Hydrogen Intensity and Real-Time Analysis
Experiment: 256-element array status and overview

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Abstract. The Hydrogen Intensity and Real-time Analysis Experiment (HIRAX) is a radio interferometer array currently in development, with an initial 256-element array to be deployed at the South African Radio Astronomy Observatory Square Kilometer Array site in South Africa. Each of the 6 m, $f/0.23$ dishes will be instrumented with dual-polarization feeds operating over a frequency range of 400 to 800 MHz. Through intensity mapping of the 21 cm emission line of neutral hydrogen, HIRAX will provide a cosmological survey of the distribution of large-scale
structure over the redshift range of $0.775 < z < 2.55$ over $\sim 15,000$ square degrees of the southern sky. The statistical power of such a survey is sufficient to produce $\sim 7\%$ constraints on the dark energy equation of state parameter when combined with measurements from the Planck satellite. Additionally, HIRAX will provide a highly competitive platform for radio transient and HI absorber science while enabling a multitude of cross-correlation studies. We describe the science goals of the experiment, overview of the design and status of the subcomponents of the telescope system, and describe the expected performance of the initial 256-element array as well as the planned future expansion to the final, 1024-element array.

Keywords: 21 cm; intensity mapping; cosmology; dark energy; radio transients; interferometers.

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1 Introduction

In recent years, the statistical distribution of large-scale structure in the late-time universe has been measured with increased precision. Current state-of-the-art measurements primarily come from baryon acoustic oscillation (BAO) studies from galaxy and Lyman-$\alpha$ surveys as well as weak lensing probes.\textsuperscript{1-7} However, tomographic measurements in the visible/infrared bands become increasingly difficult beyond $z \sim 1$, requiring complex optical systems and long integration times. Intensity mapping with the 21 cm (1420.4 MHz) line of neutral hydrogen has the potential to push beyond these limitations, with observations in the range of $0 < z \lesssim 30$ being achievable with current and planned instruments. The abundance of hydrogen and the optically thin nature of the emission will enable detailed tomographic measurements of the distribution of matter over large, cosmological volumes.\textsuperscript{8-10} In the postreionization epoch, by observing the BAO feature in the matter power spectrum, intensity mapping enables cosmological measurements that can break parameter degeneracies in current combinations of early universe and late-time measurements, as well as constrain the dynamical nature of dark energy over the transition from matter-dominated to dark-energy dominated expansion.

Modern advances in computer and communication hardware as well as the relatively simple, low-frequency receivers required for these observations have motivated the development of large, $\sim 100$ to 1000 element interferometer (IF) arrays, such as CHIME,\textsuperscript{11} CHORD,\textsuperscript{12} HERA,\textsuperscript{13} PUMA,\textsuperscript{14} and Tianlai.\textsuperscript{15} Such telescopes focus their sensitivity on cosmologically relevant angular scales, favoring compact arrays with “redundant” configurations, where the constituent radio telescopes are placed with regular spacing. This type of array architecture additionally provides a natural platform for the detection and monitoring of radio transients, with wide fields of view, fast mapping speeds, and the real-time processing power required for fast radio burst (FRB) detection and pulsar searches, as demonstrated by CHIME in Refs.\textsuperscript{16-20}.

The Hydrogen Intensity and Real-time Analysis Experiment (HIRAX)\textsuperscript{21} is a radio IF array that will employ a compact, redundant layout. HIRAX is currently funded for the construction of an initial 256-element array (HIRAX-256) that will comprise a subset of the planned 1024-element array. The telescope will conduct a large 21 cm intensity mapping survey, targeting cosmological constraints on the dark energy equation-of-state parameters, while additionally operating as a platform for transient and HI absorber searches. The cosmological survey requires careful control of systematics due to significant risk of contamination by residuals from foregrounds, which are up to six orders of magnitude brighter in power. The radio transient detection pipeline for HIRAX will focus on searches for FRBs and millisecond pulsars. FRBs are currently under intense study since the nature of their emission processes is not yet understood. HIRAX-256 is expected to detect multiple FRBs per week (Based on the all-sky FRB rate estimate from Ref.\textsuperscript{19}, scaled to the HIRAX field of view, noting that HIRAX-256 has a similar collecting area to CHIME.) and future proposed HIRAX outrigger sites with very long baselines ($\sim 1000$ km).
will aid in the localization of FRB detections to within 0.1 arc sec. Pulsar searches will be performed on beam-formed data at full baseband, allowing for searches over a wide parameter space. Additionally, the flexible digital backend will allow for the monitoring of known pulsars (aiding existing pulsar timing studies) as well as resampling the full baseband data to $\sim 3$ kHz spectral resolution, which will be used to conduct a blind HI absorber search. Such a search will provide an informative accounting of the state of cold gas in galaxies out to $z \sim 2.5$, encompassing the peak of the global star-formation rate density at $z \sim 2$. Finally, as shown in Fig. 1, the $-60 \ deg \lesssim \delta \lesssim 0 \ deg$ declination range of the HIRAX survey has significant overlap with a range of other large surveys of the southern and equatorial sky, thus enabling a wide range of potential cross-correlation studies. These include optical/infrared galaxy and lensing surveys from eBOSS, DES, KiDS, HSC, DESI, Rubin/LSST, Euclid, and Roman as well as ground-based cosmic microwave background surveys from Advanced ACTPol, SPT-3G, and the Simons Observatory.

These science goals are highly synergistic with those of the SKA and its precursors. For example, the combined MeerKLASS and HIRAX intensity mapping surveys will have the potential to produce a cosmological analysis over a redshift range of $0 \lesssim z \lesssim 2.5$, with contrasting systematic challenges from the differing observing modes and instruments. HIRAX will share significant overlap with the proposed SKA1-MID intensity mapping survey in terms of sky area ($\Omega_{\text{SKA1-MID}} \approx 20,000 \ deg^2$; in Figure 1, this covers most of the southern sky) and redshift range ($0 < z_{\text{SKA1-MID}} < 3.06$), which will be useful for validation and testing systematics. At the same time, HIRAX will be complementary to the SKA1-MID single dish (SD) and IF intensity mapping surveys in terms of angular scales probed, which leads to complementary scientific constraints as discussed in Sec. 3. The blind HI absorber surveys with HIRAX will extend observations beyond the redshift limits of ongoing surveys, such as the MeerKAT Absorption Line Survey, to investigate the relationship between cold atomic gas and the evolution of star formation and AGN activity.

In this work, we present the current status and design of HIRAX-256, as well as the analysis work that has been done to inform these design choices. In Sec. 2, we introduce the instrument and briefly outline the various subcomponents. Section 3 overviews the forecasted cosmological constraints and current analysis methodologies. In Sec. 4, we describe how forecasts and analysis of simulated data have constrained the design of the instrument, and finally in Sec. 5 we discuss the current status of the project.

### 2 Instrument and Subsystems

#### 2.1 Overview

The overall design of HIRAX is driven by optimizing sensitivity to the restricted range of angular scales corresponding to the BAO signature. The BAO science goals thus naturally dictate the high-level instrument configuration. The redshift range $0.775 < z < 2.55$, which captures the...
onset of the influence of dark energy on the expansion rate at $z \sim 2$, sets the observing frequency range of 400 to 800 MHz. The 150 Mpc BAO characteristic length $^{16}$ corresponds to angular scales of 3 deg to 1.3 deg at 400 to 800 MHz, thus setting a minimum baseline length range of 15 to 60 m. Along the line of sight, the BAO characteristic length translates into frequency scales of 12 to 20 MHz, thus setting an absolute minimum requirement of $\sim 100$ frequency channels over 400 to 800 MHz. Finally, because the BAO signal is faint ($\sim 0.1$ mK), the instrument must have a large collecting area and low system temperature. The basic HIRAX instrument parameters are summarized in Table 1, and a rendering of the array is shown in Fig. 2. The HIRAX array, which will initially consist of 256 elements, will be installed as a guest instrument at the South African Radio Astronomy Observatory (SARAO) site in the Karoo Desert, South Africa, at 30°41′47″ S and 21°34′20″ E, ~12 km from the core of MeerKAT. As a guest instrument, HIRAX will benefit from shared power and telecommunications infrastructure provided under agreement with SARAO. From this site, HIRAX will be able to access $\sim 15,000$ deg$^2$ of the southern sky, as illustrated in Fig. 1.

To keep the total data volume at a manageable level, we will take advantage of the redundant configuration of HIRAX to average visibilities within groups of nominally identical baselines. A continuous few-day buffer of the full set of raw visibilities will be stored while the calibration and averaging process is performed, after which the raw data will be deleted. This averaging process is highly sensitive to differences in telescope pairs, since even small mismatches may couple with Galactic emission, which is up to $10^3$ times greater in amplitude than the BAO signal, subsequently offsetting the calibration and introducing systematic errors in the observations. Redundant radio telescope arrays that average visibilities early in this way, such as HIRAX, therefore operate in a unique regime that demands precise control—not merely

| Parameter           | Value                          |
|---------------------|--------------------------------|
| Number of dishes    | 256                            |
| Dish diameter       | 6 m                            |
| Dish focal ratio    | 0.23                           |
| Collecting area     | 7200 m$^2$                     |
| Frequency range     | 400 to 800 MHz                 |
| Frequency resolution| 1024 channels, 390 kHz         |
| Field of view       | 5 deg to 10 deg                |
| Resolution          | 0.2 deg to 0.4 deg             |
| Target system temp  | 50 K                           |

Fig. 2 Artist’s impression of the HIRAX array in the Karoo desert.
characterization—over possible departures from redundancy. The methodology for deriving the HIRAX instrument specifications is discussed in further detail in Sec. 4.

The degree to which baselines are redundant and the angular scales over which that redundancy is distributed are important considerations in determining the optimal HIRAX array layout. Evaluating array layouts that strike a balance between redundancy and more uniform $uv$-plane coverage\textsuperscript{37} is an active area of study. Key factors favoring maximal redundancy include reduced raw data rate and ease of redundant calibration, whereas key factors favoring less than maximal redundancy include the array chromatic response, taking into account dish-feed and dish-dish coupling across the array, and the impact of instrument errors that cause systematic departures from redundancy.

Figure 3 illustrates the HIRAX signal chain. At the focus of each telescope dish, the incoming radio signals are received and amplified by a dual-polarization active feed, band limited to 400 to 800 MHz, and converted to optical light with an RFoF transmitter at the dish focus. Optical fiber transports the signals to an RFoF receiver, which converts the signals back into RF and applies additional amplification and filtering before digitization. An ICE-based system performs the digitization, channelizing, and corner turn. The data are then passed to the GPU X-engine for correlation.

**Fig. 3** HIRAX signal chain schematic. In each dish, an active dual-polarization feed receives and amplifies incoming radio signals. The signals are filtered, further amplified, and converted to optical light with an RFoF transmitter at the dish focus. Optical fiber transports the signals to an RFoF receiver, which converts the signals back into RF and applies additional amplification and filtering before digitization. An ICE-based system performs the digitization, channelizing, and corner turn. The data are then passed to the GPU X-engine for correlation.

2.2 **Dishes and Mounting Structure**

Each HIRAX telescope will have a parabolic reflector with a diameter of 6 m and focal ratio of $f/0.23$. The dish size was chosen to maximize collecting area over the minimum baseline lengths, and the low focal ratio allows the entire receiver support structure to sit below the aperture plane, thus reducing cross-talk between neighboring dishes. Each dish will be supported by a mounting structure that is stationary in azimuth and that can be manually repositioned in zenith angle over a range of $\pm 30$ deg to incrementally build up sky coverage. The HIRAX redundancy requirements have strict implications for the allowed tolerances on the dish surface and the mount alignment, which impact the on-sky beam shape and pointing, respectively. In general,
the requirements on dish and mount precision are far more stringent than the requirements on accuracy. The precision requirements are discussed in further detail in Sec. 4.

Dish fabrication methods using composite materials with an embedded reflective layer are well suited for meeting the HIRAX requirements while being cost effective. Fabricating all of the dishes using a small number of molds ensures that variations across the array are kept to a minimum. Composite materials also have high strength-to-weight ratios and are therefore excellent candidates for minimizing gravitational distortion of the dish surfaces as the telescopes are repointed. One prototype composite dish has been installed at the HIRAX test site at the Hartebeesthoek Radio Astronomy Observatory (HartRAO), and other prototyping efforts are currently underway. Further details about the HIRAX prototype dishes and design are available in Ref. 39.

2.3 Dual-Polarization Cloverleaf Feed

HIRAX will use a dual-polarization cloverleaf feed based on the design that was developed for CHIME. In contrast to the CHIME feed, which is passive, the HIRAX feed is active and provides on-board amplification with a powered balun. Each polarization of the HIRAX feed consists of a balun that uses an Avago MGA-16116-dual amplifier, providing a gain of 22 dB, and the difference between the outputs are amplified by 21 dB using a Mini-Circuits PSA4-5043+. Each feed is mounted inside a cylindrical can, which circularizes the beam and helps reduce cross-talk. Each feed and can assembly will be supported at the dish focus with a radio-transparent central column that extends upward from the vertex. The column will provide environmental protection by fully enclosing the feed assembly, and the cables will be routed along the boresight axis to minimize their impact on beam asymmetry and sidelobe levels. Measurements of the noise performance of the HIRAX feed and its repeatability is described in Ref. 41.

2.4 Radio Frequency over Fiber System

HIRAX will make use of a purpose-built RFoF system to transmit the received radio frequency signals to the digital backend for processing. Signals received by the HIRAX feed are band limited to 400 to 800 MHz and passed through an additional 22 dB amplification stage before being intensity modulated on an optical carrier at the focus using an RFoF transmitter. Optical fibers carry these signals to a central processing hub, where RFoF receivers convert the signals back into RF. The RF signals are subsequently amplified and filtered again (25 dB gain, 400 to 800 MHz) before being passed to the digitizer. For the long (~1 km) length of the HIRAX cable runs from the telescopes to the central hub, especially looking ahead to the planned 1024 element array, the combination of RFoF electronics and optical fibers provide a more cost-effective solution than copper coaxial cables. The RFoF transmitter and receiver design is based on technology that was developed by CHIME (although ultimately unused in the final experimental configuration). The transmitter contains a laser diode (AGX Technologies, FPMR3 series) that is intensity modulated by the incoming RF signal, and the receiver contains a photodetector (AGX Technologies, PPDD series) that converts the transmitted optical signal into RF.

2.5 ICE-Based F-Engine

The digital backend for HIRAX consists of an FX correlator, with the F-engine composed of an ICE-based digitization and channelization system. The F-engine for HIRAX-256 will be made up of 32 ICE boards, each processing 16 inputs from 8 dual-polarization feeds. These ICE boards are contained in two ICE crates, each hosting 16 boards. The system for HIRAX will match that of CHIME which is described in more detail in Refs. 38 and 45. Briefly, the ICE boards use custom FPGA-based electronics to digitize the incoming signals from the RFoF system at a precision of 8 bits (7.2 effective number of bits, K. Bandura, Private Communication.) over the full 400 MHz of bandwidth. For the channelization step, these digitized signals are processed by a polyphase filter bank and fast Fourier transform (FFT)-based pipeline, producing the 1024 frequency channels (390 kHz wide) that are passed to the correlator. This system also performs the real-time corner-turn operation, which arranges the outgoing data such that each node of the
X-engine receives data streams from all inputs over the subset of the bandwidth to be processed by that node. This corner-turn is performed in multiple stages with data reshuffling occurring via communication within ICE boards, between ICE boards mounted in the same ICE crate, and finally between ICE crates. After this stage, the outgoing data streams are transferred to the GPU-based X-Engine over a dedicated 40 Gbps network. For the 1024-element array, this system will be scaled up to 128 ICE boards and 8 ICE crates. For HIRAX-256, this system will process and forward data to the correlator at a rate of 1.65 Tbps, with the 1024 element system processing 6.6 Tbps.

2.6 GPU Correlator

The HIRAX-256 X-engine is a dense, GPU-based system consisting of 8 nodes, each processing 128 channels or 50 MHz of bandwidth using a pair of NVIDIA A40 GPUs. These nodes will perform full $N^2$ correlation of the incoming data streams from 512 inputs (two orthogonal polarizations per dish). The full specifications of each of these correlator nodes is shown in Table 2. This system will produce raw visibility data for each baseline with an integration time of $\sim 10$ s. Additional outputs from these nodes will include formed beams for the FRB and HI absorber search pipelines as well as for the pulsar search and monitoring systems, described in more detail in Sec. 3.2. This system represents a very dense and powerful correlator, processing 1.6 Tbps of data in a single rack, eight times more bandwidth per node than the CHIME X-engine. This has largely been enabled by making use of the increased I/O performance of PCIe 4.0 for both the GPU and network card interconnects. The X-engine makes use of the kotekan software also used by CHIME and CHORD. The correlator will be scaled up for the 1024-element array, potentially with an even denser layout depending on hardware developments.

2.7 On-Site Science Data Processing

Both the visibility data and the beam-formed data from the X-engine will be sent to the on-site science data processing system. This system will handle the initial calibration and baseline stacking operations for the cosmological analysis, produce data products for the HI absorber studies, and perform the real-time transient searches. Additionally, it will manage and accumulate incoming housekeeping data streams for later use. Reduced data products will be synchronized to offsite computing centers for further processing and long-term storage.

3 Data Analysis Methodology

3.1 Cosmological Survey

HIRAX will operate as a survey instrument to map the large volumes required for precise measurements of the BAO signal. The 21 cm cosmology science goals largely drive the system...
requirements (Sec. 4) for the array as a whole and the constituent telescopes. Here we begin by outlining the top-level survey parameters that are required to meet the HIRAX BAO science goals.

To reduce cosmic variance, HIRAX will survey \( \sim 15,000 \) deg\(^2\) from declinations \(-60 \leq \delta \leq 0\) deg (Fig. 1) over a 4-year period with an observing efficiency of \(\sim 50\%\). The amount of time per fixed-elevation pointing of the array will be chosen to deliver a survey sensitivity uniform in declination across the mapped sky area to within 1.5\%. To probe the 21 cm power spectrum on BAO scales requires sensitivity to radial wavenumbers in the range \(0.03 < k \parallel < 0.2\) Mpc\(^{-1}\), which can be achieved with the specified bandwidth and channelization, and sensitivity to transverse wavenumbers in the range \(0.05 < k \perp < 0.16\) Mpc\(^{-1}\), which can be achieved with baseline separations covering a minimum range of 8 to 110 m, as can be seen in Fig. 4(a). The HIRAX survey sensitivity is shown in Fig. 4(b), which demonstrates that HIRAX is optimized to measure BAO scales where it is competitive with other planned intensity mapping and galaxy redshift surveys (for more details on the calculation of these sensitivity estimates, see Refs. 9 and 50).

The angular scales probed by HIRAX, targeted at constraining dark energy by making use of the BAO feature, complement the angular scales and thus the science probed by the SKA1-MID surveys as can be seen in Fig. 4(b). The SKA1-MID SD survey will probe very large angular scales and be sensitive to ultra-large scale features such as primordial non-Gaussianity and general relativistic corrections to cosmological observables,\(^{51}\) whereas the SKA1-MID IF survey will be sensitive to smaller angular scales and thereby constrain the density and bias of neutral hydrogen on small scales.

### 3.1.1 Fisher forecasts

We evaluate the cosmological constraints that can be achieved with HIRAX using the Fisher forecast method following the approach of Ref. 9 (for reviews on observational approaches to constraining cosmological parameters with BAO measurements, see Refs. 52–54). Our analysis is restricted on small scales to linear modes, on large transverse scales by the minimum baseline length, and on large radial scales by filtering of foreground modes below \(k_\parallel^{\text{BG}} \sim 0.01\) Mpc\(^{-1}\).
In Fig. 5(a), we show forecasts for the measurement of the BAO signal in the power spectrum, demonstrating that HIRAX should resolve this feature with high significance. This in turn leads to percent level constraints on the volume-averaged distance measure,

$$DV(z) = \frac{czD_M(z)}{H(z)}^{1/3},$$

in several redshift bins as shown in Fig. 5(b). Also shown in Fig. 5(b) is a compilation of recent BAO constraints from SDSS galaxy, quasar, and Lyman-α surveys.\textsuperscript{1,56–63}

We explore cosmological parameter constraints for three different cosmological models, ΛCDM, wCDM, and $w_0w_a$CDM. Here $w$CDM allows for variation in a fixed dark energy equation-of-state parameter $w$, whereas $w_0w_a$CDM fits for an evolving equation-of-state $w(a) = w_0 + (1 - a)w_a$, as in Ref. 52. Marginalized constraints on a subset of the full parameter set are shown in Table 3 for the HIRAX 256-element and 1024-element arrays including priors based on constraints from the Planck Satellite.\textsuperscript{55} These are compared to current state-of-the-art constraints from the eBOSS cosmology analysis,\textsuperscript{2} which are combined with constraints from Planck, Pantheon SNe Ia,\textsuperscript{64} and DES Y1.\textsuperscript{65}

In Figs. 5(c) and 5(d), we show marginalized parameter contours for the dark energy equation-of-state parameters as well as large-scale structure parameters $\Omega_M$ and $\sigma_8$, respectively, for both the HIRAX 256-element and 1024-element arrays with Planck priors. The computed dark energy figures of merit (FoM\textsuperscript{52}), corresponding to the inverse of the area enclosed by the 68% confidence contours in the marginalized $w_0 - w_a$ constraints, are 60 for HIRAX-256 and 360 for HIRAX-1024. This is competitive with other planned dark energy experiments.\textsuperscript{7}

In Fig. 5(a), we show forecasts for the measurement of the BAO signal in the power spectrum, demonstrating that HIRAX should resolve this feature with high significance. This in turn leads to percent level constraints on the volume-averaged distance measure, $DV(z) = [czD_M(z)/H(z)]^{1/3}$, in several redshift bins as shown in Fig. 5(b). A prior based on Planck\textsuperscript{52} results has been added. We note that the change in degeneracy direction for the $\Omega_M$ and $\sigma_8$ contours between HIRAX-256 and HIRAX-1024 is due to the different relative contributions of the Planck prior to the combined constraints.

Fig. 5 Forecast constraints on (a) the BAO feature of the matter power spectrum; (b) distance scale, $DV$ evolution; (c) dark energy equation of state parameters $w_0$ and $w_a$; and (d) large-scale structure parameters $\sigma_8$ and $\Omega_M$, for HIRAX-256 and HIRAX-1024. The parameter contours shown represent 68% and 95% confidence intervals (shaded and lightly shaded regions, respectively). A prior based on Planck\textsuperscript{52} results has been added. We note that the change in degeneracy direction for the $\Omega_M$ and $\sigma_8$ contours between HIRAX-256 and HIRAX-1024 is due to the different relative contributions of the Planck prior to the combined constraints.
Planck prior dominates the $\Omega_M$ constraint but that the HIRAX 1024-element array, in particular, can further constrain $\Omega_M$ and $\sigma_8$.

### 3.1.2 Cosmological analysis pipeline status

We can obtain more realistic forecasts for HIRAX 21 cm power spectrum constraints using detailed telescope simulations. We adopt the $m$-mode approach,\textsuperscript{66-68} which is appropriate for a drift-scan instrument such as HIRAX. Decomposing daily scans into $m$-modes along the sidereal time direction allows us to decouple these modes and analyze them independently, which makes the analysis of large arrays computationally tractable. The simulated visibility $v = Ba + n$ can be written, for all baselines and frequencies, as a sum of the sky signal $a$ processed by the instrument response or so-called beam transfer matrix $B$ and instrument noise $n$. The beam transfer matrix encodes information about the telescope beam and pointing, the baseline layout, and the instrument noise. Here we consider a Gaussian primary beam but directivities estimated from electromagnetic simulations of the HIRAX antenna\textsuperscript{39} can also be used in the simulation pipeline. The input sky model comprises simulated 21 cm fluctuations with Gaussian statistics and simulated Galactic and extragalactic foregrounds. Currently, these are generated using Gaussian random field realisations of an input 21 cm power spectrum as well as a Galactic foreground model based on that of Ref.\textsuperscript{69} with the large-scale spatial distribution of the signal constrained to be similar to that of the Haslam 408 MHz map.\textsuperscript{70} Future efforts include making use of a more sophisticated signal model based on an empirical HI halo model applied to $n$-body simulations. Given an instrument model and survey specification, the beam transfer matrix can be computed and is used to generate synthetic visibility data. In the results shown here, we use a compact grid of $7 \times 7$ dishes (covering the most cosmologically relevant angular scales) and assume a survey conducted over declinations from $-40 \text{ deg}$ to $-20 \text{ deg}$ through seven repointings of the array. The noise is scaled such that the redundancy of the baselines of this $7 \times 7$ subarray is equivalent to that of the 1024-element array with a survey length of 4 months of integration time per simulated fixed-elevation pointing of the array.

The process of estimating a power spectrum from simulated data is adapted closely from Ref.\textsuperscript{67} but we briefly outline it here. In the results shown here, the simulated visibilities are assumed to have negligible calibration residuals but the inclusion of a realistic calibration

|                      | $\sigma_8$ | $\Omega_M$ | $w_0$   | $w_a$   |
|----------------------|-----------|------------|---------|---------|
| **HIRAX-256 + Planck** |           |            |         |         |
| $\Lambda$CDM        | 0.0044    | 0.0039     | —       | —       |
| $w$CDM               | 0.0047    | 0.0042     | 0.0739  | —       |
| $w_0w_a$CDM          | 0.0053    | 0.0043     | 0.1223  | 0.4332  |
| **HIRAX-1024 + Planck** |           |            |         |         |
| $\Lambda$CDM        | 0.0027    | 0.0034     | —       | —       |
| $w$CDM               | 0.0028    | 0.0036     | 0.0316  | —       |
| $w_0w_a$CDM          | 0.0038    | 0.0037     | 0.0506  | 0.1965  |
| **eBOSS + Planck + SNe Ia + Lens.** |           |            |         |         |
| $\Lambda$CDM        | 0.0056    | 0.0047     | —       | —       |
| $w$CDM               | 0.0092    | 0.0066     | 0.027   | —       |
| $w_0w_a$CDM          | 0.0093    | 0.0069     | 0.073   | 0.5200  |
pipeline and handling for data excised due to radio-frequency interference, is being developed. The visibility dataset is then compressed by filtering out modes that the HIRAX baselines are insensitive to using singular value decomposition. The next step involves deprojecting galactic and extra-galactic foregrounds, which is the main challenge for a detection of 21 cm intensity fluctuations. Foreground removal relies on smooth spectral behavior of the foregrounds and involves high-pass spectral filtering of the data to retain primarily the high-frequency spectral 21 cm modes. Here we apply a Karhunen–Loève filter based on an ideal instrument with perfect statistical knowledge of the foregrounds. The power spectrum binned in $k$ and $k_{\perp}$ is then estimated from the filtered data.

Fig. 6 Estimated relative errors in recovered $P(k, k_{\perp})$ band-powers (from diagonal elements of the derived covariance matrices) more than 100 MHz subbands spanning the HIRAX bandwidth using the $m$-mode pipeline. A foreground filter has been applied here assuming ideal knowledge of the instrument.

The plots in Fig. 6 show examples of the estimated power spectra constraints using the $m$-mode approach for a Gaussian beam in four different uniform frequency bands. In this case, the mixing matrix for an unwindowed estimator is used (see Ref. 68 for a detailed discussion on different quadratic power spectrum window functions). At the relevant scales of interest as mentioned above and depending on frequency channel considered, we find the binned power spectrum is recovered with relative error from 5% to 8% in the approximate range of $0.05 < k < 0.10 \, h \, \text{Mpc}^{-1}$, noting that the set of baselines considered in these simulations also affects these limits. A minimum-variance power spectrum estimator reduces the uncertainties by about a factor of two at the price of a more complicated correlation structure between the bins. In future work, estimated cosmological constraints will be derived from these power spectrum estimates and contrasted with the Fisher matrix results in Sec. 3.1.1.

### 3.1.3 Systematics analysis

We have additionally extended the above analysis to examine the effect of unmodeled systematics on the extraction of accurate power spectra. This involves injecting systematic perturbations to the simulated visibilities by assuming distributions of systematic parameters that affect the primary beam, pointing or array layout of the simulated telescope. For the primary beams, electromagnetic simulations of the HIRAX dish-feed systems have been performed, including parameter sweeps of physical tolerances of the system under investigation such as feed positioning relative to the dish. Linear models for the perturbations arising from small changes in these tolerances on the beam directivities are then constructed and propagated to the visibilities which
are run through the power spectrum estimation pipeline. For layout-based effects such as errors in dish positioning, a similar approach is used where the linear order perturbation on the visibilities due to these uncertainties are propagated through the pipeline. In both cases, care is taken to keep track of systematic correlations between baselines due to sharing systematics from the same dishes. This analysis was used to inform aspects of the system level requirements outlined below in Sec. 4.

3.2 Beamforming and Real-Time Analysis

HIRAX will sum the channelized baseband data from the array elements to form beams on the sky for use in the transient/FRB, pulsar, and HI absorber searches. The HIRAX beamforming will be fully described in future work, but we provide a brief overview here.

The summing required for the beamforming operation reduces to a Fourier transform for a calibrated, planar array. Each location of a formed beam on the sky then corresponds to a frequency-dependent \( k \) in this Fourier transform. For a close packed array, there are roughly as many independent beams inside the primary beam as there are antennas so, for \( n \) antennas, and with \( n \) beams, the total computational cost becomes an order \( n^2 \) matrix multiplication. The visibilities already cost \( n^2 \) to generate, and so this brute force beamforming at worst increases the computational burden on the correlator by a constant, order unity factor. For regularly spaced antennas, FFTs can be used at single frequencies to potentially significantly speed up this process. However, FFTs naturally pick out integer values of \( k \) and therefore require additional steps to align the beams across frequencies, which is important for detecting dispersed signals. Since modern GPUs are sufficiently performant at the low-bit-depth matrix multiplications required by the brute force beamforming, we find this approach attractive for a 256-element array. For example, for 4-bit operations, the NVIDIA RTX 3090 as well as the NVIDIA A40s in use in the HIRAX-256 X-engine are capable of over 500 tera operations per second. If this processing rate can be achieved in practice, a single GPU has enough processing power to form 256 beams from 256 HIRAX antennas. Preliminary GPU kernels have been developed and found to perform within a factor of two of the theoretical limit.

With the decision to use a brute force beamformer, we can now describe how the HIRAX beamforming will work. The beam-crossing time is relatively short for HIRAX (\( \sim 1 \text{ min} \)) and so we will use tracking beams that follow sources as they transit the primary beam. The RMS per-antenna errors introduced using 4-bit arithmetic are \( \sim 3 \text{ deg} \) with an RMS amplitude fractional error of 0.035. Since the data from the F-engine arrive as 4-bit integers, and the errors introduced by 4-bit beamforming are small, we plan to use 4-bit arithmetic to do the beamforming. The beamforming phases will be updated approximately every second. We plan to beamform the intensity data only, using both \( XX \) and \( YY \) polarization, and do not plan to form real-time cross-polar beams. Since many scientific uses of the formed beams require higher frequency resolution than that provided by the F-engine, the formed beams will be upchannelized (resampling at higher frequency resolution and hence number of channels, see Refs. 71 and 72) before being squared and summed to produce high-frequency-resolution power beams. These upchannelized beams can then either be integrated in the X-engine for the 21 cm absorber search or passed to the FRB backend for the FRB search. We additionally will send a small number (\( \sim 10 \)) of non-squared beams to the pulsar backend for the pulsar search. This gives the pulsar backend the option of carrying out coherent dedispersion for millisecond pulsar searches. The utility of HIRAX-256 for pulsar studies is still under study but we expand upon the planned FRB survey below.

3.2.1 Fast radio burst survey

The HIRAX FRB survey will use the search pipeline developed for CHIME. 71 Briefly, the formed, upchannelized beams will be sent to a separate search engine, where they will be searched for transient events incoherently (for efficiency). The search will be carried out by a computationally efficient tree-dedispersion algorithm. Detected FRBs will be flagged, and baseband data will be written to disk for offline analysis. The instantaneous detection threshold will be around 10 \( \sigma \), though the exact threshold will need to be tuned on-site and will depend on
the false positive rate from local RFI. At 256 dishes, HIRAX has similar collecting area and sensitivity to CHIME, and so we expect the redshift and DM distributions will be similar to the CHIME FRB catalog. With a smaller field of view, we expect an event rate roughly half of CHIME’s or about 1 FRB per day.

We will build a minimum of two outrigger stations of 8 to 16 dishes each in order to localize FRBs detected by HIRAX to subarcsecond accuracy. The central goal is to localize the FRBs to within a host galaxy for the large majority of HIRAX FRBs. Additionally, with ~1000 km baselines, we hope to localize FRBs to tens of milliarcseconds (mas) for studies of FRB environments within their host galaxies. Bandwidth constraints prevent us from continuously streaming baseband data, so the outriggers will store 1 to 2 min of baseband data in memory (45 GB/s/dish required). When the core detects an FRB, it will send a trigger to the outriggers that will then write their baseband data to disk, for offline correlation. Postprocessing of the core data will typically result in a higher SNR than the initial detections. Reasons include the ability to reform a beam directly on the FRB, coherently dedisperse the data, and expend more effort on RFI mitigation. We expect 15σ to be typical for the postprocessed SNR. We target 5σ detections between the core and each outrigger station, which results in outrigger station sizes of 16 to 24 dishes. At a fixed false-positive rate, there is an increase required in the SNR due to the possibly large phase space over which one is searching for possible FRBs. For two-dimensional searches using narrowband, very long baseline interferometry data, this factor can be large. However, since we are targeting a detection by each station when correlated against the core, the result is a single timing offset from broadband data, so calculations show the phase-space effect is small for HIRAX. Further, the bulk of the expected false positives arise from small enough timing errors that we would still localize the FRB to the correct galaxy.

Localizations will be fundamentally tied to astronomical calibrators, and we plan to be able to calibrate using observations up to ~1 h after the FRBs occur. We have demonstrated moderately priced off-the-shelf clock systems that are capable of holding the sub-ns timing accuracy we need on multi-hour timescales. At HIRAX frequencies, ionospheric corrections are important, and we plan to use a combination of astrometric calibrators, GNSS satellites, and real-time publicly available ionospheric maps. The worst-case scenario of using publicly available ionospheric maps/models corresponds to a typical uncertainty of a few tenths of a TEC unit (The total electron content or TEC of the ionosphere is reported in units of $10^{16}$ e$^{-}$/m$^2$. 1 TEC unit corresponds to a DM of $3.3 \times 10^{-7}$), which translates to roughly 1 ns. For outrigger separations of ~1000 km, this corresponds to a 60-mas error, and so we do not expect the ionosphere to limit our ability to assign FRBs to host galaxies.

## 4 Instrument Requirements

With the science requirements and analysis methods described in Sec. 3, we can now define the following high-level system requirements for the HIRAX array. The system requirements are derived by propagating the higher level science requirements, starting from the top-level requirement on the dark energy FoM, to lower level system requirements based on the simulations methodology described in Sec. 3. The survey and array layout system requirements were described in Sec. 3.1, and here we focus on the requirements for the ensemble of telescopes comprising the array. Since there are typically multiple system requirements that are derived from any given individual science requirement, we consider trade-offs in tolerances for the system requirements to allocate the error budget. Across the HIRAX array, we find that the gains must be stable to 1% over 1-min integrations across the full bandwidth, relative bandwidths must be stable to 0.75% over the beam crossing time, and the tolerance on the primary beam FWHM must be 0.05% across the full bandwidth. In addition, the dishes should have an aperture efficiency of 0.7, the antenna cross-talk should contribute an excess noise level of no more than 10 K on the two shortest dish separations, and the antenna spill should have a maximum noise level of 5 K at 400 MHz, increasing to 10 K at 800 MHz. Finally, telescope pointing and positioning must be repeatable across the array: we require that the dish boresight vectors must be parallel within 5’ RMS, the foci of all dishes must lie in a plane with <5 mm RMS deviation orthogonal to the plane, and the foci must form a regularly spaced grid with separation distances precise to
We note that the analyses used to derive these constraints were based on science targets for the 1024-element array as the requirements will be fixed across the expected array deployments.

The system requirements for the array as a whole form the foundation for defining more specific requirements for the HIRAX telescope mechanical structure, comprising the dish, mount, and receiver support structure. In total, we have defined over 60 specifications that are discussed in detail in the HIRAX telescope mechanical assembly requirements document, which is available online. Broadly speaking, tolerances related to redundancy fall into two general categories: pointing or positioning error and beam error. Pointing and positioning errors are analyzed with a simple geometric model of the telescope to compute the error stackup. Starting with the requirements for boresight vector parallelism and foci positioning within a plane, the error budget is allocated to various telescope subcomponents in accordance with the mechanical difficulty of meeting each target. The telescope parameters that are governed by this geometric error stackup include the dish vertex position relative to the elevation axis, orthogonality of the dish boresight vector and elevation axis, position and alignment angle of the elevation axis within the array, and the elevation pointing angle. Errors in the beam shape are assessed with electromagnetic simulations of the dish, receiver, and receiver support structure. We use CST Studio Suite to simulate the impact of the receiver position with respect to the dish focus, receiver orientation angle relative to the boresight vector, and deviations in the dish surface with respect to the average best-fit paraboloid. Table 4 summarizes the target precision values for the most important telescope mechanical parameters.

<2.5 mm RMS. We note that the analyses used to derive these constraints were based on science targets for the 1024-element array as the requirements will be fixed across the expected array deployments.

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5 Current Status and Conclusions

The design of most aspects of the 256-element HIRAX deployment has been finalized, and site development is expected to commence in 2022. Currently, multiple hardware testing activities are underway, with instrumented prototype \( f/0.38 \) and \( f/0.25 \) dishes deployed at HartRAO for RF front-end characterization, and parallel efforts in progress at Dominion Radio Astrophysical Observatory and the Green Bank Observatory. Beam characterization analyses using drone-based and holographic measurements are being carried out. The design of the F- and X-engine systems are complete and the 256-element X-engine is assembled, with one node deployed at the Bleien Observatory in Aargau, Switzerland, for trial operation using on-sky data. A significant milestone has been reached in the finalization of the specification for the telescope mechanical system, with the expectation that initial deployed dishes making use of the final design should be assembled for testing in 2022.

HIRAX-256 will be a powerful instrument for 21 cm cosmology, radio transient, and HI absorber science. While much emphasis has been placed on the control of systematics from

### Table 4 Target precision values for HIRAX telescope mechanical structure.

| Telescope mechanical parameter                                      | Target precision (RMS)       |
|---------------------------------------------------------------------|------------------------------|
| Receiver position relative to focus                                 | 0.5 mm                       |
| Receiver orientation relative to boresight vector                   | 2.5′ polar and azimutal      |
| Dish surface deviations                                            | 1 mm                         |
| Dish vertex position relative to elevation axis                     | 1 mm                         |
| Orthogonality of boresight vector and elevation axis                | 1′                           |
| Elevation axis position within the array                           | 0.5 mm in array plane         |
|                                                                   | 1 mm out of array plane       |
| Elevation axis alignment within the array                          | 1′                           |
| Elevation pointing angle                                           | 1′                           |
a priori studies, we expect the analysis of the initial on-sky data to be extremely informative for progressing the analysis techniques in use as well as the design of future 21 cm experiments.

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