–121].

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