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CRYO-MECHANICAL DESIGN OF ALPACA: A MIXED-MATERIAL RADIO-FREQUENCY TRANSPARENT VACUUM VESSEL OPERATING AT 20 K

Stephen C. Parshley [a,1], German Cortes-Medellin [b], Amit Vishwas [c], Donald B. Campbell [a], Terry Herter [a]

[a] Astronomy Department, Cornell University, Ithaca, NY
[b] Aerospace Systems, Northrop Grumman Corporation, Redondo Beach, CA
[c] Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY

ABSTRACT

One of the most promising technologies to enable and enhance large survey capabilities for radio astronomy is the use of focal plane phased array antenna feeds, or more simply, phased array feeds (PAFs). PAFs allow for full and continuous coverage of the telescope's field of view (FoV), and combined with cryogenic amplifiers, can result in survey speed improvements several orders of magnitude better than current multiple-feed-horn cameras. In order to locate cryogenic PAF elements and amplifiers at the telescope focal plane, a radio-frequency transparent vacuum vessel is required. Unlike typical radomes, the transmission properties must be exceptionally good when dealing with weak astronomical signals. The dome must also be sufficiently strong to carry the mechanical load on the vacuum vessel due to atmospheric pressure. Furthermore, the thermal loading on the internal cryogenic stages from the dome must be manageable for the cooling system. We have solved these problems by using a combination of welded polyethylene sheet to maintain the vacuum integrity and a closed-cell rigid foam to transfer the mechanical load to the opposite side of the vessel (a welded aluminum structure). The PAF elements and amplifiers operate at 20 K, while the foam transfers the mechanical load through an 80 K temperature stage, which also serves as a low-temperature radiation shield for the 20 K sections. The poor thermal conductivity of the foam, combined with G10-CR thermal standoffs on the opposite side, ensures the 80 K stage is sufficiently thermally isolated from room temperature conduction. The radiative loading is reduced via the usual employment of multi-layer insulation. In order to facilitate instrument maintenance and future upgrades, a modular PAF element mechanical strategy is employed. The design is such that a PAF-element-amplifier unit can be replaced without accessing the 20 K stage owing to the use of a "cryo-clamp" that uses materials with different coefficients of thermal expansion to tightly hold the units when cold. Cooling is supplied by three two-stage Gifford-McMahon cryo-coolers. This paper presents these design details for the cryostat of the ALPACA (Advanced L-Band Phased Array Camera for Arecibo), an instrument currently being designed and built for the 305 m radio telescope of the Arecibo Observatory in Puerto Rico.

Keywords: Cryogenic vacuum vessel, phased array camera, cryo-clamp, thermal isolation, large vacuum window.

1. INTRODUCTION

The Advanced L-Band Phased Array Camera for Arecibo (ALPACA) will be a new facility instrument, operating from 1.3 to 1.7 GHz, located at the feed phase center focus in the Gregorian dome of the 305 m telescope at the Arecibo Observatory (AO) in Puerto Rico (Figure 1). The ALPACA will be a fully cryogenic phased array feed (PAF), cooling both the low noise amplifiers (LNAs) and the antenna elements; unique among PAFs. The instrument is currently in the detailed design phase. The PAF geometry has been optimized [1] for maximum survey efficiency on AO, resulting in 69 antenna/amplifier modules arranged in a close-packed hexagonal array with 135 mm spacing. Each module is roughly 13 cm tall, and the dipole arms span about 9 cm across (Figure 2). These units will operate at 20 K. The ALPACA is schedule for commissioning in 2022. It will enable a broad range of radio science observations, expanding the boundaries of our knowledge of gravitation waves, radio transients, and dark matter, among other areas of active astronomical research.

[1] Contact author: scp8@cornell.edu

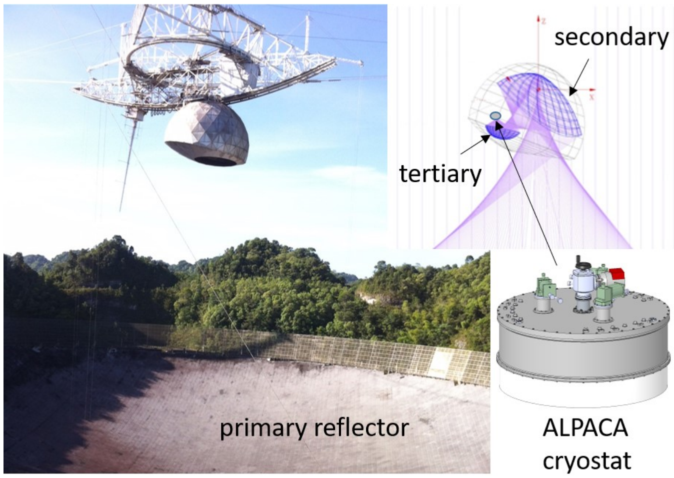

FIGURE 1: *Left:* Photo of the 305 m telescope at AO showing the suspended Gregorian dome and a portion of the primary reflector. *Upper Right:* Ray trace schematic showing the secondary and tertiary reflectors inside the dome, bringing the collected energy to a focus. *Lower Right:* Model of the 1.4 m diameter ALPACA cryostat, which is to be mounted at the focus.

The ALPACA can be roughly divided into two major subsystems, typically referred to as the frontend and backend. The frontend consists of the cryostat, contains the dual polarization antenna array elements and LNAs, enables their operation at 20 K, and interfaces to the telescope structure, receiving the collected light at the telescope focus / phase center. The backend, located off the telescope in the control building, consists of digitizers, FPGAs, network switches, and PCs with GPUs, which allow real time digital signal processing, and multiple digitally synthesized beams. The two subsystems are connected with a fiber optic link.

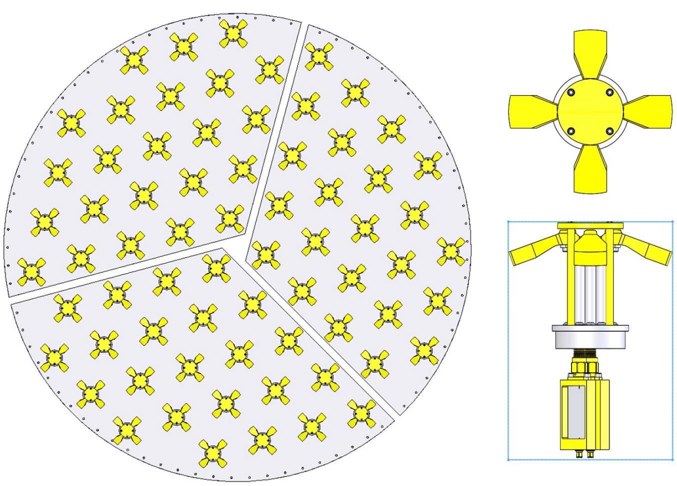

FIGURE 2: *Left:* The hexagonal array of 69 antenna/LNA units is divided in 3 sections inside the cryostat; each section is cooled by its own cryo-cooler. *Right:* Top and side views of the dual polarization dipole antenna unit. The mating cylinder is hidden to show the LNA boxes inside the module. For reference, the blue bounding box is 9 x 13 cm.

For the cooling system design, it was decided early on in the process to avoid the use of liquid cryogens in order to simplify operations and be compatible with AO best working practices. Given a cryostat of this size (roughly 0.6 m tall and 1.4 m in diameter), a single-stage, 300 K to 20 K design would require substantial cooling capacity at 20 K. Since it is more efficient to intercept environmental heat loads at higher temperatures, an 80 K 1st cold stage "surrounds" the 20 K 2nd cold stage, sinking room temperature thermal radiation before it reaches the 2nd stage, and providing a temperature guard for wiring and structural components. This two stage configuration is readily aligned to commercial two-stage Gifford-McMahon cryo-coolers. In our case, three M1020 cold heads from Trillium [2] are sufficient to handle the load. However, the distance between the antennas and LNAs must be small to minimize signal loss and added noise. This results in a unique design where the 20 K antennas stick out of the 80 K shield (Figure 3).

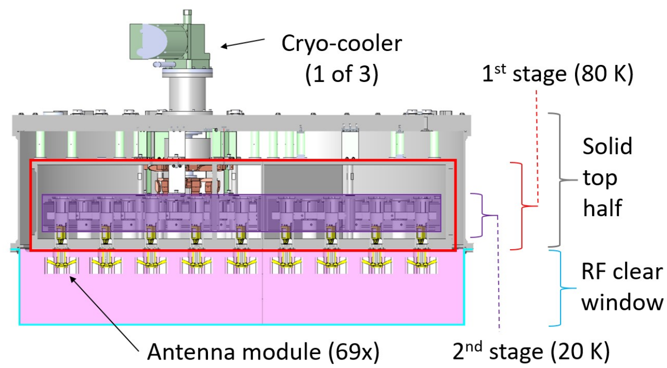

FIGURE 3: Section view of the ALPACA cryostat along a row of antennas. The radio frequency transparent window consists of HDPE (blue) over 3 layers of Rohacell 71 HF foam (pink). The 20 K antennas penetrate the 1st stage (red highlight) and into the foam. The 2nd stage is completely shielded from room temperature heat loads. The vacuum vessel solid top half is welded aluminum.

2. BACKGROUND

Unlike feed-horn based receivers, which place as many beams on the sky within the field-of-view as there are horns, phased array feeds have the ability to capture the entire field of view of the telescope instantaneously. This results in faster mapping of the sky, a key performance parameter. The interest in cryogenic PAF systems is driven by the fact that survey speed is proportional to the inverse square ($\propto 1 / Tsys^2$) of the system noise temperature, *Tsys*. Fundamentally, the sources of noise contributing to *Tsys* include the astronomical "sky" background, the Earth's atmosphere, scatter from the telescope optics, and the receiving instrument itself [3]. Since the sky and atmosphere terms are fixed for the observing frequency of interest, and the scatter term depends strongly on the telescope design, the receiver noise is essentially the only variable that can be adjusted to gainfully influence *Tsys*. For the ~1 GHz observations of the ALPACA, the sky is dominated by the cosmic microwave background (2.73 K), the atmosphere is a few K, and the AO 305 m optics are estimated at about 4 K. By maintaining the physical operating temperature of the receiver components at roughly 20 K, we hope to achieve a system noise temperature of no more than 35 K and, possibly, much better.

Prior efforts have paved the way for the ALPACA, determining the best approach and retiring design risks along the way. In 2010, a 19-element ambient temperature PAF was used to measure the available AO focal plane, characterizing the -1 and -3 dB field of view (FoV) areas by physically scanning the PAF across the telescope focus [4]. In 2013, a fully cryogenic 19-element PAF was field tested at AO [5], verifying the ability of the Rohacell [6] foam to function in a cryogenic vacuum environment, validating the modular antenna/LNA design approach, and confirming the operation of the cryo-clamps (see Sec. 3). This prototype was subsequently modified and physically tested in the lab to validate the concept of using high-density polyethylene (HDPE) over the foam for the window in 2015, creating an unobstructed view for the antennas (Figure 4).

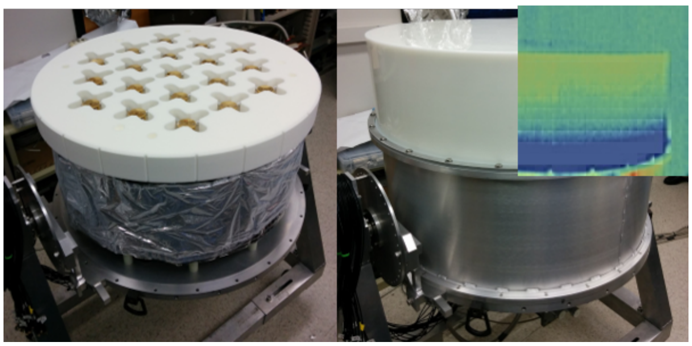

FIGURE 4: *Left:* The prototype 19-element PAF, rotated upside down for assembly, awaiting two more layers of foam, the solid top half, and the HDPE cover. *Right:* Fully assembled prototype under vacuum and operating at cryogenic temperatures. The false-color infrared overlay shows the temperature of the lower third of the window exterior surface runs slightly below room temperature.

3. DESIGN

The cryogenic vacuum vessel forms the frontend portion of the ALPACA system, and is commonly referred to as the receiver, as this is the unit capturing the incoming radio signal. The total weight of the ALPACA system at the telescope focus is limited to approximately 1000 kg, in order to avoid overloading the Arecibo rotary floor structure. Due to ancillary equipment needs (electronics, mounting structure, rotator, cabling, etc.) that require being mounted on top of, or directly next to, the receiver, the cryostat weight is limited to about two-thirds of this; 640 kg or less.

The shape of the vacuum vessel is a simple cylinder. Non-circular cross sections were considered but discarded on the basis of little or no additional FoV coverage and an increase in design and manufacturing complexity. The cylinder height (~0.6 m) is determined by the internal cryogenic components and structures. The diameter of ~1.4 m allows the cryostat to fit between the main beams of the primary structure of the observatory floor (Figure 5). This is required in order to bring the PAF to the correct focal position.

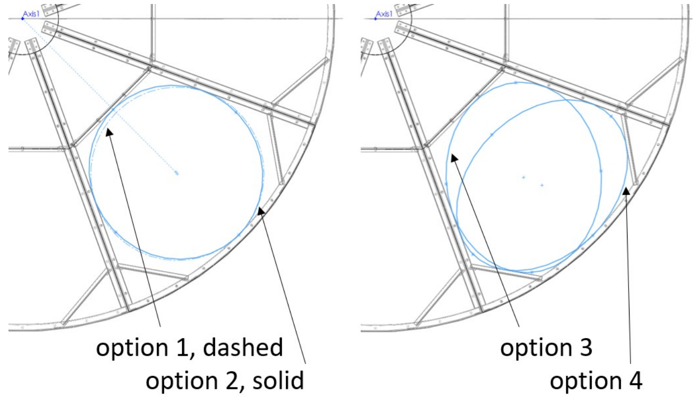

FIGURE 5: AO Gregorian dome rotary floor primary structure. *Left:* Circular (dashed) and slightly elliptical (solid) outlines for possible instrument shapes. *Right:* Two strongly elliptical options. Options 1, 2, and 3 have approximately the same useable area, while option 4 has roughly 10% less and has a poorer FoV overlap with the telescope. The conventional circular option (option 1) was chosen for the cryostat.

Unique aspects of this receiver design include a large radio frequency (RF) transparent vacuum window, modular antenna/LNA units with cyro-clamp receptacles, single-piece flexure-based compliant thermal links between the cryo-cooler cold heads and 1st and 2nd stage base plates, and use of both blade flexure and sliding column thermally insulating standoffs. These items are each discussed in more detail in the following subsections, as well as the overall heat budget.

3.1 RF Transparent Vacuum Vessel

The vacuum vessel operates at less than 15 psi working differential pressure, so it is not bounded by ASME BPV code. The vessel can be divided into two main parts: the solid top half, and the RF transparent window (Figure 3). The top half consists of a light-weighted 6061-T6 aluminum top plate and a welded aluminum shell. The top plate has all the feedthroughs for vacuum, cryogenic, metrology, and signal readout components, and provides the interface for mounting the instrument to the AO floor. The shell of the PAF prototype used 6061-T6 aluminum as the base material and 4043 filler rod for the welds. The welded assembly was then heat treated and helium gas quenched to recover the yield strength of the base metal. Test coupons showed that near -T6 material properties were recovered. However, given the size of the ALPACA (double the size of the prototype), a post-weld heat treatment step may not be ideal, and the use of non-treatable 5000 series aluminum, such as a 5083 base with 5183 filler, is planned in order to ensure moderate material yield strength in the heat affected zones near the welds. While not as straight forward to achieve vacuum tight welds as for example stainless steel, aluminum's lower density (roughly a third) and subsequent weight savings is worth the extra work, and indeed in the case of ALPACA is essential in order to meet the weight limit requirement.

The functional requirements for the window are that it must be vacuum tight, RF transparent, structurally sound, and transmit a manageable heat load to the internal cryogenic stages. For receivers with small windows, this is typically achieved with a sheet of a suitably RF transparent material attached to an opening in the vacuum vessel, which is otherwise a stainless steel or aluminum structure. For the ALPACA, the window area represents over 40% of the total room temperature surface area of the vessel. Just the room temperature radiative heat load on the 80 K aluminum surface would be on the order of a hundred Watts, prohibitively high for our configuration. A “multi-layer window” could solve this problem (similar to multi-layer reflective insulation) but the required window thickness to support the ~160 kN (16 tons) atmospheric load across a flat plate is prohibitively thick for any suitable plastic; at least 6 cm for high density polyethylene (HDPE). The resulting signal transmission loss and significant weight addition (~90 kg) makes this approach simply not practical. Furthermore, the 20 K antennas require an unobstructed, 2-pi steradian view, meaning the window needs to be not just a plate across an opening in the metal vessel, but in fact a dome or closed cylinder “top hat” that terminates level with the base of the antennas. Such a cylinder wall would add another 15 kg. A dome would be structurally more efficient but does not solve the high radiative heat load.

Our solution is to functionally separate the vacuum from the structural and thermal requirements. As demonstrated with our PAF prototype, a durable vacuum tight structure is achieved with a welded HDPE top hat that is only ~3mm thick. An RF transparent foam, Rohacell 71 HF, fills the vacuum side of the HDPE, supporting it from within and keeping it from collapsing. The foam transfers the atmospheric load to the 1^{st} cold stage, which in turn transmits it to the top plate of the vacuum vessel where it is balanced by the atmospheric load on the other side (Figure 6). This design also solves the black body heat load problem because the foam is opaque in the infrared. This changes the window heat transfer method from radiation to conduction, and since the thermal conduction of the foam is rather poor (0.025 W/m/K), the heat load on the 1^{st} stage is reduced to a more manageable 50 W (factor of two improvement).

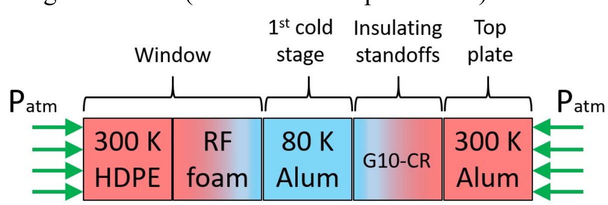

FIGURE 6: Schematic diagram showing the sequence of components along the axis of the cryostat that support the atmospheric pressure load when the ALPACA is under vacuum. Materials and their operating temperatures are noted. For the radial pressure load, the solid foam/window is self-supporting, and the aluminum shell takes the load for the top half of the vacuum vessel, i.e. like a typical pressure vessel.

3.2 Cryo-clamp

The ALPACA contains 69 PAF elements arranged in close-packed hexagon pattern (Figure 2). The elements feature a dual-polarization antenna design with integrated low-noise amplifiers, and must operate at about 20 K to maintain low noise and good sensitivity. Furthermore, the LNA’s generate heat when operating and therefore must also be well thermally sunk to the 2^{nd} cold stage to avoid self-heating. A bolted connection would easily achieve this. However, based on prior experience [5], [7], the only item inside the vacuum vessel that will require occasional replacement is the LNA. This will be done in situ on the telescope, necessitating a repair procedure as simple as possible. To facilitate this, we designed a demountable joint that uses no mechanical fasteners; at room temperature the PAF units simply plug/unplug from the 20 K base. They are retrievable from the window side, thus only requiring the HDPE and foam components to be removed for access. Good thermal contact between the PAF module and the 2^{nd} stage bath is achieved using a cryogenically actuated clamp (cryo-clamp). The design utilizes the thermal contraction of different materials to form a physically tight connection when cold.

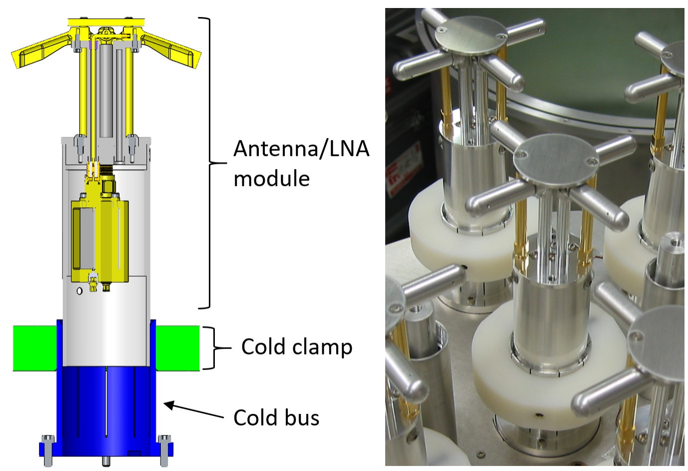

FIGURE 7: *Left:* Section view of a PAF module (yellow & gray) inserted into the cryo-clamp. The cold bus (blue) is functionally like a collet and is mounted to the 20 K base plate. The cold clamp (green) radially compresses the joint together when cold. *Right:* Prototype cryo-clamps installed with early design antenna modules.

The cryo-clamp is shown in Figure 7, and is based on [8]. A ring of Nylon surrounds an aluminum cold bus which is bolted to the 20 K base plate. The bore of the bus provides a sliding fit with the base of the antenna module (also aluminum) at room temperature. Slits are cut into the cold bus to provide radial compliance, similar to a collet on a machine tool. As the system cools down, the ring radially contracts on the joint since the integrated thermal contraction, from room temperature to 20 K, of Nylon is much greater than that of aluminum (over a factor of 3). The ring strongly clamps the aluminum components together ensuring good thermal conduction across the joint and thereby keeping the LNAs well thermally sunk. Combined with the modular design of the antenna/LNA units, the cryo-clamp simplifies field repairs and facilitates future upgrades.

3.3 Cryogenic System & Components

Using an in-house thermal model, all the radiative, conductive, and Ohmic heat loads on the 1^{st} and 2^{nd} temperature stages are estimated and totaled. This forms the basis of the cryogenic system design. First stage radiative loads include vacuum shell/plate to 80 K shell/plate, while second stage loads are between the 20 and 80 K shell/plates, and between the antennas and the lower portion of the foam window. Conductive loads for both stages come from the thermal isolation structures, wires, and for the 1st stage, the foam window. For the 2nd stage, the LNAs generate a significant amount of heat when operating. See Figures 8 and 9 for percent breakdowns by source. These loads necessitate using three M1020 cryo-coolers, which is nicely compatible with the 3-fold symmetric pattern of the antenna array.

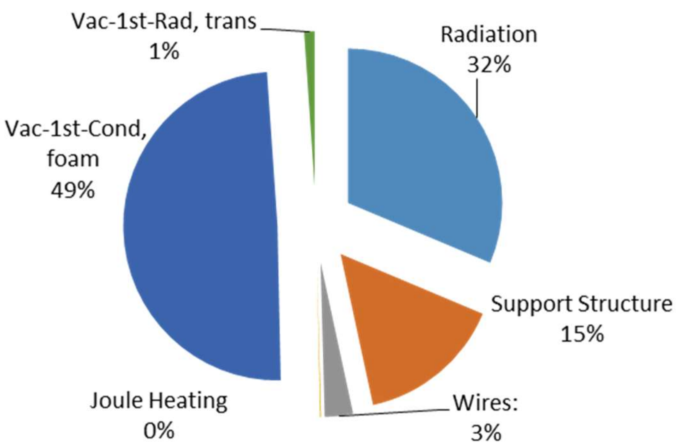

FIGURE 8: First temperature stage heat loads by source. The total estimate load on the 80 K stage is about 100 W.

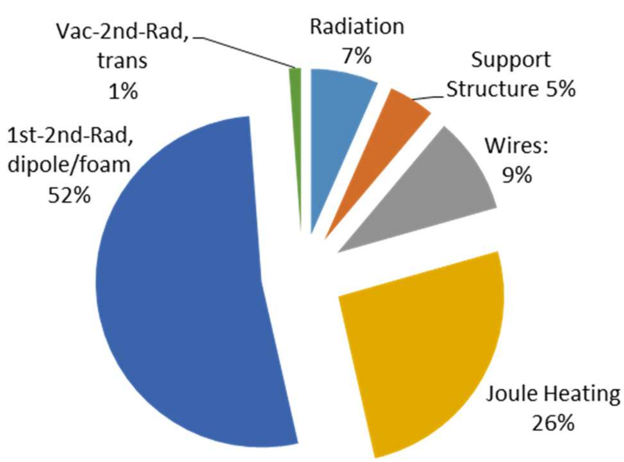

FIGURE 9: Second temperature stage heat loads by source. The total estimate load on the 20 K stage is about 11 W.

Vacuum-to-1st-stage radiation is minimized with the use of low-emissivity multi-layer insultation (MLI), consisting of stacked aluminized Mylar sheets separated by a fine plastic mesh. Antenna-foam radiation is reduced by gold coating the antenna components to lower their emissivity. Conduction heat loads are minimized for both stages by limited the cross-sectional conducting area and by material selection. For cryogenic support structures, the figure of merit is elastic modulus divided by thermal conductivity, *E/k*. At 80 K, G10-CR (a glass fiber composite) has over three times the *E/k* of 300 series stainless steel. For wires, small sizes (e.g. AWG 36) and/or highly alloyed metals (e.g. Phosphor Bronze) are used to restrict conducted heat. To help manage temperature gradients within the stages, 1000 or 3000 series aluminum is use where 6061 is not needed for strength.

Two key aspects of cryogenic design are finding the right balance of thermal isolation and thermal conduction wherever they are needed. In the ALPACA, standoffs physically support the 2nd stage from the 1st stage, and the 1st stage from the vacuum plate, while minimizing the conducted heat load to the colder stage. Between the base plate of each stage and the cold heads, copper parts maximize thermal conduction, minimizing temperature gradients. We use a flexure based thermal link to provide good thermal conductivity while remaining compliant to relative motion (radial and vertical) between the cold head and the base plate, preventing high strains from building up and possibly damaging the cold head. This concept proved successful for the prototype PAF (Figure 10).

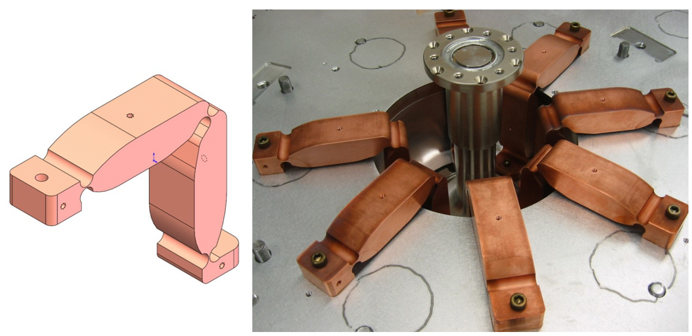

FIGURE 10: *Left:* CAD model of the 80 K thermal link (20 K link follows a similar design). The three notch flexure joints in the monolithic link simplifies manufacturing while still permitting relative motion, avoiding potentially damaging strains when cold. *Right:* Seven of eight 80 K links installed around the cold head on the prototype PAF. The ALPACA will reuse this design.

Due to the atmospheric load on the window, and its transference to the vacuum top plate via the 1st cold stage, considerable insulating supporting structures are provided to handle the load. Two forms of support are used: blade flexures, and rigid columns. The blade flexures are copied from a previous instrument design [9] and constrain the assembly contraction point to be coincident with the axis of the cold head, for each third of the cryostat. The columns, being fixed to the vacuum top plate, feature a PTFE pad contacting the 1st stage base plate. This allows relative lateral motion of the base plate, critical for avoiding high strains due to thermal contraction, while provide axial support for the atmospheric load. These columns were successfully prototyped in the 19-element PAF (Figure 11). The two ends of the column feature metal interfaces adhesively bonded to the G10-CR with 3M Scotch-weld 2216B/A epoxy. On the 80 K side of the column, Nitronic 60 is used, rather than simply stainless steel, to reduce the thermal strain of bonded components at operating temperature.

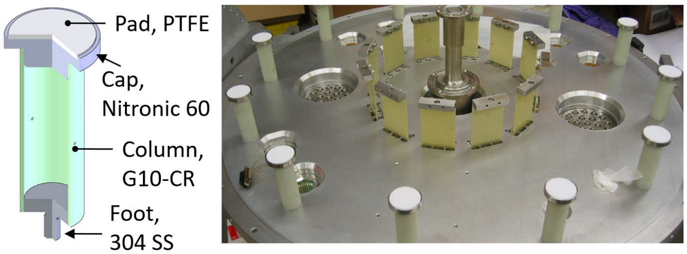

FIGURE 11: *Left:* Partial cut view of thermally insulating support column. The foot is screwed into the vacuum top plate (300 K). *Right:* Columns and blade flexures on the prototype PAF. The blades allow for relative movement along the base plate radius but together form a rigid mount, while the columns take up the vertical load from the atmosphere. The PTFE pad in the column cap allows the base plate to move laterally, preventing bending moments.

4. CONCLUSION

Radio astronomy is a continually evolving science. Large, single dish telescopes benefit greatly from multi-beam cameras. Low temperature receivers enable low system noise and faster mapping speed. The ALPACA will be the world's first fully cryogenic PAF, cooling both the LNAs and the antenna elements.

Building upon prior work, the cryogenic and mechanical design of the ALPACA is nearing completion. Details of some of the design choices of the system have been summarized. Specifically, the vacuum vessel design with its large RF-clear window has been prototyped on a smaller scale and has been shown to work, proving the foam can work structurally and without fouling the vacuum. The 3-fold symmetry of the cryostat is compatible with both the number of cold heads required for cooling and the antenna element array layout. The design of the modular antenna units with their cryo-clamps has also been successfully validated, as has the compliant copper thermal links. Thermal isolation provide by G10-CR flexure blades and columns have also been presented. In all cases materials selection plays a critical role in the creation of an efficient, reliable design.

ACKNOWLEDGEMENTS

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