Accessible Balloon RAdiometer: Detecting the Cosmic Microwave Background

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Introduction

We present the design of ABRA, short for Accessible Balloon RAdiometer . The project goal is to design and take measurements using a system to independently verify known information about the Cosmic Microwave Background (CMB). Specifically, this was to be done by building, simulating, testing, collecting and postprocessing data from a microwave radiometer, with the aim of showing the well-known fact that the spectrum of the CMB is a blackbody peaking at frequencies on the order 10 GHz. A balloon-based experiment was chosen to mitigate ambient noise at the ground level.

Due to the COVID-19 pandemic, testing and manufacturing could not be carried out, which we took as an opportunity to redesign some aspects of the system for improved eventual performance. This project will be continued through the fall semester, and will hopefully be able to report positive results soon!

Background and Motivation

CMB radiation is one of the most fundamental and rich sources of data on the early universe. Having been originally detected as additional noise in one of the telescopes at Bell Lab, subsequent study of the CMB revealed vast amounts of hidden structure. Anisotropies in the CMB lent credence to the idea of an expanding universe, hence the Big Bang Theory, with small temperature variations matching what we know about the structure of the universe. [Durrer, 2015]

Despite being discovered almost 60 years ago, CMB detection experiments are still an active field of research, with at least 15 survey programs currently active. Instruments for detecting the CMB have developed to become significantly more sensitive in order to extrapolate more information out of the same underlying structure. The more sensitive equipment gets, the more expensive it tends to be. However, it isn't as apparent as other ways of observing the cosmos — it is easy to buy and set up an amateur telescope, but independently verifying the existence and properties of the CMB proves to be difficult. Our objective is therefore to independently verify measurements of the CMB by building, simulating, testing, and collecting data from a radiometer at significantly lower costs than most research currently allows.

Methods: Logistics of Balloon Flight, Tracking, and Recovery

Materials and Methodology

We intend to launch the telescope using a high altitude weather baloon which are relatively easy to handle and behave predictably. The telescope will be contained in an insulated styrofoam container, which will be attached inline with the balloon and parachute.

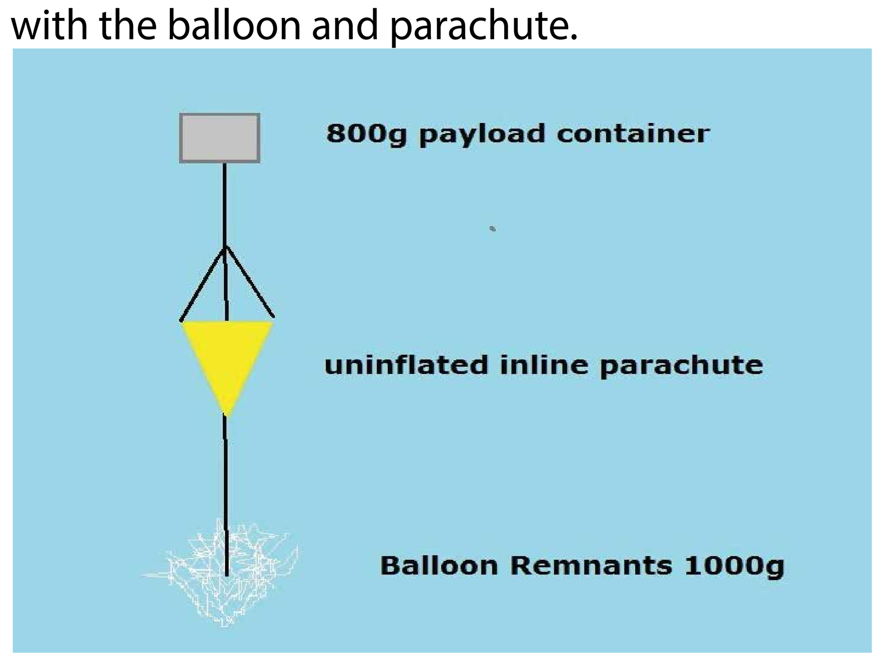


Figure: Illustration of the parachute in-line deployment method, relying on the balloon's weight to deploy upon bursting. (paulkar)

Additionally, we intend to inflate the balloon using 100 cubic feet of helium from Praxair, which will be enough to reach a burst altitude of 20,000 meters, which can be approximated from the ideal gas law. With a gas inflator, we will be able to inflate and launch the balloon in an open space.

Atmospheric Variables

The trajectory of the balloon is dependent on the atmospheric pressure at a given altitude along its path. We used US Standard Atmosphere to calculate and plot ideal atmospheric conditions for the flight.

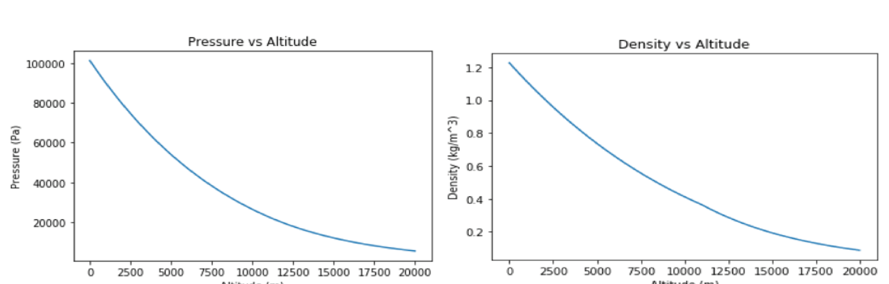


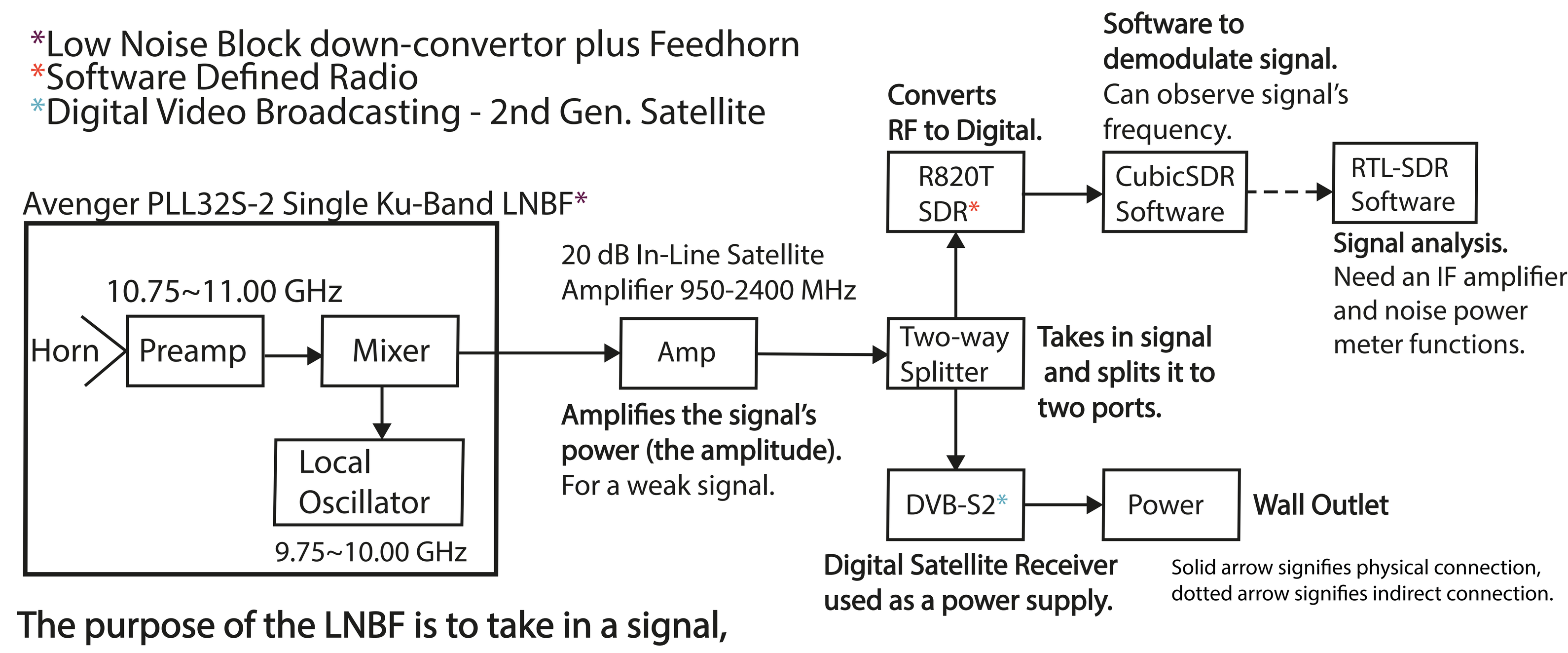
Figure: Plots of air pressure and density as a function of altitude up to 20km. The density is used to calculate the balloon buoyant force during its flight.

APRS: Radio Tracking

Once we've launched our balloon, we require some means of tracking its position. The two best tracking options, used widely in high altitude ballooning, are GPS Messaging Systems and Amateur Radio Tracking. We have chosen to implement a self-constructed APRS (Automatic Packet Reporting) system, which will allow us to receive position data and telemetry in real-time via Radio Frequency communications. This design is centered around the NEO-6M GPS breakout module. This APRS system is composed of a circuit board that is populated with GPS capabilities, a radio transmitter, and sensors for temperature, pressure, and altitude as well as an Arduino which hosts the power supply and microcontrollerr for the set-up.

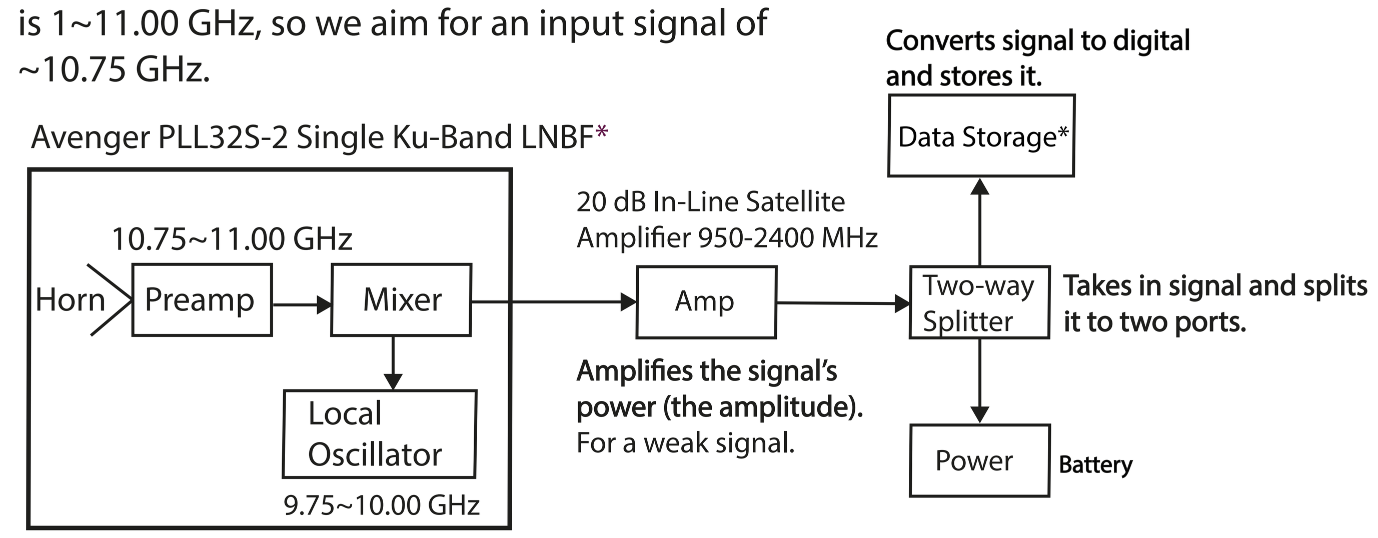
Methods: Hardware Design

The detector can be constructed through a combination of custom parts connected mostly in series. Here, we show the designs for ground-based testing as well as for the actual detector. Testing and iterative design on the ground setup are ongoing even through the pandemic, and we are optimistic about the results!



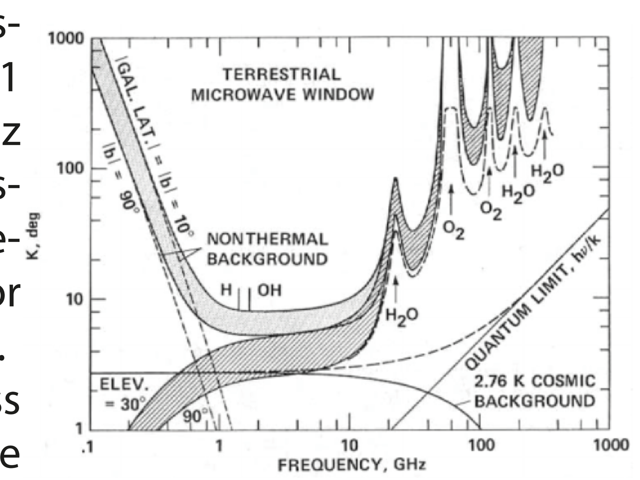
The purpose of the LNBF is to take in a signal, provide slight amplification, and covert the signal to a lower frequency. This LNBF has a input range of 10.70~12.75 GHz.The output is 950~2150 MHz. Our CMB radiation target range is 1~11.00 GHz, so we aim for an input signal of ~10.75 GHz.

Above: Ground-Based LBNF Signal Testing
Below: Balloon Microwave Receiver



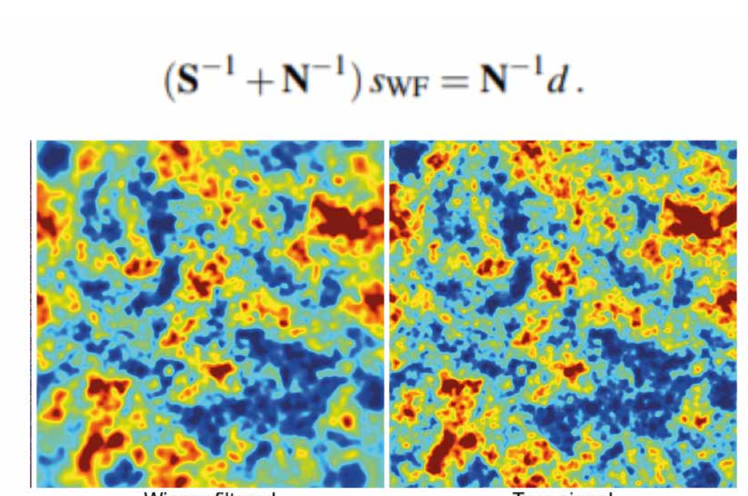
Methods: Postprocessing, Recovering the Temperature Map

For the purposes of detecting the variable atmospheric noise sources in the frequency band from 1 GHz to 10 GHz, we will utilize a 2.4 GHz to 5.8 GHz Microwave Sensor that will extract out local atmospheric frequencies (see design review for more details). The figure to the right details noise sources for CMB experiments at varying frequencies (Gelfand). Within the instrumentation, we apply a high-pass filter to be selective with our frequencies. Ideally, we could receive a map of signals on the full expansion of the sky - instead, we get a partial view and convert frequencies to temperature using Planck's Law for blackbodies (which relates the peak frequency of a blackbody to its temperature).



$$\nu_{\text{peak}} = \frac{2.82kT}{h}$$

Figure: CMB noise sources.



$$(\mathbf{S}^{-1} + \mathbf{N}^{-1})\, s_{\mathrm{WF}} = \mathbf{N}^{-1} d\,.$$

Figure: A demonstration of Wiener filtering on a sample CMB map, and comparison to a ground truth map showing them to be nearly identical.

We utilize LensIt (J. Carron et. al) a maximum a posteriori estimator (i.e. most probable lensing map) that employs a Wiener filter (least squares procedure) on a temperature map - corrects for gaussian and inhomogeneous noise. The main linear system for the Wiener filter is shown to the right, with s_WF representing the solution to the MAP. Built-in functionality within LensIt (which builds on the spherical harmonic expansion of the sky) allows us to fit our polarization map - within our projected frequency band - to already verified multipoles of the CMB.

Methods: Thermal Effects and Contingency Planning

ABRA is a complicated design with many potential failure conditions, which we enumerate and discuss in this section. It is particularly important to deal with thermal effects.

A major consideration for Cosmic Microwave Background (CMB) experiments is dealing with noise. This noise comes primarily from nearby objects emitting thermal radiation in the infrared levels. It may compromise the signal one is trying to detect from the CMB. Cooling the instrumentation will lower the amount of radiation given off, thus reducing noise. In professional and highly funded experiments, liquid helium is utilized to calibrate the temperature scale and cool equipment to temperatures near absolute zero. Due to budgetary and experiential constraints, this was beyond our scope.

The option of flying liquid nitrogen was previously ruled out, but in our efforts to redesign after the pandemic started, we have reopened this option and begun to talk to Berkeley EH&S regarding safe protocols. Our default plan is to cool a thermally conductive material (a block of steel, due to good thermal conductivity) in liquid nitrogen before loading it on the payload and allowing it to act as a source to cool the equipment, or the area near the detector. We would then encase this block inside a styrofoam container along with the detector, cooling the detector's surroundings while not affecting the operating temperature of the electronics. Combined with the already cold ambient temperatures at the altitudes to which we plan to fly, this should be sufficient to significantly reduce the interference frrom ambient thermal sources and allow us to capture the CMB spectrum.

Beyond this, the following table lists our potential failure or delay cases, and ways in which we can or have been able to mitigate them.

Title	Mitigation	Course of Action & Prevention
Wrong Budget Estimation	Transfer	Pass to ULAB staff
Adjustments to scope of project		Timeline reassessment.
Failure to communicate across subgroubs	Control	Post notes of subgroup meetings in Slack detailing progress/ any issues that may have arisen
Team Member Injury	Control	Refer to safety procedures for handling LN2; wear appropriate clothes & PPE in lab; report any safety hazards; exercise caution
Shipment delays	Accept	Timeline reassessment.
Issues/delays in securing workspace	Control	Mitigated; workspaces located.
Mistakes due to miscommunication among team members	Control	If your work depends on the work of another team member, keep up regular communication with them (Slack, call, meet up, etc.)
Loss of Supplies (stolen or misplaced)	Control	Never leave project components lying around; keep records of workspace locations; appropriately secure workspace before leaving
Fail to consider important factor(s) in the simulation	Control	Be extremely thorough in defining parameters; verify sim with peers/prof. familiar with sims for cryo calibration
Oxygen Deficiency (suffocation/asphyxiation)	Control	Make sure the room is well-ventilated if using LN2 indoors
Oxygen Enrichcment (explosion risk)	Control	Keep dewar away from combustible materials; make sure the room is well-ventilated if using LN2 indoors
High Pressure (due to warming of LN2)->flash vaporization	Control	Liquid withdrawal should be done at low pressure to prevent flash losses
LN2 storage dewar tips over	Control	Folllow correct dewar transportation procedures
Accidental release/overflow	Control	Handle LN2 slowly; dewar should never be filled up to more than 80% its capacity
Thermal Burns	Control	Wear PPE (long sleves&pants, loose-fitting insulated gloves, etc.); handle LN2 slowly; use tongs to remove objects immersed in LN2
Delayed Assembly (components unavailable, etc.)	Control	Lessen impact by restructuring the project timeline to advance in areas which don't require the missing components
Warping/cracking/breaking of mechanical components	Control	reduce heat; improve cooling ; handle PCB and all components carefully; see safe handling procedures
We don't know what we're doing: Design	Control	Ask PCB Decal people, knowledgable peers, or profs. for assistance/ to check if design looks correct for our purposes
We don't know what we're doing: Assembly	Control	Perform tests!; ask PCB Decal people, knowledgeable peers, or profs. for assistance/ to check if construction looks correct for our purposes
Short Circuit (high current)	Control	post-manufacturing electrical tests; opt for larger distance between copper connections and pads
Short Circuit (pin or trace discoloration)	Control	post-manufacturing electrical tests; opt for larger distance between copper connections and pads
Short Circuit (component burned)	Control	post-manufacturing electrical tests; opt for larger distance between copper connections and pads
Data not sufficient to produce BB spectrum	Avoid	Change project scope; Data analysis on existing, historical data; or if time and resources permit, fly again.
Development of working code takes longer than expected	Avoid	Change project scope to compensate; shoot for deadline earlier than needed
Don't know how to code onto PCB	Control	Ask knowledgable peers/ profs for assistance; online research
Poor Weather Conditions	Avoid	Choose a day with good weather predictions; if predictions are wrong, reschedule launch (or drive to launch site that escapes bad weather)
Damaged Balloon (pre-flight)	Control	Place the balloon in a safe place where it will not be touched until launch day; or order a backup balloon (if budget allows)
Balloon out of range of radio tracking	Accept/Control	If Accept: Hopefully we'll regain signal during the balloon's descent/ If Control: Use GPS instead (or other alternative method)
Balloon lands further from Berkeley than anticipated	Accept	Acquire car for a short roadtrip
Parachute fails to activate	Control	Spend time making sure the parachute placement, material, size, etc. are optimal; Engineer our payload to cushion the landing
Balloon bursts too early	Control	Employ backup balloon and fly again

Figure: Contingency planning.

Conclusion and Acknowledgements

The COVID-19 pandemic set back our design and manufacturing cycle significantly, due to the lack of in-person meetings, access to hardware and workspaces, and testing and flight plans having to be postponed. However, we were abe to use this as an opportunity to reassess our plans and begin to incorporate more learning opportunities. We are optimistic that this will lead to a better product and better learning environment when conditions improve and we are able to fly as originally planned!

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