GROUND SUPPORT ENGINEERING for the PRIMORDIAL INFLATION POLARIZATION EXPLORER

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ABSTRACT

PIPER is a 5,500-lb. instrument, flown on a balloon to an altitude of 20 miles, which measures the polarization of the cosmic microwave background (CMB.) The experiment seeks evidence of primordial gravity waves caused by a distinct inflationary era during the formation of the universe. PIPER directs the microwave signal to bolometer detector arrays with a complex system of mirrors and polarizing grids. A 3,000 liter bath of liquid helium (LHe) cools the telescope to 4 K, and continuous adiabatic demagnetization refrigerators (ADRs) chill the detectors, immersed in LHe inside the 'submarine,' further to 0.1 K. PIPER is ready for its inaugural engineering flight during the fall 2017 campaign. The PIPER project's needs vary widely during the pre-launch crescendo; as interns, we are tasked with providing on-demand engineering support.

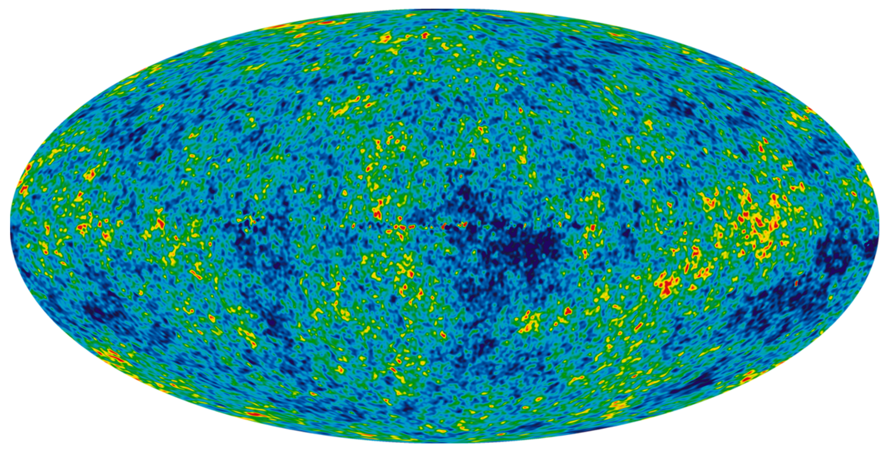


Fig. 1. The most detailed map of the CMB available to date, as made by the Wilkinson Microwave Anisotropy Probe (WMAP) in the wake of the Cosmic Background Explorer (COBE) mission. PIPER seeks to increase the resolution of this survey by several orders of magnitude.

BACKGROUND

- The light from the CMB is 2.72 K; PIPER's detectors must be colder than the CMB to avoid saturation.
- PIPER will make eight scientific flights, four in each hemisphere, to map the entire night sky in different wavelengths. These comparative maps allow us to filter out other noise, such as that from interstellar dust.
- PIPER looks for characteristic patterns in CMB polarization, separating radiation with a grid of 35μm-wide copper-coated tungsten wires spaced to 40-μm intervals by wrapping in a CNC machine.
- PIPER is windowless; the flow of the expanding helium keeps air and water from falling into the dewar and icing on the telescope.

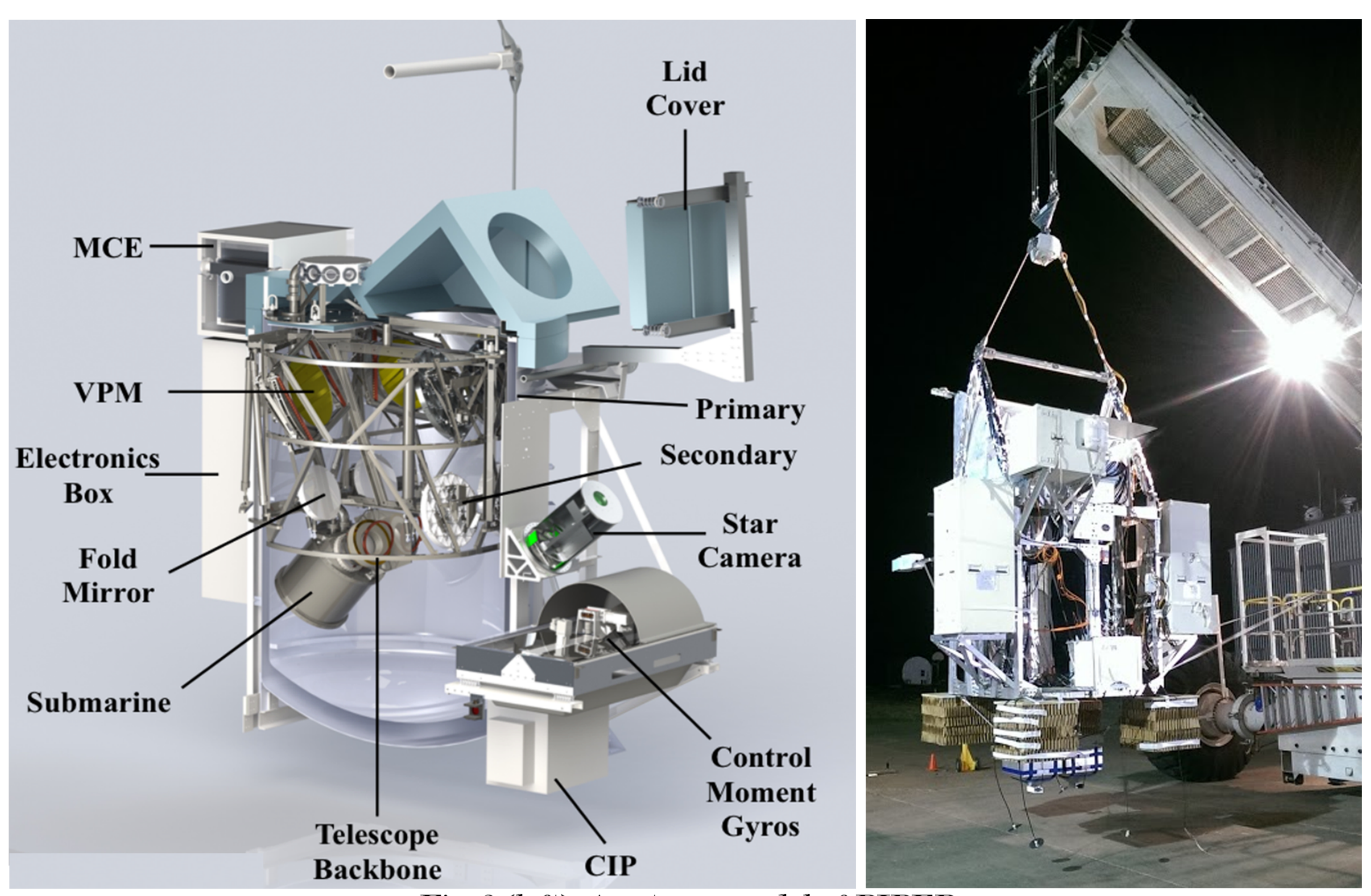
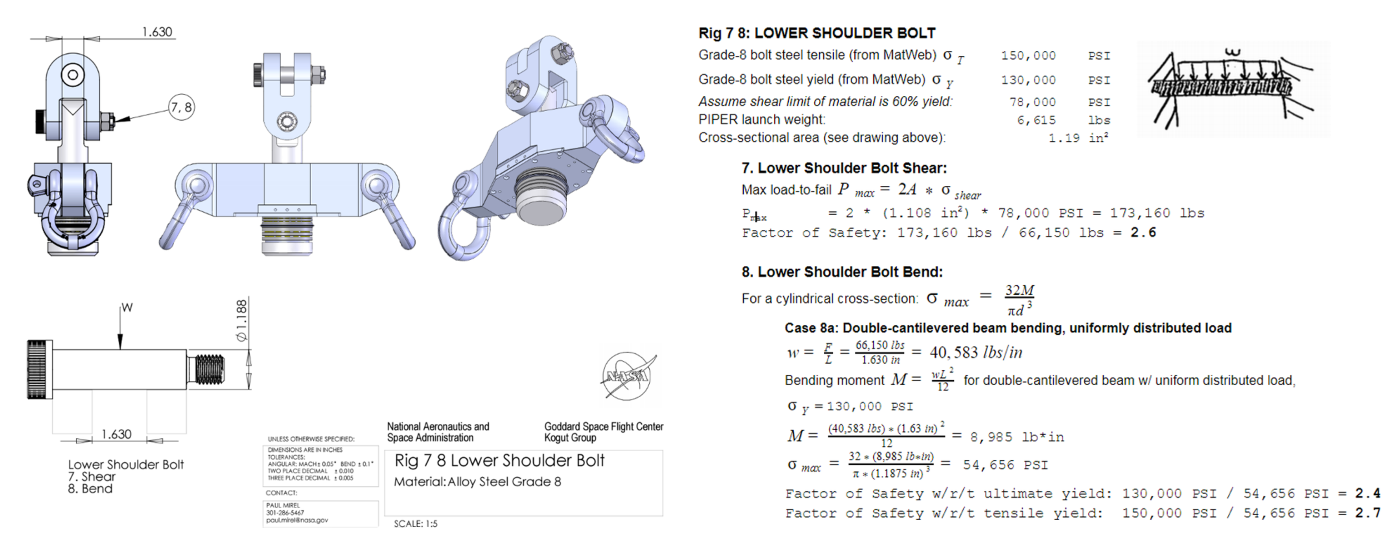


Fig. 2 (left): A cutaway model of PIPER.
(right): Hanging PIPER off of the launch vehicle, "Big Bill," in preparation for a predawn flight. The flight was later scrubbed due to high winds.

Engineering Challenge #1: Stress Analysis

PIPER is suspended from the balloon by a system of wire ropes, nylon cables, steel shackles, and aluminum hardware that optimizes the angles at which the strain is communicated down the assembly. This assembly is known as "rigging." Due to recent difficulties with rigging failures on other balloon missions, PIPER needed to demonstrate our ability to withstand the shock of parachute deployment. When the payload is first cut down from the balloon via remote command, there is insufficient atmosphere (float altitude is 122,000 ft.) for the parachute to bite into. Atmospheric density increases during free-fall, eventually forcing the parachute to fully deploy open. This process happens very quickly, and, depending on the orientation of the payload, can deliver multiple-G-force shocks to the rigging chain.

We needed to show all the different worst-case failure modes (i.e. ways in which it might break or deform) under the mandated 10G safety factors required by the balloon facility. PIPER has since been re-cleared for flight.



Rig 7 8: LOWER SHOULDER BOLT

Grade-8 bolt steel tensile (from MatWeb) σ_T	150,000	PSI
Grade-8 bolt steel yield (from MatWeb) σ_Y	130,000	PSI
Assume shear limit of material is 60% yield:	78,000	PSI
PIPER launch weight:	6,615	lbs
Cross-sectional area (see drawing above):	1.19	in²

7. Lower Shoulder Bolt Shear:

Max load-to-fail $P_{max} = 2A * \sigma_{shear}$

P_{max} = 2 * (1.108 in²) * 78,000 PSI = 173,160 lbs

Factor of Safety: 173,160 lbs / 66,150 lbs = **2.6**

8. Lower Shoulder Bolt Bend:

For a cylindrical cross-section: $\sigma_{max} = \frac{32M}{\pi d^3}$

Case 8a: Double-cantilevered beam bending, uniformly distributed load

$w = \frac{F}{L} = \frac{66{,}150\ lbs}{1.630\ in} = 40{,}583\ lbs/in$

Bending moment $M = \frac{wL^2}{12}$ for double-cantilevered beam w/ uniform distributed load,

$\sigma_Y = 130{,}000$ PSI

$M = \frac{(40{,}583\ lbs) * (1.63\ in)^2}{12} = 8{,}985$ lb*in

$\sigma_{max} = \frac{32 * (8{,}985\ lb*in)}{\pi * (1.1875\ in)^3} = 54{,}656$ PSI

Factor of Safety w/r/t ultimate yield: 130,000 PSI / 54,656 PSI = **2.4**

Factor of Safety w/r/t tensile yield: 150,000 PSI / 54,656 PSI = **2.7**

Fig. 4: Two excerpts of our rigging analysis report to Columbia Scientific Balloon Facility (CSBF) staff.

Engineering Challenge #2: PROTEUS

For future projects such as the Primordial Inflation eXplorer (PIXIE), a satellite version of PIPER that will survey the CMB from L2, we needed a larger thermal vacuum chamber. Chief Systems Engineer Paul Mirel has been designing one for many months; we were tasked with designing and building a heat exchanger.

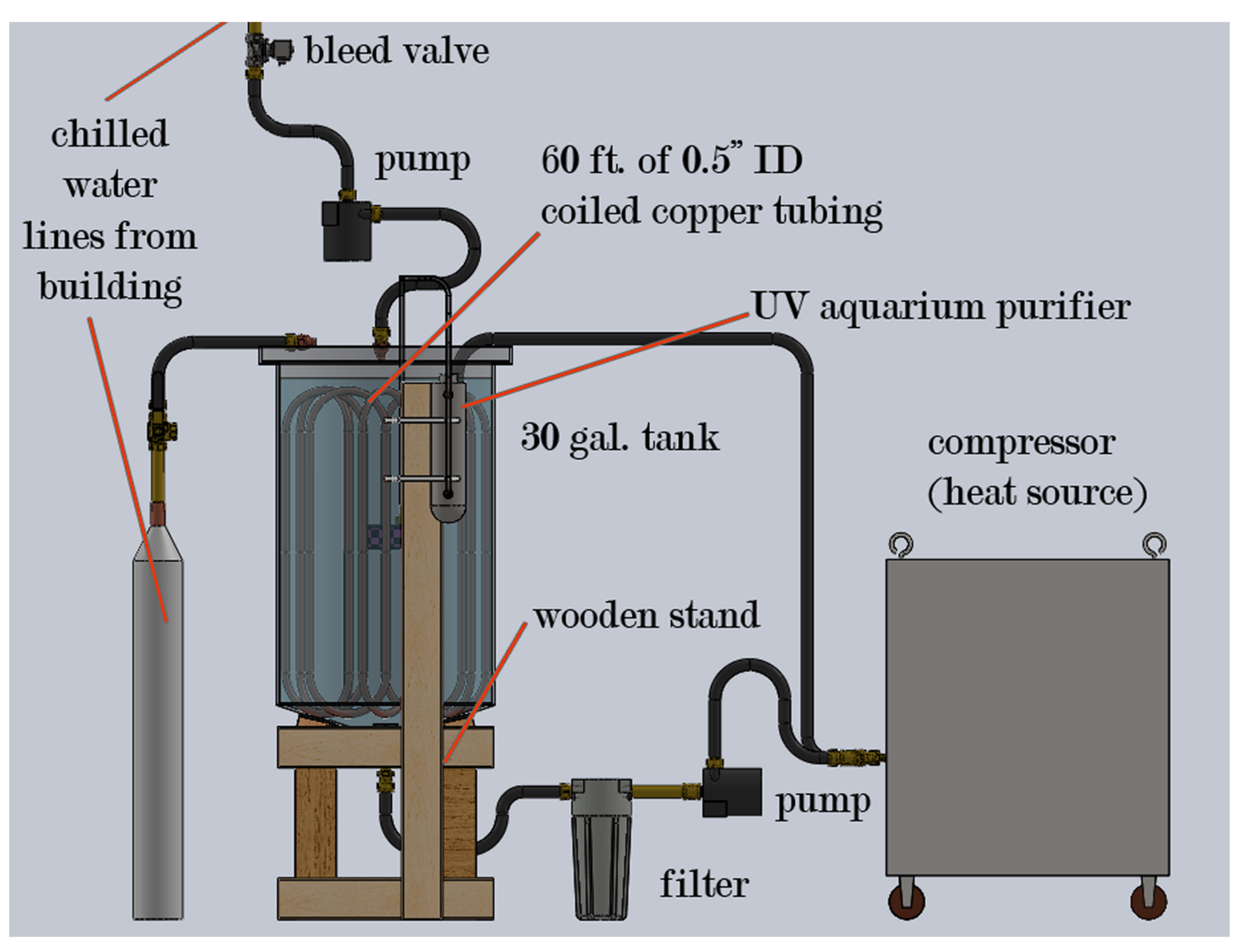


Fig. 5: SolidWorks model of the completed assembly. Top of tank stands 52 inches off of the ground.

The heat exchanger needed to disperse 11kW of heat generated by PROTEUS' compressor, which pumps pressurized helium to cool down to 4 K. Another ADR will cool the PROTEUS chamber down to the 0.1 K needed to simulate regular operation.

We evaluated the constraints of the problem: using chilled water lines from the building, how much water would we need in a bath to cool the working fluid cycling through the compressor? How much surface area was needed, and what size pump would move the fluids at sufficient speeds without creating destructive back-pressure?

The heat exchanger is complete, pending the construction of a chilled water line.

Engineering Challenge #3: Automated Thermal Cycling Testing

The PIPER team often needs to test their hardware to ensure that it will survive repeated cycles of chilling down to extremely low temperatures and returning to room temperature. Hardware frequently fails after cryo cycling, due to coefficient-of-thermal-expansion (CTE) mismatches, when one piece of an object (e.g. a copper base plate) shrinks more rapidly than the piece to which it's attached (e.g. an epoxy bond.) This testing is essential, long, and tedious, making it a perfect candidate for automation. I was tasked with porting over the old, deprecated control system to a lighter, cheaper Arduino-run system. This required writing a control loop in C++, wiring up the Arduino to read sensors in and to send commands to various relays, heaters, and pistons, and displaying a log and interface to the supervising human. It also required separating the various components in into careful modules for ease of debugging, testing, and assembly.

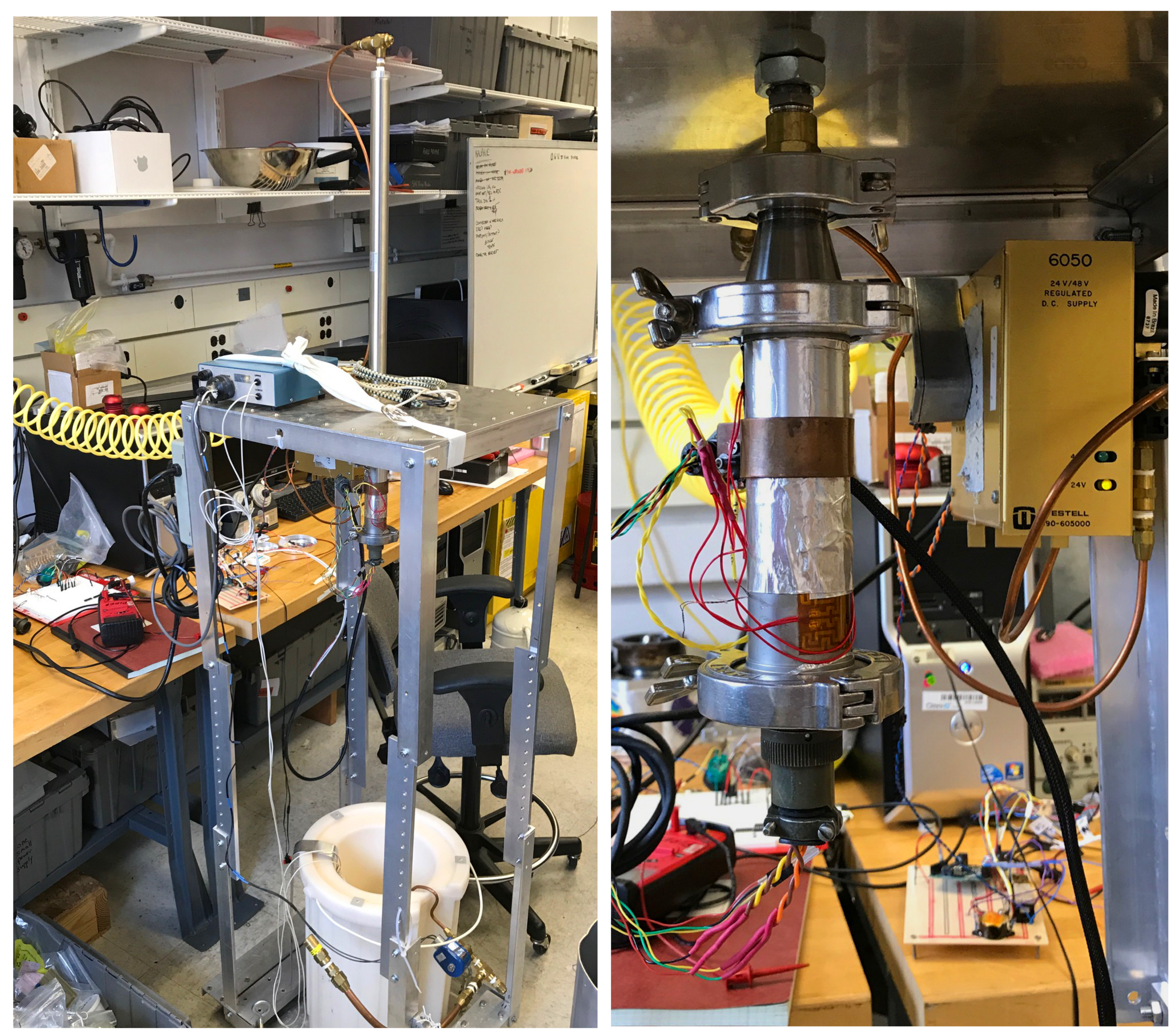


Fig. 6: The "Ralphie" test stand. Pictured top in the left image is the air cylinder which raises and lowers the aluminum-wrapped steel sample holder (closeup, right) into the white insulated liquid nitrogen (LN_2) bucket.

The automated tester, "Ralphie," will have all core functionality completed with a limited interface by the time you read this poster. A stretch goal for the summer is to pipe the output to an independent onboard display rather than a terminal session.