Adaptive Beam-forming for Radio Astronomy On GPU

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Abstract

The LOFAR radio telescope consists of tens of thousands of dipole antennas that combine their signals to operate as a single large radio telescope. The truly innovative aspect of this new telescope is that its pointing system is not mechanical. It is steered by combining the electric signals from different elements using advanced beam-forming software. Imaging software is one of the important aspects of processing the high-volume data streams produced by LOFAR, and is one of the best places to use GPUs to achieve processing speed. We were able to achieve up to 30 times performance gain compared to the CPU implementation in novel, computationally intensive techniques such as the Minimum Variance Distortionless Response (MVDR). We have gained 5-6 times speed-up compared to the CPU implementation for standard imaging algorithms.

1. Theory

The fundamental equation that relates the sky brightness distribution to the interferometric measurements in Radio Astronomy is:

$$V(u,v,w) = \int \frac{I(l,m)B(l,m)}{\sqrt{1-l^2-m^2}} e^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))} dldm \quad (1)$$

$V(u,v,w)$ are the so-called "visibilities" recorded by the interferometer. $I(l,m)$ is the image of the sky. $B(l,m)$ is the directional antenna sensitivity pattern. l,m are the directional cosines on the tangent plane of the sky. Assuming that all the antennas are in the same plane, i.e, $w \approx 0$, this reduces (1) to (2).

$$V(u,v,w=0) = \int \frac{I(l,m)B(l,m)}{\sqrt{1-l^2-m^2}} e^{-2\pi i(ul+vm)} dldm \quad (2)$$

In other words, the band-limited image of the sky can be obtained by applying an inverse Fourier transform on the "visibilities" recorded by the interferometer. Because V(u,v) is sampled at a finite number of points (baselines), the resulting image is the true underlying sky convolved with the point-spread-function (PSF), which is the Fourier transform of the spatial sampling function. The goal of interferometric imaging, is to correct the image for the effect of the PSF sidelobes, while retaining the image fidelity.

The Minimum Variance Distortionless Response (MVDR) imaging technique addresses this issue by estimating the optimal PSF at each pixel of the image based on the data itself (non-parametric) and minimizing the side-lobe gains. Despite this very desirable feature, it is computationally very intensive $\sim O((N_{data}N_{pix})^2)$.For a given direction (l,m) in the image plane, the pixel value $I(l,m)$ is calculated using the array steering vector $a_k(l,m)$ as follows:

$$a_k(l,m) = \begin{pmatrix} e^{\frac{2\pi i}{\lambda}(lU_0+mV_0)} \\ \ldots \\ e^{\frac{2\pi i}{\lambda}(lU_P+mV_P)} \end{pmatrix} \quad (3)$$

$$I_k(l,m) = \frac{1}{KP^2}\sum_{k=0}^{K} a_k^H(l,m) R_k a_k(l,m) \quad (4)$$

P is the number of antennas, K is the number of epochs, R_k is correlation matrix, that contains the measured visibility data, and the superscript H denotes the Hermitian transposition operation. Equation (4) is the classic (Bartlett) beamformer with weight vector $W_k(l,m) = \frac{1}{P}a_k(l,m)$. In the more general case, for a weight vector $W_k(l,m)$, the dirty image is given by

$$I(l,m) = \frac{1}{K}\sum_{k=0}^{K} W_k^H(l,m) R_k W_k(l,m) \quad (5)$$

The weight vector for the MVDR beam-former is given in Equation (6)

$$W_{mvdr}^H = \frac{a^H R^{-1}}{a^H R^{-1} a} \quad (6)$$

The weight w_{mvdr}^H minimizes the influence of the interfering sources in the field of view in a given direction i.e, (l,m), while ensuring that the output is undistorted in the absence of noise. Since the matrix R^{-1} may not always exist, we use regularization (diagonal loading) to ensure the matrix is invertible. This regularization factor is later used to decide if a particular epoch image is useful for the final MVDR image.

2. Implementation

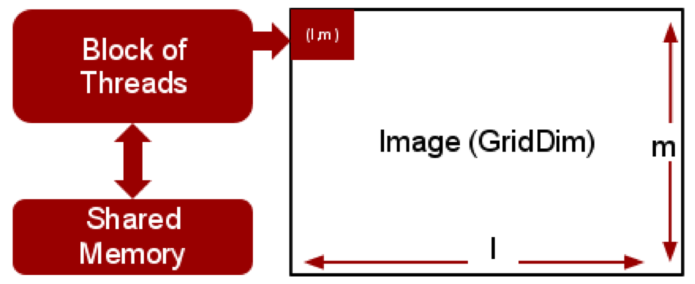

Figure 1: *Block representation of MVDR on GPU*

The kernel is run for each epoch and the output dirty image is saved to disk. These images are then averaged on the GPU to produce the final image.

3. Results

Figure 2: *Aerial view of the LOFAR core stations at Exloo, the Netherlands.*

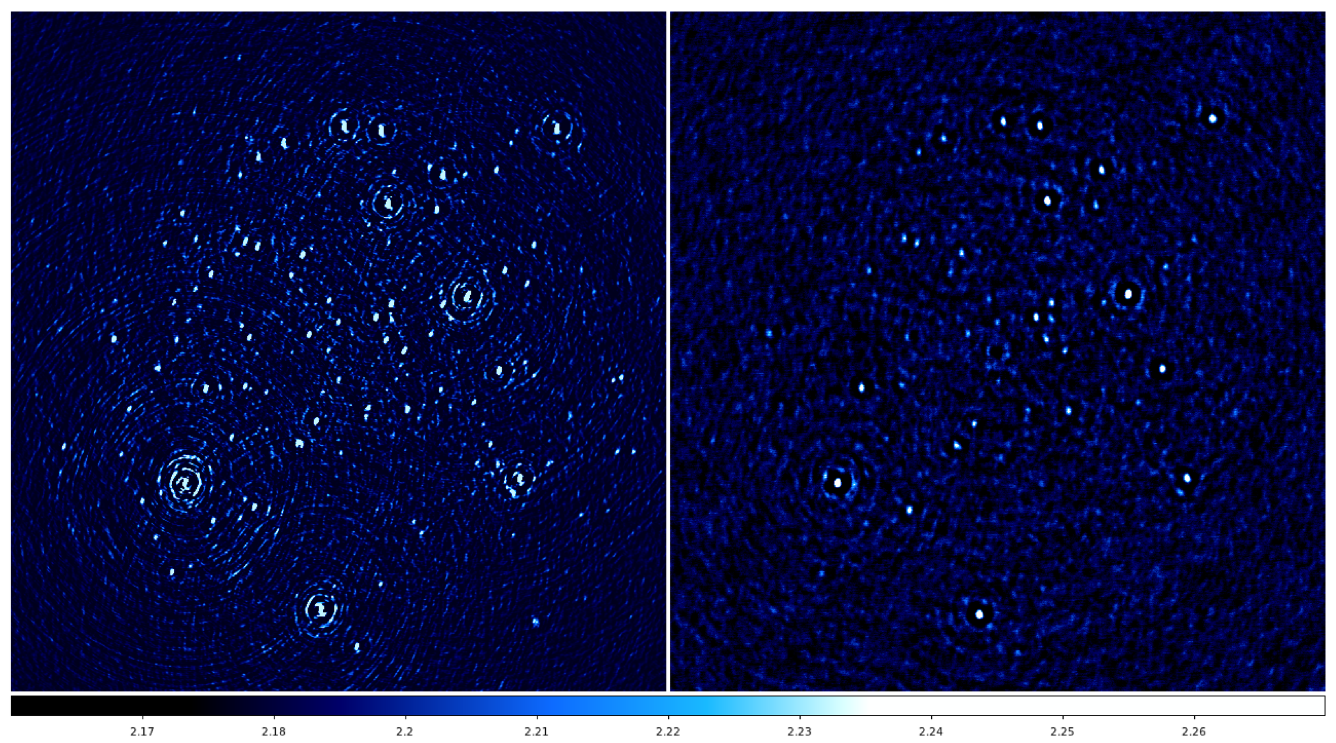

Figure 3: *Image of 3C196 field using the FFT based imager(left) and the MVDR(right). Note that these images have not been deconvolved.*

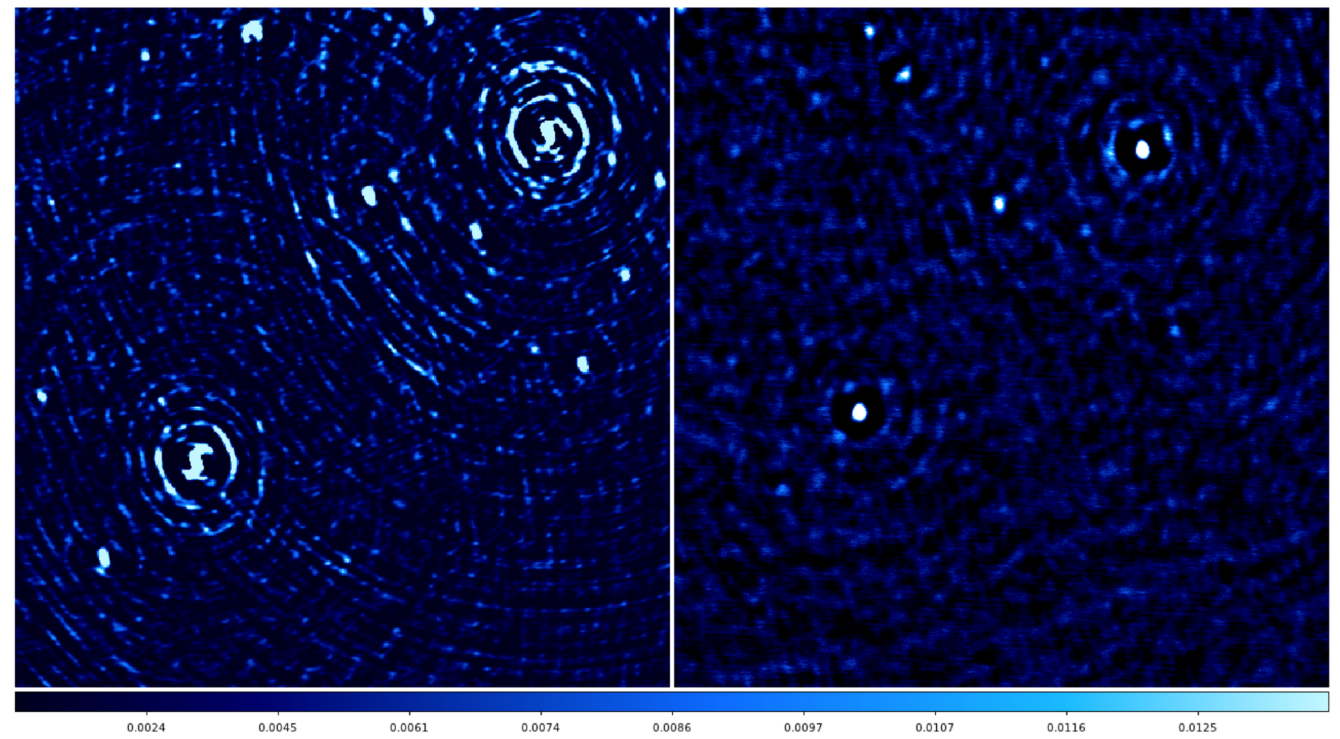

Figure 4: *Zoomed-in region of the previous image using the FFT based imager(right) and the MVDR(left)*

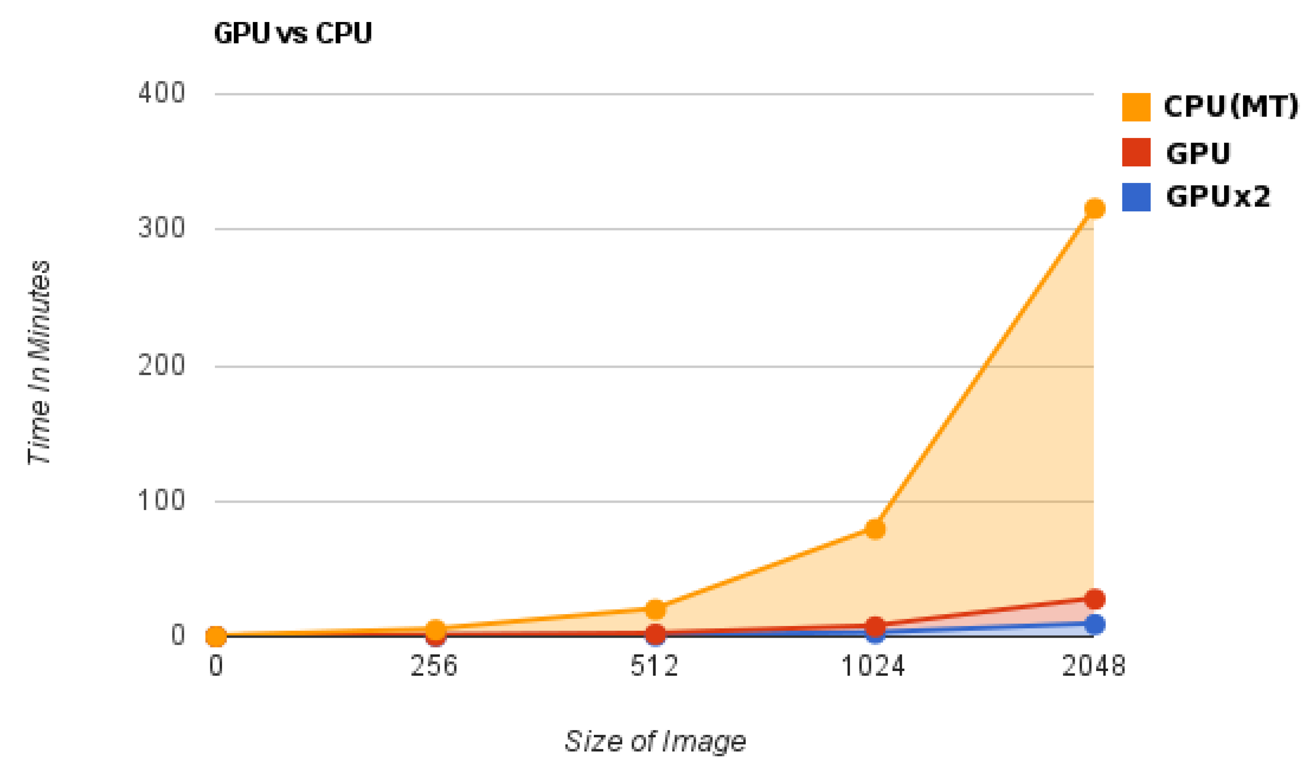

Figure 5: *Performance comparison of the MVDR algorithm on GPU versus the multi-threaded CPU version.*

4. Conclusions

Our work demonstrates that the use of GP-GPU enables us to use optimal imaging algorithms that would otherwise be ruled out because of their computational complexity.

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