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Deep radio interferometric imaging with POLISH

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Abstract

Radio interferometry allows astronomers to probe small spatial scales that are often inaccessible with single-dish instruments. However, recovering the radio sky from an interferometer is an ill-posed deconvolution problem that astronomers have worked on for half a century. More challenging still is achieving resolution below the array's diffraction limit, known as super-resolution imaging. The upcoming 2000 antenna deep synoptic array (DSA-2000) will be the first true "radio camera". Its enormous data rate precludes the preservation of raw visibility data and requires imaging to be automated, fast, and in the image plane. To this end, we have developed a new deep learning-based approach for radio interferometric imaging, leveraging recent advances in the classical computer vision problems of single-image super-resolution (SISR) and deconvolution. We have developed and trained a high dynamic range residual neural network to learn the mapping between the dirty image and the true radio sky. We call this procedure POLISH, in contrast to the traditional CLEAN algorithm[1], because dirty images from a radio camera are already relatively high fidelity. POLISH provides super-resolution and achieves more accurate image reconstruction than the traditional image-plane CLEAN algorithm.

1 Introduction

High-resolution imaging of astronomical radio sources plays a critical role in studying our Universe. For next-generation radio surveys such as the DSA-2000, standard imaging algorithms are not adequate: super-resolution and image-plane deconvolution are both required, and neither CLEAN nor Bayesian inspired regularized maximum likelihood (RML) methods can provide both. The feed forward nature of learning-based approaches such as POLISH will therefore be critical for radio cameras. In this summary paper we show that POLISH achieves super-resolution, and we demonstrate its ability to deconvolve real observations from the Very Large Array (VLA). The VLA data prove that POLISH can be used as a generic deconvolution algorithm for radio astronomy, and not just in the special case of radio cameras. Super-resolution on DSA-2000 will allow us to measure the shapes and orientations of several hundred million star forming radio galaxies (SFGs), making it a powerful cosmological weak lensing survey and probe of dark energy. We forecast POLISH's ability to constrain the lensing power spectrum, finding that it will be complementary to next-generation optical surveys such as Euclid.

Bandwidth (MHz)	$PSNR_{\mathrm{POLISH}}$	$PSNR_{\mathrm{CLEAN}}$
1300	55.9±4.7	50.0±6.0
10	55.1±3.8	47.4±3.6

Table 1. Results from a comparison between POLISH and CLEAN for the full-band case (1300 MHz) and the single-channel scenario (10 MHz). POLISH achieves a higher PSNR and SSIM than CLEAN, indicating better pixel-wise and perceptual fidelity, respectively.

2 POLISH

Deconvolution is a classic inverse problem that aims to reconstruct a sharp image by removing an imaging system's PSF from its measured blurry image [2, 3]. The application of neural networks to super-resolution and deconvolution have recently been shown to outperform traditional imaging algorithms in a number of fields. The neural network is trained with a large number of image pairs (dirty image/true sky, or I_d/I_{sky} in our case) such that, when fed an input image the network can reproduce an accurate reconstruction of I_{sky} in less than a minute on a laptop. In Figure 1 we show the POLISH imaging pipeline.

In order to train POLISH, we simulate the microJansky radio sky that DSA-2000 will observe, which is dominated by star-forming radio galaxies (SFRGs). We then add sky noise and convolve with a forward-modelled point spread function (PSF) to generate image pairs, I_d/I_{sky}. To simulate calibration errors and ionospheric effects, each image is convolved with a slightly different PSF, randomly drawn from a physically realistic distribution of PSF perturbations. We then compare image reconstruction performance using the pixel-wise peak signal-to-noise ratio (*PSNR*) and the perceptual metric, structural similarity index measure (*SSIM*)[1]. Results for *PSNR* are shown in Table 1.

[1] https://en.wikipedia.org/wiki/Structural_similarity

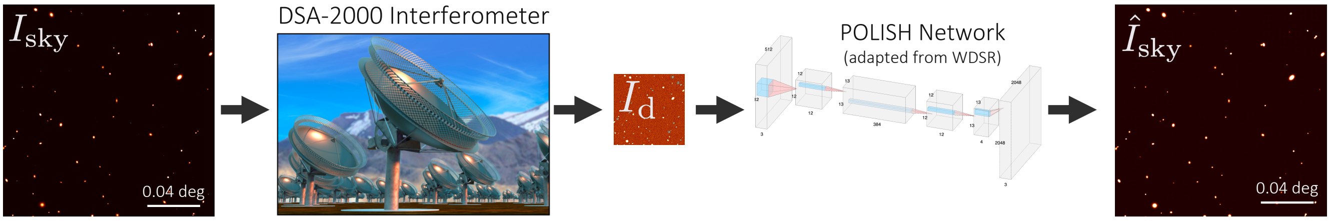

Figure 1. A schematic of the POLISH method of image reconstruction, showing how the true sky is transformed by a radio interferometer and then recovered by our neural network.

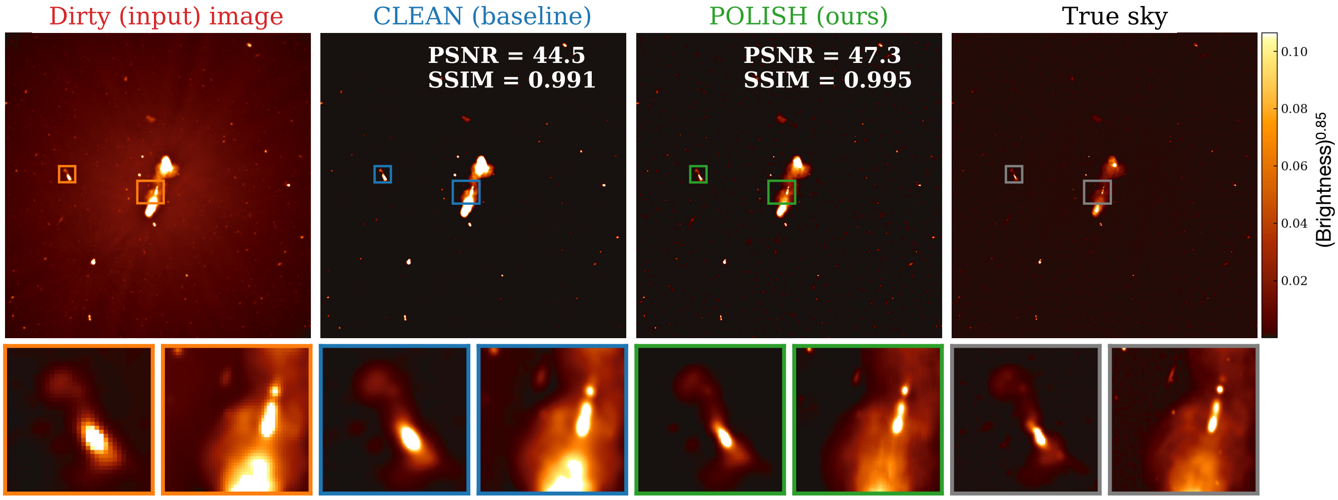

Figure 2. An example of the ability of our neural network POLISH to deconvolve a structured astronomical image. Training data was significantly different from the radio sky image used in this example (training images were composed entirely of simple elliptical Gaussian shapes.

3 Real data from the VLA

In practise, POLISH will be trained offline on simulated data and then applied to real data in quasi-real time. We therefore wanted to test if it can be used to deconvolve real astronomical data. We obtained a dirty image from the Very Large Array (VLA), a Y-shaped, 27-telescope interferometer in New Mexico, including a modelled PSF for that observation's configuration. We then trained a POLISH model on simulatd image pairs using the modelled VLA PSF. POLISH can deconvolve the real VLA dirty image, leaving behind fewer imaging artifacts than a comparison reconstruction using the image-plane CLEAN algorithm. This result is very promising for two reasons. First, we have shown that a relatively simple simulated data set can train a neural network that will deconvolve real radio inteferometric data. Second, the VLA's sampling of the Fourier plane is much less complete than that of DSA-2000, indicating that POLISH can be used as a generic astronomical deconvolution algorithm.

4 Cosmological weak lensing

Resolution below the diffraction limit of $\approx 3''$ on DSA-2000 will allow us to measure the shapes and orientations of several hundred million radio galaxies, enabling a powerful radio weak lensing survey. Weak lensing cosmology can be used to probe the dark matter powerspectrum over cosmic time and to constrain the physical nature of dark energy. By using POLISH in place of image-plane CLEAN, we find that DSA-2000 will significantly outperform the Square Kilometer Array (SKA-1 mid) in radio weak lensing, and will complement optical / near infrared weak lensing studies from the Rubin Observatory and Euclid.

References

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