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A New Synthesis Imaging Tool for ALMA Based on Sparse Modeling

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Abstract. A new imaging tool for radio interferometry has been developed based on the sparse modeling approach. It has been implemented as a Python module operating on Common Astronomy Software Applications (CASA) so that the tool is able to process the data taken by Atacama Large Millimeter/submillimeter Array (ALMA). In order to handle large data of ALMA, the Fast Fourier Transform has been implemented with gridding process. This imaging tool runs even on a standard laptop PC and processes ALMA data within a reasonable time. The interface of the tool is comprehensible to CASA users and the usage is so simple that it consists of mainly three steps to obtain the result: configuration, gridding, and imaging. A remarkable feature of the tool is that it produces the solution without human intervention. Furthermore, the solution is robust in the sense that it is less affected by the processing parameters. For the verification of the imaging tool, we have tested it with two extreme examples from ALMA Science Verification Data: the protoplanetary disk, HL Tau as a typical smooth and filled image, and the lensed galaxy, SDP.81 as a sparse image. The comparison between our results and those of traditional CLEAN method will also be provided.

1. Introduction

In radio interferometry, synthesis imaging from the observed visibility is a crucial step to investigate the detailed spatial structure of the astronomical source. Although the visibility is basically a Fourier Transform of the intensity distribution on the sky, the imaging process is not that simple. An essential and unavoidable problem is that visibility measurement is incomplete so that only part of the Fourier components is known. The most successful algorithm to overcome this is the CLEAN algorithm, which mainly consists of two steps: Fourier Transform to obtain the image with artifacts due to incomplete visibility sampling, and deconvolution no remove those artifacts.

On the other hand, different approaches have recently been introduced to interferometric imaging. We employ the sparse modeling approach, which is known as a technique to solve an underdetermined problem. The method has already been applied to the imaging of Very Long Baseline Interferometry (VLBI) data and it has been shown that the sparse modeling technique is promising method for synthesis imaging (Honma et al. 2014; Akiyama et al. 2017). Based on these results, we have developed the Python module for Radio Interferometry Imaging with Sparse Modeling (PRIISM) to perform synthesis imaging on the data taken by Atacama Large Millimeter/submillimeter Array (ALMA). To facilitate the processing of ALMA data, PRIISM operates on Common Astronomy Software Applications (CASA) and accepts visibility data as a native data format of CASA. In this paper, we briefly describe underlying mathematics and basic usage of PRIISM. We also demonstrate the capability of PRIISM based on the ALMA Science Verification data and comparison with those images generated by CLEAN.

2. Formulation

We formulate the synthesis imaging as least square minimization problem with penalty terms. Given observed visibility v, we find the image x that minimizes

$$\frac{1}{2}|v - F(x)|^2 + \lambda_1|x| + \lambda_{\mathrm{TSV}}\mathrm{TSV}(x), \tag{1}$$

where λ_1 and λ_{TSV} are regularization parameters for two penalty terms. In equation 1, F represents Fourier Transform operator and TSV is the Total Square Variation (TSV) of the intensity distribution (Kuramochi et al. 2018), which is a squared sum of difference between neighboring data. For two-dimensional data, it is represented as

$$\mathrm{TSV}(x) = \sum_{i,j}\{(x_{i,j} - x_{i+1,j})^2 + (x_{i,j} - x_{i,j+1})^2\}. \tag{2}$$

The first term in equation (1) is an ordinary least-square term while the second and third terms are the penalty terms, which are the indicator of a sparsity and a smoothness of the solution, respectively. In each pair of λ_1 and λ_{TSV}, we obtain one image as a solution of the minimization problem. The k-fold cross validation is used to determine the best choice of λ_1 and λ_{TSV} (The value of k can be customized. By default, the 10-fold cross validation is performed). The choice of these two parameters strongly depends on the property of the observed source.

3. Usage of PRIISM

PRIISM is a Python implementation of synthesis imaging problem described in section 2. It has a comprehensible API specific for ALMA (`priism.alma`) as well as a primitive, extendable API, `priism.core`. Typical usage of the `priism.alma` consists of three steps: (1) configuration including solver setup, data selection, image configuration, and gridding setup, (2) visibility gridding, and (3) solve the problem and find the best image by means of the cross-validation. Since PRIISM accepts visibility data as a native data format of CASA, any ALMA data imported into CASA can directly be processed with PRIISM. Example script will be provided with the source code, which only consists of less than 60 lines including comments and spaces for readability. Users of PRIISM can use the example script as a template to process their visibility data. This will facilitate the imaging with PRIISM. With user-specified parameter ranges for λ_1 and λ_{TSV}, PRIISM generates the resulting image automatically. The parameter range should be refined until it hits the most reliable pair of parameters. To accomplish this, two or more iterations might be required. Installation of PRIISM is easily done through `cmake`. Once all the prerequisites are satisfied, PRIISM will immediately be available by running `cmake` with appropriate options followed by `make install`. Currently, PRIISM only supports 1-channel continuum imaging of Stokes I although it accepts multi-channel, multi-polarization (correlation) visibility data. Spectral line and full Stokes imaging will be implemented in the future.

4. Application to the ALMA Science Verification Data

As a verification and demonstration of PRIISM, we generated images from ALMA Science Verification data[1]. We selected two images from the 2014 ALMA Long Baseline Campaign: the protoplanetary disk, HL Tau (ALMA Partnership et al. 2015a), and the lensed galaxy, SDP.81 (ALMA Partnership et al. 2015b). Kosugi et al. (2019) found that the solution immediately converges with modest number of iterations in the case of ALMA data. Therefore, we set maximum number of iterations to 1000 to reduce the computational cost. Indeed, the difference between the images obtained by 1000 and 10000 iterations was negligible. We compared our results with the images provided as a reference that are generated by CLEAN. Figure 1 shows the images for HL Tau and SDP.81 obtained by PRIISM as well as the ones generated by CLEAN. As shown in the figure, PRIISM successfully reproduced striking features for both HL Tau and SDP.81. Several gap features in the disk of HL Tau can easily be recognized. Also, clumpy structure in the Einstein ring of SDP.81 coincides well with the CLEAN image. Figure 1 demonstrates that PRIISM has sufficient ability and flexibility of handling various types of images ranging from smooth, extended sources to clumpy, sparse ones. The figure also illustrates that PRIISM is an effective tool for ALMA that targets a wide variety of astronomical sources.

5. Summary

We developed a new synthesis imaging tool, PRIISM, based on the sparse modeling technique. PRIISM has an interface specific for ALMA and accepts visibility data as a native data format for CASA so that it is possible for users to process ALMA data directly. With minimal set of configurations, PRIISM produces the optimal image automatically. We compared our results with the reference images of the ALMA Science Verification data to demonstrate the capability of PRIISM. We showed that PRIISM successfully reproduced striking features of the target sources. Our result indicates that PRIISM and the underlying sparse modeling technique is a promising tool for the synthesis imaging.

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[1]`https://almascience.nao.ac.jp/alma-data/science-verification`

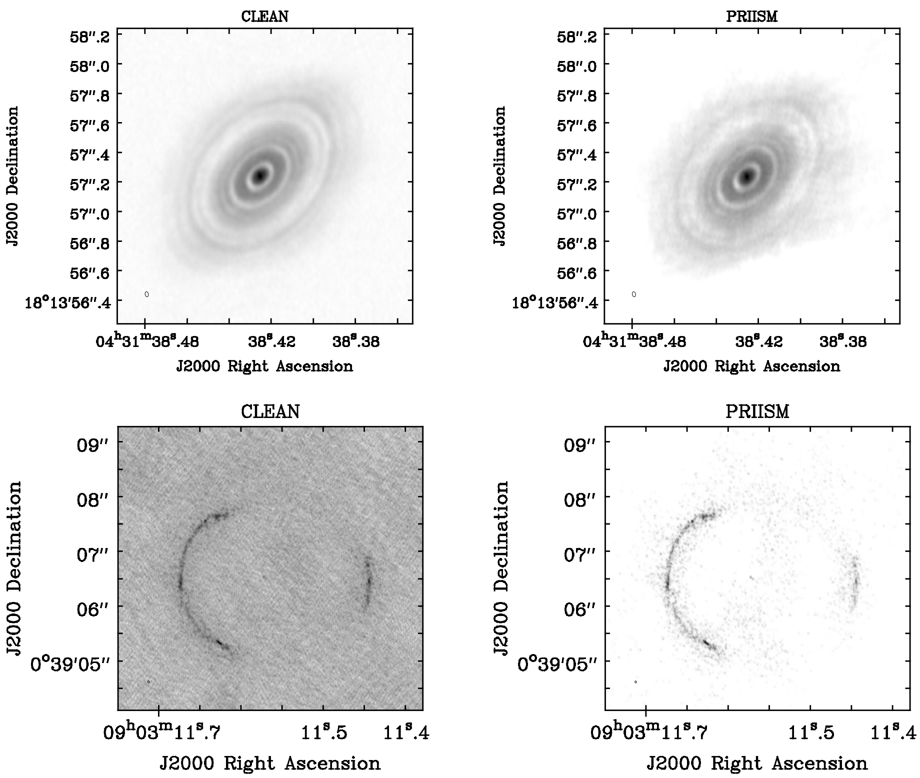

Figure 1. *Top Left:* HL Tau image generated by CLEAN (ALMA Partnership et al. 2015a). *Top Right:* HL Tau image generated by PRIISM. *Bottom Left:* SDP.81 image generated by CLEAN (ALMA Partnership et al. 2015b). *Bottom Right:* SDP.81 image generated by PRIISM.

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References

Akiyama, K., et al. 2017, ApJ, 838, 1

ALMA Partnership, et al. 2015a, ApJ, 808, L3

— 2015b, ApJ, 808, L4

Honma, M., Akiyama, K., Uemura, M., & Ikeda, S. 2014, Publications of the Astronomical Society of Japan, 66, 95

Kosugi, G., Nakazato, T., & Ikeda, S. 2019, in ADASS XXVIII, edited by P. J. Teuben, M. W. Pound, B. A. Thomas, & E. M. Warner (San Francisco: ASP), vol. 523 of ASP Conf. Ser., 575

Kuramochi, K., Akiyama, K., Ikeda, S., Tazaki, F., Fish, V. L., Pu, H.-Y., Asada, K., & Honma, M. 2018, ApJ, 858, 56