The Journal of Open Source Software

EMBERS: Experimental Measurement of BEam Responses with Satellites

A. Chokshi[1, 3]**, J. L. B. Line**[2, 3]**, and B. McKinley**[2, 3]

1 School of Physics, University of Melbourne, Parkville, Victoria, 3010, Australia **2** International Centre for Radio Astronomy Research, Curtin University, Perth, WA 6845, Australia **3** ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D)

DOI: 10.21105/joss.02629

Software

- Review
- Repository
- Archive

Editor: Monica Bobra

Reviewers:

- @teuben
- @mbobra

Submitted: 31 August 2020
Published: 25 November 2020

Introduction

EMBERS is a python package which provides a modular framework for radio telescopes and interferometric arrays such as the MWA[1], HERA[2], and the upcoming SKA[3] to accurately measure the all sky beam responses of their antennas using weather and communication satellites. Such measurements can reveal environmental factors which have perturbed ideal, simulated beam shapes in complex ways. Results from recent work such as (Line et al., 2018) reveal the presence of gradients in ground screens, dead dipoles, and the effect of foliage near the antennas. Telescopes such as the MWA, HERA & SKA, which may benefit from in-situ beam measurements, are involved in large scale surveys and the search for some of the earliest signals in our Universe. Such studies push the boundaries of precision calibration where undetermined beam errors could potentially introduce spurious contaminants and hinder detections. *EMBERS* could form the backbone of a passive parallel monitoring system for large radio telescopes, concurrently measuring beam shape without any disruption to regular observations, providing astronomers with additional information to include in their instrumental models.

Statement of Need

Large scale implementation of a satellite based beam measurement system have become necessary for the accurate calibration of cutting-edge and next generation radio telescopes. Previous efforts at such techniques have validated this method on a significantly smaller scale. The large data volume recorded over months of observations and the absence of modular, parallelized software packages, necessitated the creation of an automated pipeline for such analyses. *EMBERS* contains modules to pre-process and temporally align raw RF data, download large batches of satellite ephemerides from Space-Track.org[4] and compute the trajectories of satellites using Skyfield (Rhodes, 2019). *EMBERS* implements a unique cross-matching technique to automatically determine the transmission frequency of satellites based on their trajectories and observed RF power. Satellite signals are further processed to remove modulations due to the satellites and non-linear amplification effects, before being projected onto all-sky beam maps.

With plans for extremely large and sensitive interferometric arrays such as the SKA being proposed, the need for a in-situ beam calibration system is critical. EMBERS presents a simple framework for the analysis of large volumes of satellite data, enabling in-situ beam measurements with ease.

[1] https://www.mwatelescope.org
[2] http://reionization.org
[3] https://www.skatelescope.org
[4] https://www.space-track.org

Theory

At the heart of *EMBERS* is a simple concept. Satellite measurements are simultaneously made using multiple Antennas Under Test (AUTs) and reference antennas (ref) which enables us to account for any modulation in transmitted satellite power. The power received by the AUT is the product of the beam response B_{AUT} and the flux transmitted by the satellite F. A reference antenna with a simple, well known beam response B_{ref} is used to record the modulation of the transmitted flux, and can subsequently be used to compute the beam shape of the AUT. The power received by the AUT and reference antenna are $P_{AUT} = B_{AUT}F$ and $P_{ref} = B_{ref}F$ respectively. These expressions can be combined to obtain the beam response of the AUT:

$$B_{AUT} = \frac{P_{AUT}}{P_{ref}} B_{ref}. \tag{1}$$

With each satellite pass, we measure a cross sectional slice of the AUT beam response. With sufficient observation time, an all-sky beam response is built up.

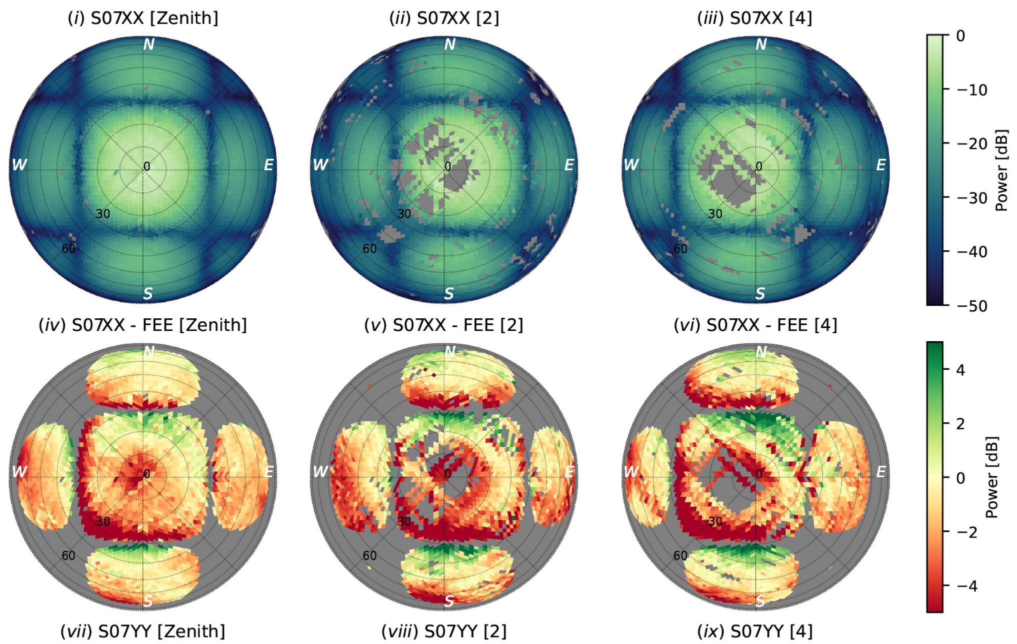

Figure 1: MWA beam maps generated using *EMBERS* with data from (Chokshi et al, in prep). The first row ((i) - (iii)) represent all sky measured beam maps, while the second row ((iv) - (vi)) represent residuals between measurements and cutting edge simulations, with the gray regions denoting the nulls surrounding the primary and secondary beams.

Acknowledgements

I would like to thank Rachel Webster for introducing me to this project and supporting my work. Further, I would like to thank Nichole Barry for her valuable suggestion for improving and expanding *EMBERS*. Parts of this research were supported by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), through project number CE170100013.

References

Line, J. L. B., McKinley, B., Rasti, J., Bhardwaj, M., Wayth, R. B., Webster, R. L., Ung, D., Emrich, D., Horsley, L., Beardsley, A., & al., et. (2018). In situ measurement of MWA primary beam variation using ORBCOMM. *Publications of the Astronomical Society of Australia*, *35*, e045. https://doi.org/10.1017/pasa.2018.30

Rhodes, B. (2019). *Skyfield: High precision research-grade positions for planets and Earth satellites generator* (p. ascl:1907.024).