

Compressed Sensing Image Reconstruction for CASA

Jonas Schwammberger

Today

Abstract

Solar Flares Abstract

Contents

1	Reconstruction from under-sampled Measurements	1
1.1	Image Reconstruction for Radio Interferometers	1
1.2	Deconvolution of the Dirty Image	2
1.3	Approximation with CLEAN	2
1.4	CLEAN as Compressed Sensing Image Reconstruction	3
2	Inverse Problem for wide Field of View Imaging	5
2.1	Directionally Dependent Effects (DDE)	5
2.2	Calibration	5
2.2.1	Self-Calibration	5
3	Compressed Sensing Image Reconstruction	6
3.1	Sparseland Prior and Overcomplete Representations	6
3.2	Choosing the Objective Function	7
3.3	Compressed Sensing Reconstruction Algorithms in Astronomy	7
3.3.1	PURIFY	7
3.3.2	Vis-CS	7
3.3.3	SASIR	8
3.4	Implementation In CASA	9
4	Reconstruction for VLA Observations	10
4.1	Sunburst Center Detection	10
4.2	Reconstruction of Supernova Remnant G55	10
5	Future in Compressed Sensing Reconstruction	15
6	Ehrlichkeitserklärung	18

1 Reconstruction from under-sampled Measurements

In Signal Processing, continuous signals are represented with discrete samples. A digital recording of music, an image of a tree, or the measured velocity of a particle, all are discrete samples of continuous signals. The Nyquist-Shannon sampling rate tells us how many samples are needed to fully represent a signal: A signal which contains at most frequency f should be sampled with a frequency higher than $2f$. For example if we record a piece of music where the highest tone is at 20kHz, sampling rate should be more than 40kHz. Then, the music piece gets recorded above the Nyquist-Shannon sampling rate. It is fully sampled and there is exactly one continuous signal(with maximum frequency f) which fits the measurement.

The Nyquist-Shannon sampling rate is not always achievable: Samples may be expensive to acquire, corrupted by noise, or incomplete by the nature of the measurement instrument. In this case we are dealing with under-sampled measurements. Many possible signals fit the measurement and from the measurement alone, we cannot distinguish the true signal from all possibilities.

With the Theory of Compressed Sensing[1][2] however, we can use prior information about the signal and find the most likely candidate from all possibilities. Under the right conditions, the most likely candidate is guaranteed to be the true signal. With the Theory of Compressed Sensing, we exploit prior information to reconstruct the true signal from under-sampled measurements.

In this project, the Theory of Compressed Sensing was applied to an image reconstruction problem of Radio Astronomy. Interferometers produce under-sampled measurements of the sky which have to be reconstructed by an algorithm. A Compressed Sensing approach was developed and implemented in the Common Astronomy Software Application (CASA). The reconstruction quality was compared to standard reconstruction algorithm in astronomy on VLA data of Supernova Remnant G55.

1.1 Image Reconstruction for Radio Interferometers

Radio Interferometers use several antennas spaced apart from each other. Each antenna pair measures the different arrival time of a radio wave. For small field of view imaging, each antenna pair measures approximately two dimensional Fourier components of the sky (called Visibility in Astronomy). An interferometer with 26 antennas measures 325 Visibilities. The distance between the antenna pair(called a baseline) dictates which Visibility of the image gets observed. The longer the baseline, the higher frequency of the observed Visibility. The longest baseline of an interferometer is therefore a rough estimate of its maximum resolution.

For wide field of view imaging, the two dimensional Fourier relation breaks apart as additional effects dominate the measurement. This project used small field of view imaging, and the two dimensional Fourier component is a good approximation. In this document, a measured Visibilitiy equals a two dimensional Fourier component.

The interferometer only samples as many Visibilities as it has antenna pairs. The task is to reconstruct the observed image from an under-sampled Fourier space. In Astronomy, the CLEAN class of algorithms[3][4][5][6] were developed for this task. New interferometers like MeerKAT also observe new phenomenons which, in an ideal world, can be included in the CLEAN prior and improve its reconstruction. This is not possible in CLEAN, the prior is a fixed part of the algorithm. It cannot be modified as our prior knowledge of radio images increases.

Compressed Sensing can be thought of as a generalization of the CLEAN algorithm. The prior can be exchanged without changing the rest of the reconstruction algorithm. Furthermore Compressed Sensing reconstructions may be able to super-resolve the image[7].

1.2 Deconvolution of the Dirty Image

The ideal interferometer would fully sample the Fourier Space and introduce no instrumental effects and the observed image can be calculated with the inverse Fourier Transform. A real world interferometer corrupts the observed image with the image with under-sampling and other instrumental effects. The inverse Fourier Transform of the Visibilities can still be calculated, but it results in a corrupted "dirty" image. The observed image is convolved with a Point Spread Function (PSF) image with a Point Spread Function(PSF). The task is to reconstruct the observed image from the dirty image and the PSF, or more formally we try to solve for x in equation (1.1), where only the PSF and I_{dirty} are known(\star is used as the convolution operation).

$$x \star PSF + N = I_{dirty} \quad (1.1)$$

A deconvolution algorithm should find the observed image x . However, there may be many possible solutions to the equation (1.1). Noise N further complicates the deconvolution. The algorithm has to decide what is the most likely x given PSF and I_{dirty} . The PSF is specific to the interferometer. It models the sampling pattern in Fourier space. A deconvolution algorithm is not limited to a single interferometer and can easily be used on other instruments¹.

CASA produces a the dirty image and the PSF for the VLA instrument.

Note that the deconvolution problem is just one way of formulating the reconstruction. It was used in this project since the CASA interface was built for deconvolution algorithms. The same problem can be formulated as in-painting the missing Visibilities: If we apply the Fourier Transform to equation (1.1), then the convolution turns to a multiplication and we arrive at a similar equation $X * M + N = V$. The Fourier Transform of I_{dirty} is just the measured Visibilities V , PSF turns into a masking matrix M . M is one for all measured Visibilities and zero everywhere else. If an algorithm can in-paint the missing Visibilities X , it has also found a solution x to the deconvolution problem of (1.1). In section 3.2 the different formulations get discussed in more detail.

1.3 Approximation with CLEAN

CLEAN assumes the image consists of single pixel wide point sources. This is true when the image contains stars, the majority of which are too far away from earth to have any extension. CLEAN therefore takes a dirty image and a PSF as input and tries to find point sources in the image. In each iteration of CLEAN, it searches the highest peak of the dirty image and removes a fraction of the PSF. It stops until the next highest peak is below a threshold, or if the maximum number of iterations was reached. The fraction of the PSF, threshold and number of iterations are tunable by the user.

CLEAN optimizes the objective (1.2) which is split in a data and a regularization term. The data term forces CLEAN to reconstruct close to the measurements, while the regularization term should account for noise. In each iteration, CLEAN searches the step which minimizes the objective the most, it uses a greedy optimization scheme. Due to the L0 "norm"², the objective is non-convex and it may have local minima. Note that the L0 "norm" acts as the sum of non-zero elements in the image.

$$\underset{x}{\text{minimize}} \quad \|I_{dirty} - x \star PSF\|_2^2 + \|x\|_0 \quad (1.2)$$

¹This is true for small field of view imaging. Wide field of view introduces additional effects that typically do not get modelled with a PSF

²The L0 "norm" in this context is technically not a norm, hence the quotation marks. The L0 "norm" is a common notation in Compressed Sensing literature, therefore it is used here.

In practice, CLEAN gets stopped before it reaches a local minima. A common stopping criteria is if the next peak in the dirty image is below 3 to 5 times the estimated noise level. In that case, CLEAN detects all peaks that are higher than 3 to 5 times the estimated noise.

CLEAN does a good approximation of the observed image, if it contains only point sources. Radio images may also contain extended emissions like hydrogen clouds, which are spread over several pixels. The maximum of extended emissions tends to be far lower than for point sources. Any pixel of the extended emission that is lower than 3 to 5 times the estimated noise gets ignored. If an extended emission is above the threshold, CLEAN approximates it with faint point sources. Instead of a hydrogen clouds, CLEAN may detect a cluster of faint stars.

To combat the problem, the reconstructed image of CLEAN gets convolved with the antenna beam-pattern. The beam-pattern is approximately a two dimensional Gaussian and represents the accuracy of the antennas. Clusters of faint stars get blurred into a more plausible cloud. This essentially lowers the resolution of the reconstructed image. The rationale is that any higher resolved structure is likely a reconstruction artefact. Over the years, the algorithm was extended, with the MS-MFS-CLEAN[6] as a recent example. All versions do blur the reconstructed image with the antenna beam-pattern.

The CLEAN prior works well for point sources, but it does not accurately reconstruct extended emissions. With the right prior super-resolved image reconstruction is possible. It was demonstrated in laboratory environment with the One Pixel Camera[8], or with the SASIR[7] reconstruction algorithm on the LOFAR radio interferometer. Since the prior of CLEAN is a fixed part of the algorithm it cannot be modified without creating a new algorithm.

1.4 CLEAN as Compressed Sensing Image Reconstruction

Compressed Sensing can be thought of a generalization of CLEAN. With that, CLEAN is a specific

An image reconstruction algorithm in the Compressed Sensing Framework consists of three parts:

- A prior function $p()$.
- An optimization algorithm.
- An objective with a data and regularization term.

CLEAN is a Compressed Sensing Reconstruction algorithm with specific choices for prior, optimization algorithm. and objective. The prior $p()$ in CLEAN is the L0 "norm", Matching Pursuit as the optimization algorithm. The objective from CLEAN needs a additional parameter λ . [which represents the trade-off between deconvolution and regularization.] the more noisy it is, the more regularization is needed. We arrive at the similar (1.3).

$$\underset{x}{\text{minimize}} \quad \|D_{\text{dirty}} - x \star PSF\|_2^2 + \lambda p(x) \quad (1.3)$$

All that was changes was an additional parameter λ , so why would one want to do this? Applying non-convex optimization techniques, Theoretical guarantees of compressed Sensing. Replacing $p()$ with anything else

Now we can minimize (1.3) with non-convex optimization techniques, we can analyse how calculate lower limits for the objective.

We assume x assumes the x contains a few point sources. In Compressed Sensing terminology, it assumes x is sparse in image space. Since x is already an image.

Compressed sensing reconstruction is able to reconstruct the observation even from undersampled measurements. Even though Shannon-Nyquist theorem is higher.

The guarantees of Compressed Sensing Reconstruction: Incoherent from the measurement space and sparse space is sparse.

Incoherence is easy. Interferometers measure in the Fourier space (This is an approximation for small field of view imaging. The approximation breaks apart in wide field of view). The image space is maximally incoherent from the Fourier space. Intuitively, A change in a single pixel will change all Fourier components. A change in a single Fourier component, changes all pixels.

maximize the information gained for each element in the sparse space.

The sparse space is here to distinguish true image from unlikely candidates. It models our prior knowledge.

Then, one can reconstruct the true image from undersampled measurements. How many measurements are needed? that depends on how sparse it is.

Taking again CLEAN as an example, if we know the image contains only one point source, we can locate it with only a few Visibilities. However if the image contains many point sources located closely together, we need more Visibilities.

The average case analysis is not trivial,

The prior and the optimization algorithm are disconnected and the prior $p()$ can be replaced for example with the L2 norm.

2 Inverse Problem for wide Field of View Imaging

So far the small Field of View inverse problem has been introduced where each antenna pair measures a Visibility of the sky brightness distribution. This leads to the small Field of View measurement equation (2.1). It is identical to the two dimensional Fourier Transform. In practice the Fast Fourier Transform (FFT) is used, since it scales with $n \log(n)$ instead of n^2 pixels.

$$V(u, v) = \iint x(l, m) e^{2\pi i(ux+vy)} dl dm \quad (2.1)$$

For wide Field of View imaging, two effects break the two dimensional Fourier Transform relationship: Non-coplanar Baselines and the celestial sphere which lead to the measurement equation (2.2). Note that for small Field of View $1 - x^2 - y^2 \ll 1$, and (2.2) reduces to the 2d measurement equation (2.1).

$$V(u, v, w) = \iint \frac{X(x, y)}{\sqrt{1 - x^2 - y^2}} e^{2\pi i(ux+vy+w\sqrt{1-x^2-y^2})} dx dy \quad (2.2)$$

Non-coplanar Baselines lead to a third component w for each Visibility. Figure 1 shows the the u v and w coordinate system. w is essentially the pointing direction of the instrument. The UV-Plane is the projection of the antennas on a plane perpendicular to the pointing direction. Which point in the UV-Plane get sampled and what w component it has depends on the pointing direction. If the instrument points straight up, the UV-Plane is a tangent to earth's surface, and the w term compensates for earth's surface curvature. If however the instrument points at the horizon, the projected UV-Plane gets squashed and w compensates for antennas which lie far behind the UV-Plane. In essence, w is a phase delay that corrects antenna positions in three dimensions. The wide Field of View measurement equation (2.2) would account for the w phase delay, but it breaks the the two dimensional Fourier relationship and the FFT cannot be used. The W-Projection [9] algorithm approximates the effect of the w term restores the two dimensional Fourier relationship.

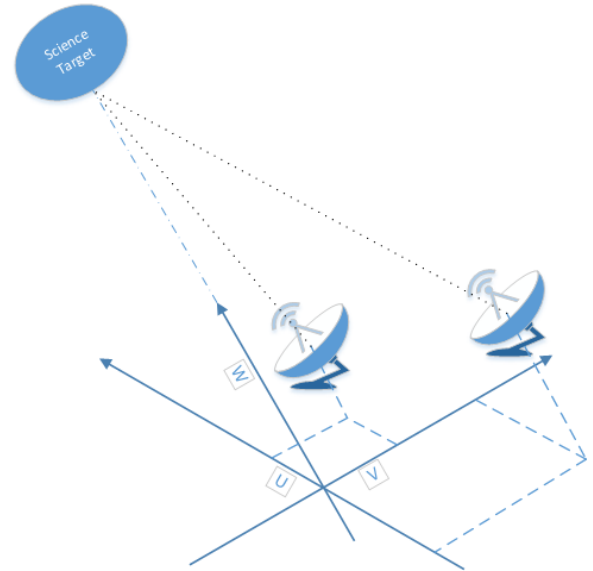


Figure 1: U V and W coordinate space

A-Projection [10]

2.1 Directionally Dependent Effects (DDE)

spread spectrum phenomenon

2.2 Calibration

2.2.1 Self-Calibration

3 Compressed Sensing Image Reconstruction

The Framework Flexibility

A lot of choice in building a reconstruction algorithm. No best

Gurobi[11] was used. constrained optimization.

3.1 Sparseland Prior and Overcomplete Representations

The prior $p()$ can be any function like the LP norm.

We could use L2, but what we mostly want in Compressed Sensing Reconstruction is sparsity. With that, L0 "norm" is often used.

The L1 relaxation however is practically guaranteed to have the same minimum as the L0 norm and results in a convex objective function. Since Gurobi works better on the L1 relaxation it was chosen for this project.

In practice, sparseland priors (3.1) have been used for Compressed Sensing reconstruction: For our signal x we create a dictionary D . Each entry in D represents a signal part of x . D is potentially a large, but has a finite number entries. However, any x we measure consists only of a few entries of D . This means the coefficients for the signal parts in the dictionary α are all zero except for s entries for all valid x .

$$\begin{aligned} x = D\alpha \quad x \in \mathbb{R}^n, \alpha \in \mathbb{R}^m, D \in \mathbb{R}^{n \times m}, \quad n \leq m \\ \|\alpha\|_0 = s \quad s \ll n \leq m \end{aligned} \quad (3.1)$$

In other words, we create a dictionary D in which our signal can be sparsely represented. Together with the L1 norm, the sparseland prior can be thought of as a detector for our signal. Any valid x can be sparsely represented, but noise tends to affect all entries.

In the Compressed Sensing Reconstruction we want to find our x in a noisy environment. The optimization algorithm locates the s significant entries in α and throws away the rest.

Reconstructing an image from measurements is related to lossy image compression. Indeed, we know our image can be compressed in a dictionary D , the same D works well for reconstruction: For example images depicting nature scenes are sparse in the wavelet domain. If x in (3.1) are nature scenes, we can create a Dictionary D of wavelets. A single image x can be represented with a few wavelets, meaning the number of non-zero entries s in α is far lower than the number of pixels n . All that is left to do for compression is save the non-zero entries of α . In the noisy environment, we save the s largest elements of α and save a de-noised image.

Find a dictionary D in which radio can be seen as finding a compression space.

Finding the right sparseland prior is a modelling task. It codes our prior knowledge about radio sources and what they might produce. Sparseland priors are in use by for example with Starlets[12] and Curvelets[13].

Any combination of functions

Sparseland priors naturally lend themselves to overcomplete representations. D has many more rows than columns.

3.2 Choosing the Objective Function

Until now, the objective function was used as a deconvolution. This is not a requirement of Compressed Sensing. It is a design choice.

Different ways of choosing the objective function with a sparseland prior.

There are three different reconstruction objectives: The analysis method, where the image x is minimized directly, the synthesis method where the sparse vector α is minimized, or by in-painting the missing Visibilities V_2 .

$$\begin{aligned} \text{analysis :} \quad & \underset{x}{\text{minimize}} \quad \|I_{\text{dirty}} - x \star \text{PSF}\|_2^2 + \lambda \|Px\|_1 \\ \text{synthesis :} \quad & \underset{\alpha}{\text{minimize}} \quad \|I_{\text{dirty}} - D\alpha \star \text{PSF}\|_2^2 + \lambda \|\alpha\|_1 \\ \text{in - painting :} \quad & \underset{V_2}{\text{minimize}} \quad \|I_{\text{dirty}} - F^{-1}MV_2\|_2^2 + \lambda \|PF^{-1}V_2\|_1 \end{aligned}$$

All three objective functions have the same global minimum. Retrieving x for the analysis objective is trivial, or the second and third objective x can be retrieved by $x = D\alpha$ and by $x = F^{-1}V_2$ respectively. [Empirical and theoretical studies have shown an advantage of the analysis objective over the other two [?]]. However, depending on the measurement space and prior, an objective might become more practical.

The analysis and in-painting objective require the inverse of the dictionary D^{-1} . It exists for orthogonal transformation like the Haar Wavelet transform and for specialized over-complete dictionaries like starlets. In general, over-complete dictionaries do not have an inverse. The synthesis objective is suited for general dictionaries as it does not use the inverse.

During this project, no reconstruction algorithm was found which uses the in-painting method. Convolutions in image space are equivalent to a multiplication in Fourier Space.

Useful when the Dictionary transformation is defined as a deconvolution.

3.3 Compressed Sensing Reconstruction Algorithms in Astronomy

multiple

3.3.1 PURIFY

Prior: Mixture of Dirac functions and Daubechies Wavelet (DB1 - DB8)

Objective: analysis

Optimizer: SDMM

Dirac is a fancy way of saying "it is sparse in pixel space"

3.3.2 Vis-CS

Prior: dictionary of gaussians

Objective: Synthesis

Optimizer: Coordinate descent

3.3.3 SASIR

Was chosen because it has an inverse. Multiscale effects included in prior.

Prior: Starlets

Multi scale prior, over complete representation but with a transformation from image space in starlet space.

Objective: synthesis

Optimizer: FISTA

3.4 Implementation In CASA

CASA is a software package built for re-constructing images for VLA.

CASA works in two separate cycles, the major and minor cycle. The major cycle transforms the Visibilities to image space and back using the Fourier Transform. The minor cycle is the deconvolution algorithm, which tries to find the true image from a dirty image and a PSF.

The first major cycle iteration creates the PSF and the dirty image. Then, several minor cycle deconvolve the dirty image. The major cycle then continues, transforms the deconvolved image back to Visibilities. The major cycle ends by calculating the residual Visibilities from the measurement and the deconvolution. The next major cycle continues by transforming the residual Visibilities. At the end of several major cycle, the model column should contain an approximation of the true visibilities while the residuals should be noise.

In CASA the major cycle is fixed. It was evaluated if it can be modified, but a modification was too time consuming in the context of the project. However CASA allows for the addition of new deconvolution algorithms.

Compressed Sensing Algorithm was implemented as a CASA deconvolver. The Data term of the objective is fixed to be the deconvolution ($D_{dirty}x - \star PSF$).

Major cycle is more expensive to compute than a CLEAN minor cycle.

CLEAN needs potentially many major cycle iterations. A Compressed Sensing Reconstruction would converge to the optimum in one major cycle. Here lies a potential speedup for the Compressed Sensing Reconstruction.

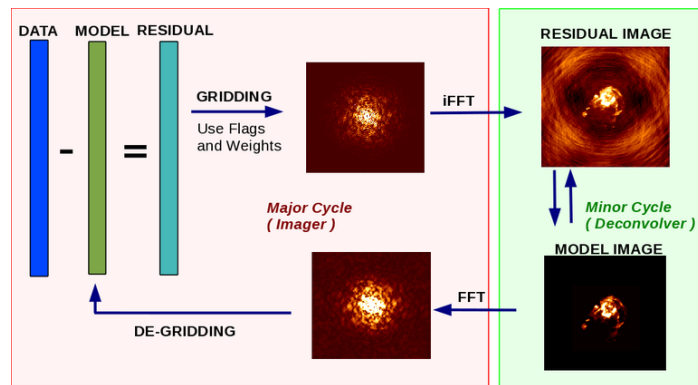


Figure 2: Casa Major Minor Cycle. Source [14]

4 Reconstruction for VLA Observations

Compressed Sensing Reconstruction used on two different tasks:

- Center detection on sunburst data
- Reconstruction from incomplete measurements of Supernova Remnant G55

Two different problems. One is the

Structure potentially smaller than the primary beam.

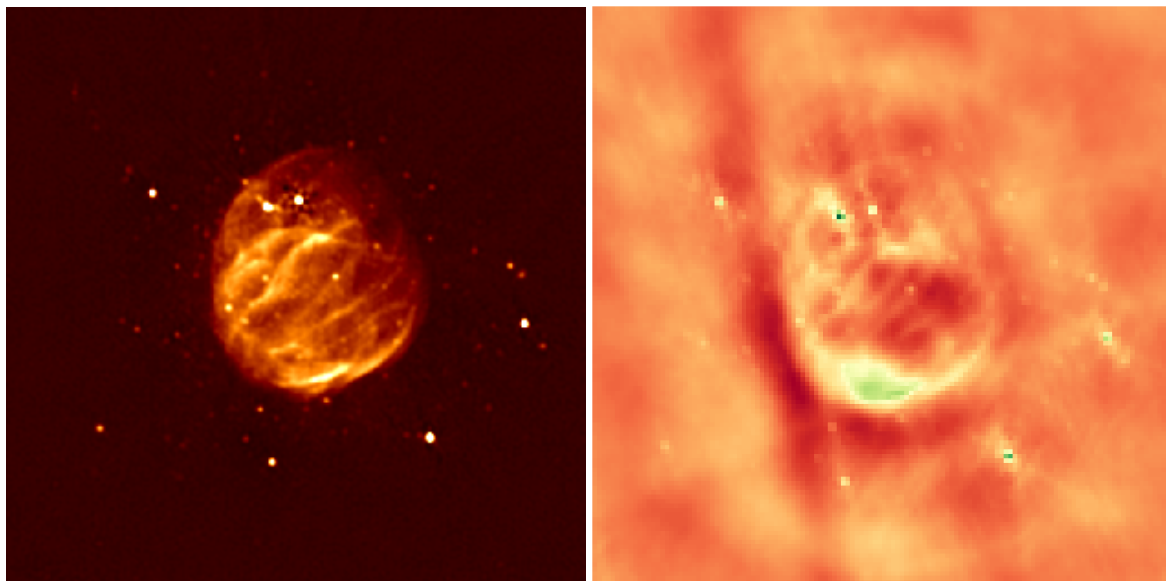
4.1 Sunburst Center Detection

Sub- Primary Beam. CS Objective Function

Figure: Dirty Map Peak, CLEAN, Single Peak Clean, Single Peak CS Reconstruction

Wider Variance

4.2 Reconstruction of Supernova Remnant G55



(a) Reconstruction by NRAO. Source:[15]

(b) Dirty Image

Figure 3: SNR G55 source observed by VLA.

The supernova remnant (SNR) G55 was observed by VLA. 10 seconds of the 8 hour observation is publicly available through the CASA imaging tutorial[16]. 3b is the dirty image calculated from the 10 second observation. The full 8 hours are not readily available. The image 3a is a reconstruction from an unknown VLA observation. The deconvolution algorithm is also unknown. For this project, the reconstructed image is assumed to show the true image of the sky.

3 shows G55 to be a slightly "egg shaped" extended emission with six strong point sources. Several fainter point sources are inside and around the egg shaped extended emission. The dirty image 3b shows a corrupted

version of G55. The six strong point sources are clearly visible as are the brighter parts of the extended emission. The dirty image also shows a negative "trench" striking through the image as well as brighter regions around the remnant.

The size of the images 3 is about twice the size of the primary beam (the primary beam is approximately the size of the extended emission). In the real world, wide field imaging would be used. In this project, small field of view imaging was used because it is quicker to compute. It limits the dynamic range of the dirty image, the whole task gets harder.

The CLEAN algorithm gets compared to Compressed Sensing Reconstructions. The parameters of CLEAN were taken from the CASA imaging tutorial[16]. The reconstructed images of Compressed Sensing are constrained to have no negative pixels. Negative pixels are not physically plausible and was shown to improve Compressed Sensing reconstructions for synthetic data[17]. In total six different priors were tested with the analysis objective:

1. No Regularization
2. L1
3. L2
4. L1+L2
5. Total Variation
6. Starlet Transform

The regularization parameter λ needs to be estimated for each prior. The Miller[18] λ estimation was used and is shown in equation (4.1). [Estimation of the noise level e , divided and E]. An approximate solution is needed to define the noise level and the amount of regularization. In this project, the result with no regularization was used for the λ estimation.

This is not an ideal estimation, the image effectively gets reconstructed twice. Other Compressed Sensing Reconstructions approximate x of equation (4.1) by running their optimizer a couple of iterations without regularization, which reduces the computational costs.

$$\lambda \approx e/E \quad \|I_{dirty} - x \star PSF\|_2^2 \leq e \quad p(x) \leq E \quad (4.1)$$

Two figures compare the Dirty Image, CLEAN and the Compressed Sensing Reconstructions. Figure 4 shows the reconstructed images on the same intensity scale. Figure 5 shows the flux profile of a cut through the reconstructed images. The Cut through the remnant is located in the center of the profile image.

CLEAN: CLEAN detects the brightest point sources, but finds only part of the extended emission. The top half of the "egg" emission is missing. The structures of the remnant are blurred compared to the Compressed Sensing reconstructions. With the parameters of the imaging tutorial, CLEAN models the trench as a region with negative emissions. This is not physically plausible, although the behaviour can be changed with additional parameters. The profile 5 shows that CLEAN accurately reconstructs the flux of the large peaks, although the peaks are wide in comparison.

No Regularization: Detects the Egghead of the remnant and the non-negativity constraint keeps it from modelling the negative trench. It detects the smaller emissions around the remnant, but also detects "fake" extended emissions. The profile 5 shows two smaller peaks in the center which also appear in 3a as do the two small point sources at the edge of the remnant. However, the dirty image has a rise in flux at the borders of the image, which is likely an artefact of the measurement, considering it does not exist in the NRAO reconstruction 3a.

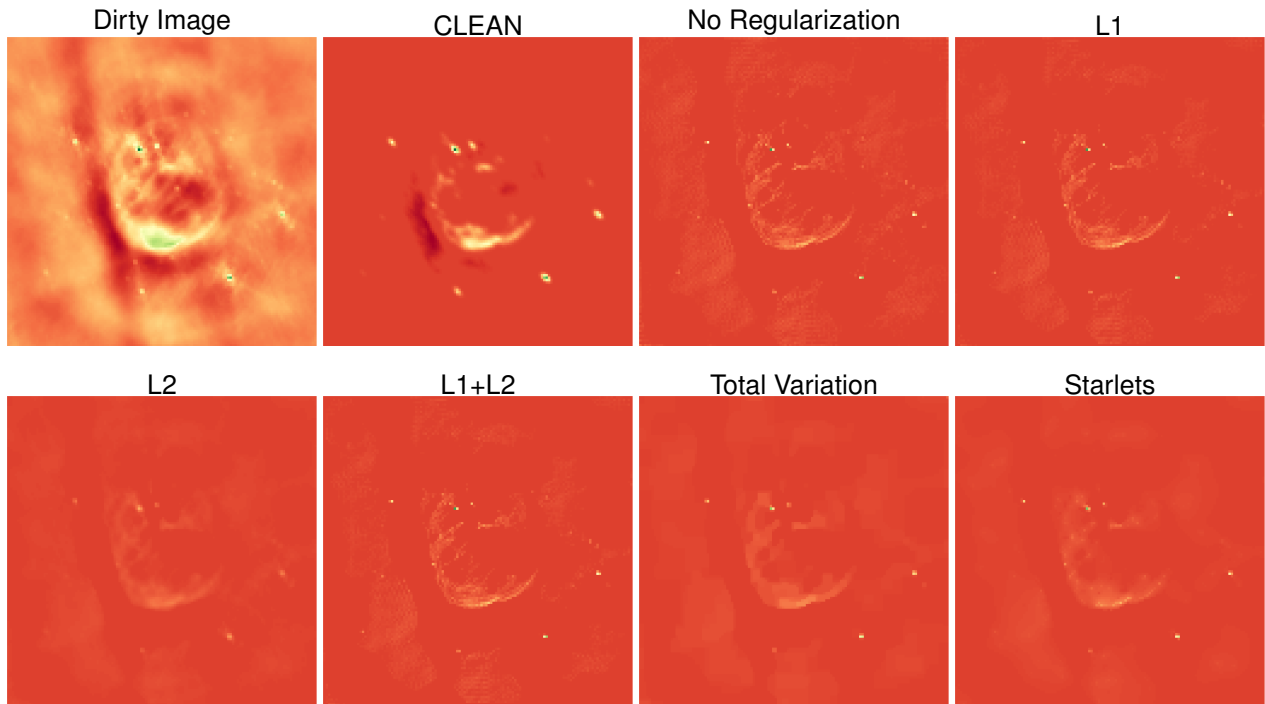


Figure 4: Reconstructed images of CLEAN and the different Compressed Sensing priors.

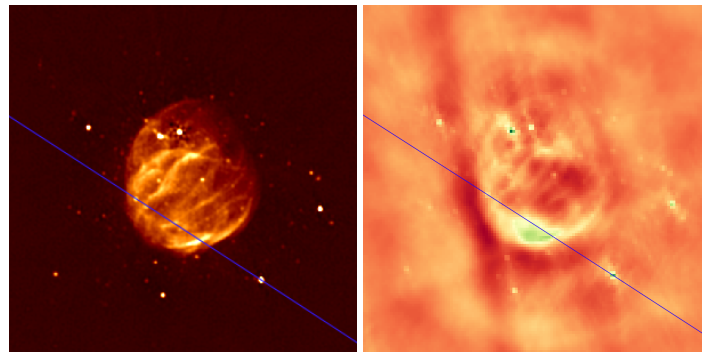
L1: There is almost no visible difference between no regularization and L1. This is possibly an interaction with the Miller λ estimation, since the result of no regularization was used to estimate the λ of L1. The L1 regularization removes part of the "fake" extended emission, particularly in the top region, but also a few structures in the center. The peaks in the profile 5 of L1 and no regularization are narrower than CLEAN, although they do not reach the same peak flux. L1 is prone to produce unlikely extended emissions: L1 also tries to approximate extended emissions with a number of faint point sources. This can introduce artefacts like pixel wide holes in extended emissions.

L2: Forces the extended emissions to be more smooth. It also considerably lowers the flux of bright point sources. The profile 5 shows L2 forces the bright peak to widen and lower. The peak is almost as wide as the CLEAN reconstruction. In the remnant center, it smoothers the smaller peaks.

L1+L2: Since L1 does a good job with point sources, but needs to be more continuous for extended emissions, why does one not combine both regularizations? The flexibility of Compressed Sensing Reconstructions allows for it. Sadly, the result is indistinguishable from the L1 regularization. In the dirty image, all pixels are very close to zero (Maximum: 0.0076 in Dirty Image). If the L1 and L2 regularization receive the same λ , the L1 term dominates. If the dirty image would contain pixels much larger than 1, then the L2 term would dominate.

Total Variation: A simple prior that has its origins in image de-noising. The objective is to reduce the gradients over the image. With an infinite λ , the Total Variation forces all pixels of the reconstruction to have the same value. The idea of the prior is to work well for both extended emissions and point sources. It has trouble with point sources inside extended emissions. In the profile, it is clearly visible how Total Variations cuts the peaks inside the remnant.

Starlets: Is a more sophisticated prior which also tries to model both point sources and extended emissions. It locates the point sources accurately. In the profile 5 it also finds the faint point sources in the extended emission. However, it also smoothed out the structure inside the remnant. For the LOFAR instrument, the starlet regularization was able to find smaller structures than the antenna beam-width[7]. The smallest starlet has a 5×5 pixels dimension. For this reconstruction, the antenna beam-width is about two pixels wide. The



(a) profile cut

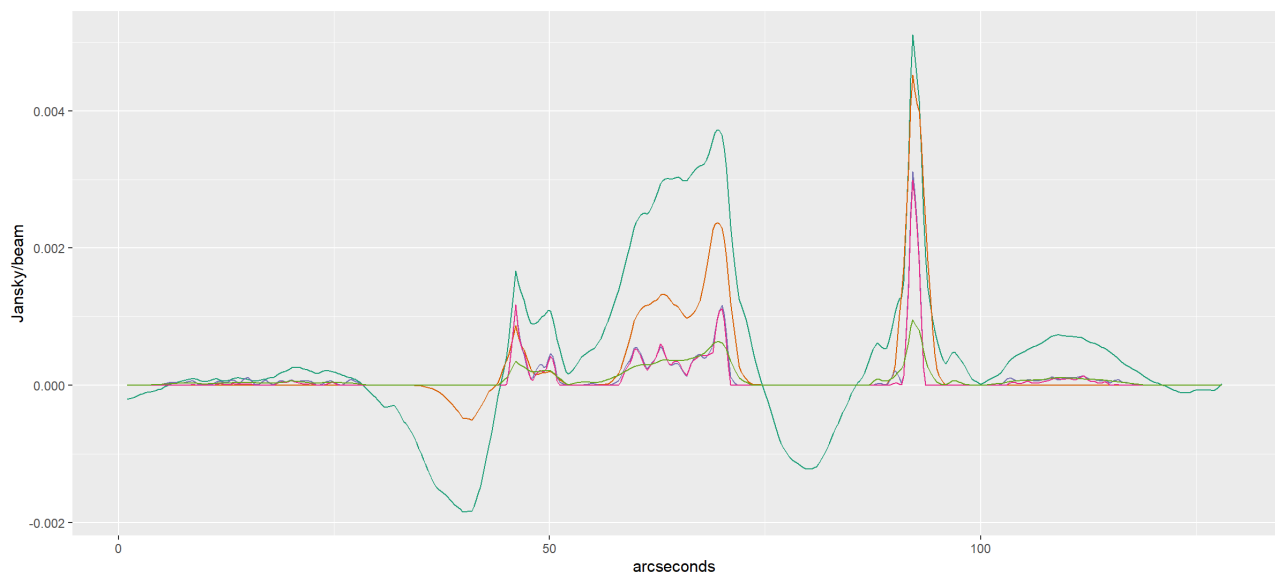


Image: Dirty CLEAN No Regularization L1 L2

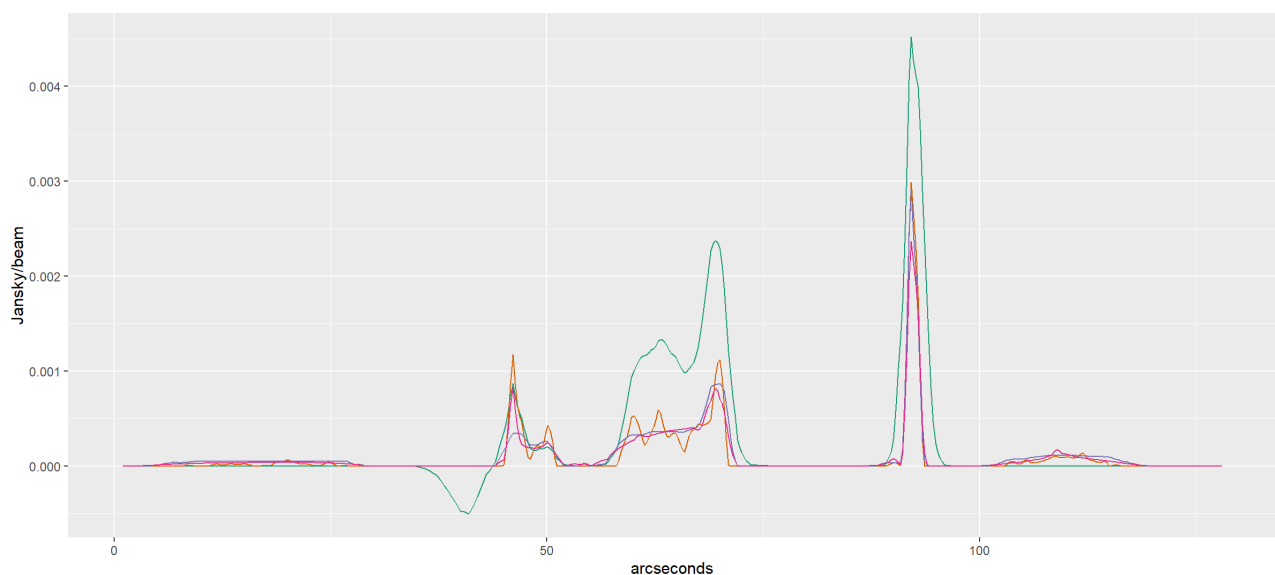


Image: CLEAN L1+L2 TV Starlets

Figure 5: Intensity profile of CLEAN and the different Compressed Sensing Regularizations.

resolution might be too coarse for the starlet regularization.

CLEAN produces the most accurate flux for strong point sources, even though in other reports Total Variation and Starlets reconstructed comparable peak flux to CLEAN [19][17]. This is due to the implementation in CASA: The PSF CASA produces does not sum up to one. Convolving an image with the PSF increases the total flux, and naturally a deconvolution decreases the flux. CLEAN is the only algorithm that comes close to the measured flux, because in the last iteration, the reconstructed image gets convolved with the beam pattern (usually a 2d gaussian function), which is also not normalized. If we also convolve the Compressed Sensing reconstructions with the beam pattern (and smear away details), the fluxes become similar.

In this example, the L1 normalization was able to find smaller, plausible structures than CLEAN inside the remnant. Outside the remnant, all Compressed Sensing Reconstructions found "fake" extended emissions. The L2 and starlet were also expected to find smaller structures. One possible explanation is that the antenna beam-width is about two pixels wide. Any structure smaller than the beam-width is one pixel wide.

For higher resolutions it is expected that L1 introduces more artefacts. The current implementation cannot increase the resolution since it needs a quadratic amount of memory per pixel: The image size of about 128^2 was the maximum which was feasible to solve on a laptop. The convolution operation $x \star PSF$ gets modelled as a matrix-vector product. The matrix therefore has 128^4 entries.

5 Future in Compressed Sensing Reconstruction

The flexibility of Compressed Sensing Reconstructions allows us to change the prior according to our previous knowledge, all while keeping the same objective and optimization algorithm. The prior can be updated as our knowledge changes. It was able to find plausible structures smaller than the antenna beam-width. Using Compressed Sensing Reconstructions gives us theoretical guarantees that, if our prior models the observation well enough, we reconstruct the true image from under-sampled measurements.

A proof of Compressed Sensing Reconstruction was implemented in CASA as a minor cycle deconvolver. It takes the dirty image and point spread function as input and calculates the optimal deconvolution according to the objective. The current implementation has a quadratic memory requirement. It does not scale to any practical image size for VLA observations. New interferometers like MeerKAT will require even larger images. The current implementation is not suited for large scale reconstructions.

Self-calibration is a task which was not covered in this project. Self-calibration aims to reconstruct both the image and the antenna gain calibration from the same measurements. Here with Compressed Sensing Reconstructions one may be able to apply complex optimization techniques to self-calibration, and find the global optimum of both calibration and reconstructed image.

New interferometers are built with wide field of view imaging in mind, which introduces new measurement effects that a reconstruction algorithm should account for. State of the art Compressed Sensing Reconstructions take the measurements as input and also correct wide field of view effects. Due to the CASA interface, the current implementation is restricted to be in the image space, the effects of wide field of view are currently handled by CASA. The next step is a Compressed Sensing Reconstruction which accounts for the effects of wide field imaging and scales to astronomical image sizes.

References

- [1] Emmanuel J Candès, Justin Romberg, and Terence Tao. Robust uncertainty principles: Exact signal reconstruction from highly incomplete frequency information. *IEEE Transactions on information theory*, 52(2):489–509, 2006.
- [2] David L Donoho. Compressed sensing. *IEEE Transactions on information theory*, 52(4):1289–1306, 2006.
- [3] JA Högbom. Aperture synthesis with a non-regular distribution of interferometer baselines. *Astronomy and Astrophysics Supplement Series*, 15:417, 1974.
- [4] FR Schwab. Relaxing the isoplanatism assumption in self-calibration; applications to low-frequency radio interferometry. *The Astronomical Journal*, 89:1076–1081, 1984.
- [5] JW Rich, WJG De Blok, TJ Cornwell, Elias Brinks, Fabian Walter, Ioannis Bagetakos, and RC Kennicutt Jr. Multi-scale clean: A comparison of its performance against classical clean on galaxies using things. *The Astronomical Journal*, 136(6):2897, 2008.
- [6] Urvashi Rau and Tim J Cornwell. A multi-scale multi-frequency deconvolution algorithm for synthesis imaging in radio interferometry. *Astronomy & Astrophysics*, 532:A71, 2011.
- [7] Julien N Girard, Hugh Garsden, Jean Luc Starck, Stéphane Corbel, Arnaud Woiselle, Cyril Tasse, John P McKean, and Jérôme Bobin. Sparse representations and convex optimization as tools for lofar radio interferometric imaging. *Journal of Instrumentation*, 10(08):C08013, 2015.
- [8] ams.org. Compressed sensing makes every pixel count, 2007.
- [9] Tim J Cornwell, Kumar Golap, and Sanjay Bhatnagar. The noncoplanar baselines effect in radio interferometry: The w-projection algorithm. *IEEE Journal of Selected Topics in Signal Processing*, 2(5):647–657, 2008.
- [10] S Bhatnagar, TJ Cornwell, K Golap, and Juan M Uson. Correcting direction-dependent gains in the deconvolution of radio interferometric images. *Astronomy & Astrophysics*, 487(1):419–429, 2008.
- [11] Gurobi Optimization. Gurobi optimizer, 2018.
- [12] Jean-Luc Starck, Fionn Murtagh, and Mario Bertero. Starlet transform in astronomical data processing. *Handbook of Mathematical Methods in Imaging*, pages 2053–2098, 2015.
- [13] Jean-Luc Starck, David L Donoho, and Emmanuel J Candès. Astronomical image representation by the curvelet transform. *Astronomy & Astrophysics*, 398(2):785–800, 2003.
- [14] National Radio Astronomy Observations. tclean overview, 2016.
- [15] National Radio Astronomy Observations. Glowing bubble of an exploded star, 2016.
- [16] National Radio Astronomy Observations. Vla casa imaging-casa5.0.0, 2017.
- [17] Jason D McEwen and Yves Wiaux. Compressed sensing for radio interferometric imaging: Review and future direction. In *Image Processing (ICIP), 2011 18th IEEE International Conference on*, pages 1313–1316. IEEE, 2011.
- [18] Keith Miller. Least squares methods for ill-posed problems with a prescribed bound. *SIAM Journal on Mathematical Analysis*, 1(1):52–74, 1970.
- [19] Hugh Garsden, JN Girard, Jean-Luc Starck, Stéphane Corbel, C Tasse, A Woiselle, JP McKean, Alexander S Van Amesfoort, J Anderson, IM Avruch, et al. Lofar sparse image reconstruction. *Astronomy & astrophysics*, 575:A90, 2015.

List of Figures

1	U V and W coordinate space	5
2	Casa Major Minor Cycle. Source [14]	9
3	SNR G55 source observed by VLA.	10
4	Reconstructed images of CLEAN and the different Compressed Sensing priors.	12
5	Intensity profile of CLEAN and the different Compressed Sensing Regularizations.	13

List of Tables

6 Ehrlichkeitserklärung

Hiermit erkläre ich, dass ich die vorliegende schriftliche Arbeit selbstständig und nur unter Zuhilfenahme der in den Verzeichnissen oder in den Anmerkungen genannten Quellen angefertigt habe. Ich versichere zudem, diese Arbeit nicht bereits anderweitig als Leistungsnachweis verwendet zu haben. Eine Überprüfung der Arbeit auf Plagiate unter Einsatz entsprechender Software darf vorgenommen werden.

Windisch, July 30, 2018

Jonas Schwammberger