HYPERION Project Book

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Contents

Chapter 1

Introduction

1.1 Purpose

The HYPERION Project Book aims to provide a complete overview of the HYPERION project, including current progress and future goals.

1.2 Overview

The Hydrogen Probe of the Epoch of Reionization (HYPERION) is a specialized low-frequency interferometer to study the Epoch of Reionization through the spatial monopole of the 21cm brightness temperature of neutral hydrogen as a function of redshift (i.e. the "global signal"). It is being developed at the University of California, Berkeley in the Radio Astronomy Laboratory. It is being funded through the NSF Faculty Early Career Development (CAREER) Grant awarded to Aaron Parsons (Award No. 1352519).

1.2.1 Science

The goal of HYPERION is to detect the monopole reionization signal. A detection of this signal could give key insights into the physics and development of our early universe, including information on the formation of the first stars and galaxies.

Refer to (Pritchard & Loeb 2010, 2012; Gnedin & Shaver 2004).

1.2.2 Design

The Epoch of Reionization is one of the most exciting frontiers of modern day cosmology, and one of the most challenging to explore. Over the past ten years, astronomers have sought to detect the Epoch of Reionization with many different experiments, and primarily focused on using redshifted 21cm emissions to map out this period of the universe's history. In the case of PAPER and HERA, astronomers have built specialized low-frequency interferometers in order to observe the overall power spectrum of hydrogen in the early universe. The interferometric honeycomb design of HERA also enables the observer to potentially image growing ionization bubbles throughout the Epoch of Reionization. The LOFAR instrument also seeks to measure this signal through a more generalized instrument, with much longer baselines (on the order of kilometers compared to PAPER/HERA's baselines, which are on the order of decameters).

Astronomers have also sought to measure the sky-averaged 21cm signal, as a way of quantifying the overall neutral hydrogen content in the universe through the use of specialized single-dish experiments. The single dish is an important, if fraught, design choice as it enables direct sampling of the spatial monopole 21cm signal (i.e. the all-sky average signal). The trouble with single dish experiments is that it is extremely difficult to effectively calibrate every source of noise that the instrument itself contributes to the overall system noise, particularly in cases where that noise is frequency dependent. One of the main benefits of interferometric designs is that the vast majority of instrumental noise largely averages itself out, which abates the very strict calibration requirements demanded by Epoch of Reionization studies.

The trouble with using an interferometer to observe the 21cm global signal is that, speaking from a purely Fourier background, an interferometer cannot be used to directly sample the monopole term, as interferometers work by imposing spatial frequencies across the sky which are then combined to form images. It is clear that a monopole signal, such as the 21cm global signal of reionization, would integrate to zero over any set of observed spatial frequencies, in the case of a perfect interferometer able to sample every mode and see the full 360° sky. However, HYPERION will circumnavigate this issue by using absorber baffles to impose an artificial horizon on the sky. This horizon interrupts the flat nature of the spatial monopole, which creates leakage from the DC-mode into modes with non-zero interferometric spacings. As discussed in Presley et al. (2015), the optimal spacing between elements is approximately one wavelength. While the baffle structure will likely force a larger separation, one consideration to be made during design is ensuring that the spacing remains as tightly packed as possible to maximize our sensitivity to the monopole term.

Refer to (Presley et al. 2015; Liu et al. 2013; Venumadhav et al. 2016) for more rigorous treatments of the above design parameters.

Chapter 2

Requirements and Specifications

These are the requirements and specifications of the HYPERION instrument.

The antennas will be constructed with a frequency range of 35.36 – 141.2 MHz and a science band of 50 – 100 MHz. This frequency range optimizes the ability to see the change in the 21cm global signal temperature as a function of frequency, as can be seen in Fig. 9 of (Pritchard & Loeb 2010).

The brightness temperature of the galaxy is very high in our science band, with $T_{sky} = 2000$ K with an observing frequency of $\nu = 70$ MHz. Factoring in the absorber baffle structure and a renormalization to keep T_{21} constant, the artificial horizon imposed by the absorber baffles must let in at least 20% of the sky in order to maintain a system temperature $T_{sys} < 6000$ K (Kundert 2016). This same test indicated that the amplifier temperature is a relatively small contributor to the overall system temperature, and no special measures need to be taken to minimize it.

The ADC needs at least -5.5dBm in order to get RMS counts of 12.5 with Gaussian noise. Assuming 10% return loss, the antenna will be receiving between -87.95 dBm at $\nu = 50$ MHz to -95.48 at $\nu = 100$ MHz. This leads to a requirement for at least 18dB of gain (Day 2016a).

Refer to (Day 2016b; Kundert 2016).

Chapter 3

Architecture

This is the overall architecture and work breakdown structure (WBS) of the HYPERION instrument.

3.1 Element

3.1.1 Overview

using styrofoam as base for antenna with dielectric constant $\kappa \simeq 1$, needs to be painted with latex/water-based paint due to UV instability

3.1.2 Requirements

3.1.3 Antenna

Overview

Need an antennas design with a frequency independent broadband beam, frequency range of antenna design is 35.36 - 141.42 MHz in order to have flat response and minimize edge effects across science band of 50-100 MHz.

Review (Day 2016b).

Requirements

3.1.4 Absorber

Need about 10 dB attenuation for reflective components, need at least 33 dB attenuation for diffractive and transmissive components (diffraction over top of baffles, transmission between antennas/baffles)

Overview

Requirements

3.1.5 Work

Needs Doing

- finalize antenna design and logistics
- simulate baffle structures to determine beam shaping properties
- finalize baffle design and logistics
- determine absorber properties – ferrite, foam, resistive mesh, charcoal...
- take beam measurements
- CEM model antenna + ground – determine best height for antenna to stand
- CEM model antenna + absorptive ground – what effects?
- CEM model of absorber baffle structures
- characterize fat dipole antenna characteristics – return loss, beam shape and frequency dependence

Already Completed

3.2 Frontend

3.2.1 Overview

PCB board + balun with 1:1 ratio, LNA with noise factor 1.1-1.2, voltage regulator, plus various caps, resistors, inductors for (DC block?) and impedance matching

3.2.2 Requirements

Refer to gain v. loss calculations, HYPERION sys specs doc, and HYPERION Memo #1

3.2.3 Receiver

Overview

Two stage filtering (low pass and high pass filter x2, may be amplifier between stages) + amplifier after filtering + bias-t (power the pcb board maybe) + any needed attenuation + battery for receiver box

Requirements

Filter to science band, need enough gain (refer to gain v. loss calculations) to get to -5.5dBm at ADC input (including cable loss) (Day 2016a).

3.2.4 Work

Needs Doing

- PCB board design
- figure out caps, resistors, inductors needed for matching
- power distribution for board
- design chassis (weatherproof)
- figure out cable strain relief
- design shielded chassis
- figure out which amplifiers to use
- figure out which low pass filter to use
- figure if we need bias-t and if so, which to use
- figure out power consumption of front end
- order batteries
- explore node design for receiver cards

- look into EM properties of 3d printer filaments for chassis design
- figure out array design and placement
- hire electrical engineering masters student to design perfect match LNA to replace balun + LNA system?
- maybe look into hiring undergrad for LNA design
- work with Ali Niknejad to hire BWRC masters student to create custom LNA

Already Completed

- order LNA and balun and LNA-balun boards
- figure out which high pass filter to use in receiver box

3.3 Backend

3.3.1 Overview

Convert from analog to digital signal, SNAP board correlator, RF shielded box, powered by battery

3.3.2 Requirements

RMS ADC counts of about 12

3.3.3 Work

Needs Doing

- finalize correlator design (check Rachel PoCo documents? Eddie SNAP documents?)
- power distribution network design
- finish chassis design or order pre-made SNAP chassis (talk to SCI-HI folks)

Already Completed

3.4 Computing

3.4.1 Overview

3.4.2 Requirements

3.4.3 Work

3.5 Analysis

3.5.1 Overview

3.5.2 Requirements

3.5.3 Work

Needs Doing

- do data analysis of PAPER-128 to search for global signal, set up initial tools

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