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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, and 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). 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. (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. The UV grid is chosen to have cells that are comparable to the instrument's beam size. This maximizes UV-resolution while keeping the covariance between UV cells small (since the UV footprint of a visibility does not extend beyond the cell significantly). 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.

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 Schosser et al. (2024).

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