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21cmSense v2: A modular, open-source 21 cm sensitivity calculator

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Summary

The 21cm line of neutral hydrogen is a powerful probe of the high-redshift universe (Cosmic Dawn and the Epoch of Reionization), with an unprecedented potential to inform us about key processes of early galaxy formation, the first stars and even cosmology and structure formation (Liu & Shaw, 2020), via intensity mapping. It is the subject of a number of current and upcoming low-frequency radio experiments, including the MWA (Tingay et al., 2013), LOFAR (van Haarlem et al., 2013), HERA (DeBoer et al., 2017) and the SKA (Pritchard et al., 2015), which complement the detailed information concerning the brightest sources in these early epochs from powerful optical and near-infrared telescopes such as the JWST (Castellano et al., 2022).

21cmSense is a Python package that provides a modular framework for calculating the sensitivity of these experiments, in order to enhance the process of their design. This paper presents version v2.0.0 of 21cmSense, which has been re-written from the ground up to be more modular and extensible, and to provide a more user-friendly interface – as well as converting the well-used legacy package, presented in (Pober et al., 2013, 2014) from Python 2 to 3.

21cmSense can compute sensitivity estimates for both map-making (Barry et al., 2019) and delay-spectrum (Parsons et al., 2012) approaches to power-spectrum estimation. The full sensitivity calculation is rather involved and computationally expensive in its most general form, however 21cmSense uses a few key assumptions to accelerate the calculation:

1. Each baseline (pair of antennas) in the interferometer intrinsically measures a dense blob of 2D spatial Fourier modes of the sky intensity distribution, centred at a particular Fourier coordinate (u, v) given by the displacement vector between the antennas forming the baseline, and covering an area in this (u, v)-space that is given by the Fourier-transform of the primary beam of the instrument. The Fourier-space representation of the sky is thus built up by collecting many baselines that cover the so-called "(u, v)-plane". `21cmSense` approximates this process of synthesising many baselines by nearest-grid-point interpolation onto a regular grid in the (u, v)-plane. Furthermore, importantly the (u, v)-grid is chosen to have cells that are comparable to the instrument's Fourier-space beam size, so that a particular baseline essentially measures a single cell in the grid, and no more. This maximizes resolution while keeping the covariance between cells small. This removes the need for tracking the full covariance between cells, and also removes the need to perform a beam convolution, which can be expensive.
2. We do not consider flagging of visibilities due to RFI and other systematics, which can complicate the propagation of uncertainties.

Some of the key new features introduced in this version of 21cmSense include:

1. Simplified, modular library API: the calculation has been split into modules that can be

used independently (for example, a class defining the `Observatory`, the `Observation` and the `Sensitivity`). These can be used interactively via Jupyter (Kluyver et al., 2016) or other interactive interfaces for Python, or called as library functions in other code.
2. Command-line interface: the library can be called from the command-line, allowing for easy scripting and automation of sensitivity calculations.
3. More accurate cosmological calculations using `astropy` (Astropy Collaboration et al., 2018; Robitaille et al., 2013)
4. Improved documentation and examples, including a Jupyter notebook that walks through the calculation step-by-step.
5. Generalization of the sensitivity calculation. The `Sensitivity` class is an abstract class from which the sensitivity of differing summary statistics can be defined. Currently, its only implementation is the `PowerSpectrum` class, which computes the classic sensitivity of the power spectrum. However, the framework can be extended to other summaries, for example wavelets (Trott, 2016).
6. Improved speed: the new version of 21cmSense is significantly faster than the legacy version, due to a number of vectorization improvements in the code.
7. Built-in profiles for several major experiments: MWA, HERA and SKA-1. These can be used as-is, or as a starting point for defining a custom instrument.

An example of the predicted sensitivity of the HERA experiment after a year's observation at $z = 8.5$ is shown in Figure 2, corresponding to the sampling of the (u, v)-grid shown in Figure 1. The sensivity here is represented as a "noise power" (i.e. the contribution to the power spectrum from thermal noise). This figure also demonstrates that the new 21cmSense is capable of producing sensitivity predictions in the cylindrically-averaged 2D power spectrum space, which is helpful for upcoming experiments.

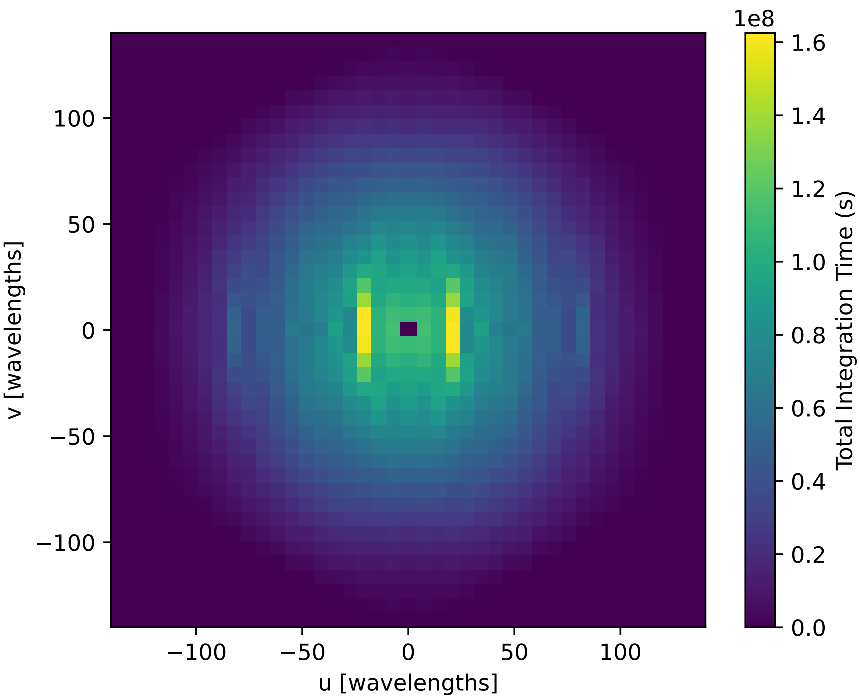

Figure 1: Sampling of the (u, v)-plane for the HERA experiment during a full year of observations.

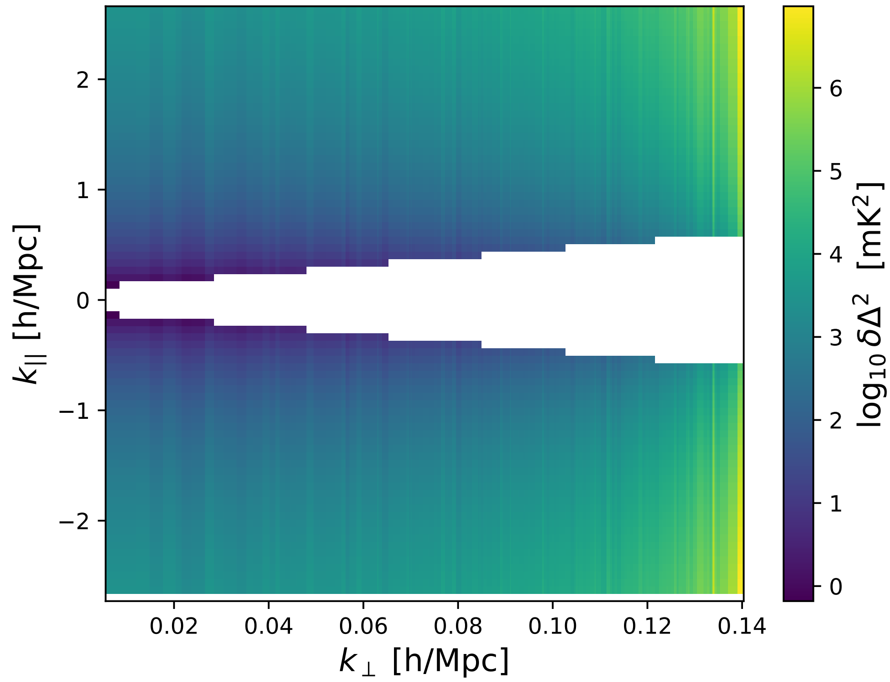

Figure 2: Predicted noise-power of 1000 hours (one year) of HERA observations, as a function of perpendicular and line-of-sight fourier scale. The noise-power is represented for each k-model.

Statement of need

21cmSense provides a simple interface for computing the expected sensitivity of radio interferometers that aim to measure the 21cm line of neutral hydrogen. This field is growing rapidly, with a number of experiments currently underway or in the planning stages. Historically, 21cmSense has been a trusted tool for the design of these experiments (Greig et al., 2020; Pober et al., 2013, 2014) and for forecasting parameter constraints (Greig & Mesinger, 2015, 2017, 2018). This overhauled, modularized version of 21cmSense provides a more user-friendly interface, improved performance, and the extensibility required for the next generation, as evidenced by its usage in the literature (Breitman et al., 2024; Schosser et al., 2024).

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