PART VI

OTHER IMAGE IMPROVEMENT METHODS

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THE METHOD 'CLEAN' - USE, MISUSE AND VARIATIONS

(Invited paper)

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SUMMARY

The mathematical background of the method CLEAN, as given by Schwarz (1978) is summarized. A method to derive source parameters (flux, position, extent) as a direct application of the theory is described. The ambiguity of the CLEAN method is discussed from a theoretical and practical point of view. Empirical results on the influence of the loop-gain are given. A new approach for the processing of maps with limited phase information is presented and a novel application of CLEAN for beam-switching observations (as an example for the case of a non-symmetric beam) is given.

1. INTRODUCTION

It is probably not necessary to give an outline of the algorithm of the method CLEAN, after its introduction by Högbom (Högbom, 1974) and first pioneering work by Rogstad (Rogstad and Shostak, 1971) eight years ago. The fact that it is still so widely used, speaks for the method or against the users.

In the first part I give a short summary of the mathematics of the method, as recently published (Schwarz, 1978, hereafter called Paper I), in order to introduce those concepts, on which the further discussion will be based. In the second part I give some direct applications of the theory. The third part is more empirically oriented, where some ambiguities and pitfalls are mentioned. In the final section some variations and other applications of the method are presented.

1.1 Algebraic Description and Convergence of CLEAN

Although the method CLEAN is conceived entirely in the map-domain, it is of great use to analyse the working of the method in the plane which is the Fourier transform of the map, the UV-plane. In order to do this one must first describe the method mathematically in the map-plane

C. van Schooneveld (ed.), Image Formation from Coherence Functions in Astronomy, 261-275.

and then as a second step interpret it in the UV-plane.

i) CLEAN in the map-plane: We can write the result of the CLEAN process (actually the first phase, namely the decomposition) after some iterations by

$$\underline{d} - B\,\underline{t}' = \underline{r} \tag{1}$$

where $\underline{d}$ is the original map (the 'dirty' map), $\underline{t}'$ the ensemble of components, $\underline{r}$ the residuals and B a matrix containing the values of the synthesized beam, $\underline{b}$, (the 'dirty' beam) as elements, such that the convolution of the components $\underline{t}'$ with the dirty beam can be written in this simple way. This notation in vector form does not mean that one is restricted to the one-dimensional case. The multi-dimensional case can be put exactly in this form as well.

The CLEAN process of searching for the maximum of the residuals and subtraction of g times (g = 'loop-gain') this value convolved with the dirty beam, $\underline{b}$, is nothing else than a well known iterative method from the pre-computer time to solve a system of linear equations

$$B\,\underline{t} = \underline{d}\;. \tag{2}$$

For our purpose this method is attractive since we can assume that the sky is almost empty; this aspect will be examined in more detail later. When discussing the convergence of the CLEAN process it is useful to introduce a norm Q. One can prove that the following norm,

$$Q = \underline{\Delta t}\; B\; \underline{\Delta t} \quad \text{with} \quad \underline{\Delta t} = \underline{t}' - \underline{t}\;, \tag{3}$$

diminishes with each iteration and hence converges to zero, if $0<g<2$ (g = loop-gain), B is symmetric and Q cannot become negative. This last condition can be fulfilled easily, as will be shown below. $\underline{t}$ is the solution of equation 2, therefore:

$$\underline{t}' \rightarrow \underline{t} = \underline{t}_o + \underline{z}_o\;. \tag{4}$$

The final solution is the 'true' map, $\underline{t}_o$, if eq. 2 has a unique solution. Normally in our applications this is not the case and any zero-eigenvector $\underline{z}_o$ ('ghost') can be added.

Since one does not know $\underline{t}$ in advance one can calculate another quantity H which is related to Q by

$$Q = Q_o - H \quad \text{with} \quad H = \underline{t}'(\underline{d} + \underline{r}), \quad Q_o = \underline{t}\;\underline{d}\;. \tag{5}$$

H increases with each iteration by

$$\Delta H = g\,(2 - g)\; r_m^2 \tag{6}$$

where g is the loop-gain and r_m the maximum residual. H is a measure of the quality of $\underline{t}'$; the starting value is 0 and can reach a maximum of Q_o, when $\underline{r} = 0$.

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ii) Interpretation of CLEAN in the UV-plane: We define the visibility, V, as the FT of the 'true' map. This visibility is observed at some sample points and is given a weight. This sampling and weighting function is w. The FT of the weighting function is the dirty beam, b. The observed visibility which includes noise we call V_o. The FT of wV_o is the dirty map, d.

Starting the iteration process with a subtraction of the convolution of the 'dirty' beam with the first component, corresponds in the UV-plane to the subtraction of a sine-wave multiplied by w. After some iterations, the FT of the residuals r is left. This can be expressed as $w\Delta V=w(V_o-V')$, where V' is the FT of the set of components, t', and $\Delta V = V_o-V'$. Since $r \rightarrow 0$, $w\Delta V$ will converge to zero. This means that V' approaches V_o. This is illustrated in Figure 1, where the first iterations of a model example are shown; since the visibility is a complex quantity, the cosine- and sine-components are shown separately with subscripts c and s respectively.

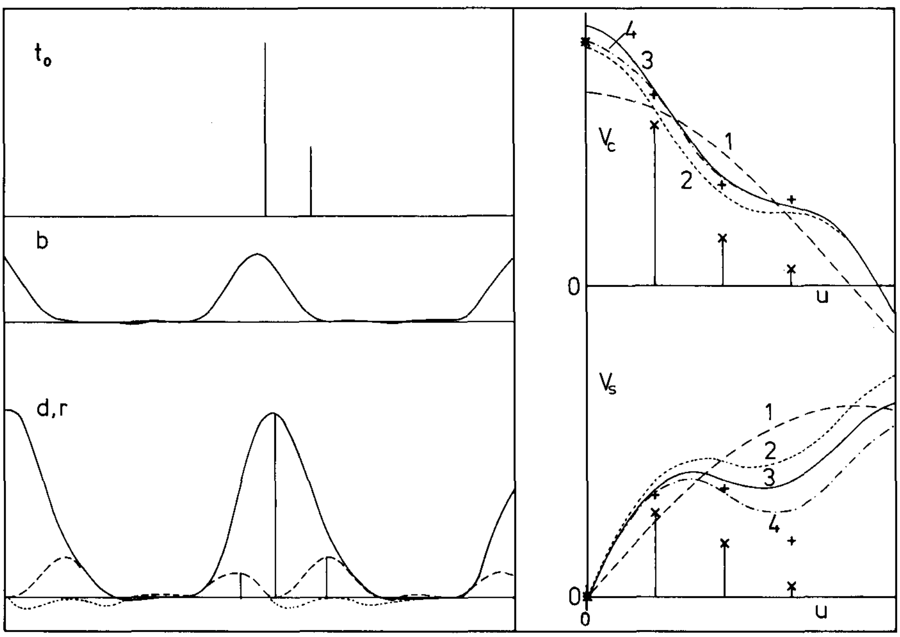

Figure 1. One-dimensional CLEAN of a double source. The first few iterations are displayed. The loop-gain is 1. Left is the map-plane, right the U-plane. Left, from top to bottom: t_o = the true map, b = the dirty beam, d,r = dirty map and residuals; the vertical bars indicate the first three components. Right at top and bottom the real and imaginary parts respectively of the following complex quantities: curves 1 to 4 = FT of the components, for the 4 first iterations. +: the visibility of the true map, at the sample points, V_o. ×: the weighted visibility wV_o. *: + and × coincide. The visibility of the components approaches closer and closer the visibility of the true map (but not the weighted ones) with increasing number of components.

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Note that V' does not approach the weighted visibility $\underline{w}V_o$, but V_o, regardless of the amplitude of the applied weighting function $\underline{w}$. This shows that the decomposition in components is in fact a deconvolution.

The convergence of ΔV to zero can be described mathematically more precisely by using the norm Q introduced above. It can be shown that

$$Q = \Sigma w_k \, \Delta V_k^2 \; / \; \Sigma w_k \tag{7}$$

is the normalized sum of squares of the difference between the FT of the components V' and the observed visibility V_o. We see immediately that one of the criteria of convergence, $Q \geq 0$, is fulfilled if $w_k \geq 0$ for all k. Since V_o is affected by random noise, Q converges towards a minimum in a proper least square sense, if the weights are 'natural' weights, i.e. inversely proportional to the μ_k^{-2}, where μ_k is the rms-error of an observation.

We can also calculate Q_o in a simple way, which is the starting value of the norm Q or the maximum value of H (cf. eq. 5):

$$Q_o = \Sigma w_k \; V_{o_k}^2 \; / \; \Sigma w_k \tag{8}$$

We can use Q as a criterion to stop the iteration process, namely, when Q reaches the value which would be expected from random noise only. For natural weighting we get from eq. 7

$$\langle Q \rangle = \Sigma w_k \; \mu_k^2 \; / \; \Sigma w_k = \mu^2 \, R/\Sigma w_k = R\sigma^2 \tag{9}$$

where μ is the noise of an observation per unit weight, and σ is the rms noise of a point in the map.

1.2 CLEAN as an Iterative Harmonic Analysis

Suppose that the true map consists of one point-like source. In harmonic analysis if one wanted to fit a sine-wave to the observed visibility one would FT the visibility and look for the largest harmonic, i.e. the maximum in the dirty map. This is idential to the CLEAN method. Therefore one could interpret the CLEAN method as an iterative harmonic analysis.

1.3 CLEAN as a Least Squares Fit

Normally the iteration process of CLEAN is stopped if the residuals become smaller than a given threshold. But in order to get the advantages of a proper least squares fitting, one has to deviate from the above scheme slightly and to distinguish between two phases:

i) The search phase: This is the usual iteration process, where the maximum residual is searched in the whole map or part of it.

ii) Optimization: The CLEAN process goes on, but the search of the maximum residuals is done only within the positions, which have already a component, say in W positions. In this way the residuals within this 'window' approach zero and one solves a subsystem of the eq. 2.

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Outside the window the residuals are not necessarily zero. The optimization insures that one has fitted the FT of W components to the observed visibility in a proper least squares fit. Naturally the number of positions W may not exceed the number of observations R (R/2 complex quantities), otherwise the matrix B_W will be singular.

1.4 Error Calculation

Now we have a standard problem for a least squares solution. It involves the inversion of a matrix, which for the case of uniform taper is just B_W^{-1}, the inverse matrix of the submatrix of order W. One easily can calculate the errors of the components or of their FT. An example is shown in Figure 4 of Paper I. There one sees, that the uncertainty of the high spatial frequencies become very large. Thus an increase in resolution requires high S/N ratios! In order to cut down the uncertain high spatial frequencies, one normally convolves the components with a 'clean' beam.

In this summary, many aspects and problems of CLEAN are not mentioned, such as the question of the clean beam, adding the residuals to the clean map, etc. Those and details of the points above can be found in Paper I.

2. APPLICATIONS OF THE THEORY

2.1 Determination of Parameters of Point-like or Slightly Resolved Sources

There are several methods to determine the parameters of discrete sources. Most use a fitting procedure in some way. Clearly the best method is to fit some model function directly to the observed visibility, but this requires quite a large computational effort, at least for the two-dimensional case. Therefore the fitting is mostly done in the 'sky'-plane; but then one must correct the parameters found for the convolution effect due to the 'dirty beam'. An alternative approach is to 'clean' the sources and to determine the source parameters using the components, $\underline{t}$. These components are implicitly based on a least squares fit to the visibility as has been shown above; they are therefore free of the effects of the convolution by the dirty beam.

A simple straightforward method to determine the source parameters is to use the <u>moments</u> with respect to the x-y coordinates in the sky. The moments up to second order are:

$$\begin{aligned} M_o &= \Sigma_i t_i \\ M_x &= \bar{x} = \Sigma_i t_i x_i / M_o \\ M_y &= \bar{y} = \Sigma_i t_i y_i / M_o \\ M_{xx} &= \Sigma_i t_i (x_i - \bar{x})^2 / M_o \end{aligned} \qquad (9)$$

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$$M_{xy} = \Sigma_i t_i (x_i - \bar{x})(y_i - \bar{y})/M_o$$
$$M_{yy} = \Sigma_i t_i (y_i - \bar{y})^2/M_o \qquad (9)$$

The zeroth order moment gives the flux, the first moments give the position and the second moments allow one to calculate parameters of models of extended sources, such as a two-dimensional Gaussian or an equal point double. An important fact to note is that the second order moments need not to be positive; they can be zero or even negative. For a point-like source they are on the average zero but deviate from zero due to statistical fluctuations.

In order to calculate the mean errors of the parameters, derived from the above moments, one needs the derivatives with respect to the components, $\partial M/\partial t_i$. These derivatives are (van Dijk, 1977, priv. comm.):

$$\partial M_o/\partial t_i = 1 \qquad (10)$$
$$\partial M_x/\partial t_i = (x_k - \bar{x})M_o \qquad \partial M_y/\partial t_i = (y_k - \bar{y})/M_o$$
$$\partial M_{xx}/\partial t_i = ((x_k - \bar{x})^2 - M_{xx})/M_o \qquad \partial M_{yy}/\partial t_i = ((y_k - \bar{y})^2 - M_{yy})/M_o$$
$$\partial M_{xy}/\partial t_i = ((x_k - \bar{x})(y_k - \bar{y}) - M_{xy})/M_o$$

For instance the error of one of the second order moments becomes then

$$\mu^2(M_{xx}) = \sigma^2 \Sigma (\partial M_{xx}/\partial t_i)(\partial M_{xx}/\partial t_k) B^{-1}_{Wik}. \qquad (11)$$

Error estimates for diameters, position angles, etc. can be calculated based on these errors in the moments. Extensive Monte Carlo tests have been made to check these errors and showed good agreement with prediction.

The method was tested with artificial sources and with real sources in synthesis maps made from Westerbork data. It was found, using typically 5 to 9 components, that for accurate positions a small area around the source must be chosen (approx. 3/2 beam diameters), but for accurate fluxes and the second moments the area should be larger (about twice as large). A compromise was found by applying a Gaussian weighting function (size about twice the beam width) to the components in order to calculate the positions. This yields typically flux accuracies of the order of 20% of the flux and in positions of 8% of the beamwidth for sources with a flux of about 10σ.

A different approach to overcome the difficulty of this 'trade-off' in accuracy between various parameters would be to use constraints on the minimization of the norm Q. The constraints can be that the second order and higher moments must agree with a model to be determined. For instance if one likes to get the flux and position of a source, assuming it to be a point-like source, then one would require that the second and higher moments are zero. Then one would get from CLEAN, components which are subject to these constraints. I have not worked out an algorithm or error analysis in CLEAN to solve this problem.

2.2 The Ambiguity of the Solution

It is obvious that if the sampling in the UV-plane is not complete there can be components of the brightness-distribution which we can never reconstruct (with any method!). The most simple example is a uniform background which will be missed completely if we do not measure the zero-spacing. The 'dirty' map contains no trace of it and in the UV-plane this contribution is contained in a single point, therefore no interpolation will help. But such a distribution contradicts our condition that the true brightness distribution is zero in most parts. We can ask the general question: Does some brightness distribution exist, which is confined in the map-plane, and whose FT is also confined in the UV-plane? This is not possible, since any confined distribution in the map can be multiplied by a box-function. In the UV-plane this corresponds to the convolution of the visibility with the FT of the box-function (in one dimension a sin x/x-function), which extends to infinity. Therefore the visibility of such a confined source must necessarily be spread over the whole UV-plane, and therefore it cannot be missed completely by the observations. This proof is not completely tight, since some brightness-distribution with periodities matched to periodities in the sampling function could escape unnoticed. These would be distributions of the type of grating responses and one can argue whether these do or do not satisfy the criterion of emptiness of the sky.

Apart from this case, it is then possible in principle to extrapolate the non-observed parts of the visibility assuming noise-free data. Can CLEAN achieve such an extrapolation? In general this will not be the case, at least in this form of CLEAN presented here, where the components are restricted to positions on a grid. However if the true map is restricted to grid-points too, then it is shown in Paper I that the solution is unique if $Q = 0$ and if the solution contains less than R/2 components (where R/2 is the number of measured complex visibilities).

The above arguments are all based on noise-free observations and hence are only of theoretical value. In presence of noise it is meaningless to make $Q = 0$, since the expectation value of Q for noise is non-zero, see eq. 9. From eq. 3 we know that if $Q > 0$ then $\underline{\Delta t}$, the difference between components and the true distribution, is not zero either. Can we make some estimates about the size of $\underline{\Delta t}$?

A simple approach is the following. How large can the total flux ΔF be of a distribution $\underline{\Delta t}$, which would produce a constant change in zero-level of the dirty map? Let us relate this zero-shift to the noise in the map, σ, say $\eta\sigma$, where η is a number smaller than one, then we get from eqs. 1 and 3

$$|B_W \underline{\Delta t}| = \eta\sigma \qquad (B_W \text{ is a submatrix of } B) \qquad (12)$$

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and therefore

$$|\Delta F| = |\Sigma \Delta t_i| = \eta \sigma \Sigma B_{W_{ij}}^{-1} \ . \tag{13}$$

For dirty beams with small sidelobe level,

$$\Sigma B_{W_{ij}}^{-1} \approx W,$$

but for beams with larger sidelobes this sum can become considerably larger. B_W^{-1} is usually not calculated explicitly, but is required if an error analysis is made.

3. PROBLEMS OF THE PRACTICE

3.1 Influence of Loop-Gain

In the many years that the method CLEAN has been used I believe that mostly a loop-gain of less than unity has been found to be optimum. In fact a very small loop-gain can be practical. It is even possible to use an infinitesimal small loop-gain by an algorithm closely related to the theory of CLEAN, being equivalent of solving a system of equations.

A systematic analysis of the problem of loop-gain has been done by Ron Harten (yet unpublished) by a purely empirical method. He cleaned a noise free point-source lying exactly in between two gridpoints, using a different number of gridpoints per halfwidth of the dirty beam, and for various loop-gains (0.9, 0.5 and 0.25). He looked at speed of convergence accuracy of flux determination and area needed, for the case of a free running CLEAN, without optimization. I would like to discuss a few aspects of this work:

i) Area required: The smaller the loop-gain the smaller the area needed.

ii) Convergence: The closer the loop-gain to unity, the higher is the frequency of oscillation. The amplitudes are in the test cases about equal. In the beginning, after only a few iterations large deviations from the true flux do occur.

iii) Influence of number of points per halfwidth of dirty beam: The more points, the smaller the amplitude of oscillation.

It is quite plausible that a small loop-gain needs a smaller area. This we see more clearly for a very small loop-gain, then the dirty map is steadily cut-down from the top, making more and more residuals equal. If one has one dominant source, CLEAN with small loop-gain will start with the highest point and steadily use new points thereby going further from the centre of the source in both directions. This is not only an advantage for extended sources but also for point-like sources giving a more accurate final result.

Interesting experiments were made by J.M. van der Hulst (1977) in connection with the observations of neutral hydrogen on the 'antenna'-pair of galaxies, NGC 4038/39, which has a negative declination and can therefore be observed at Westerbork only for a limited range in hour-angle. This missing information results in strong negative sidelobes (34% at a distance of 1.25 the beamwidth) in the antenna pattern in the EW-direction. From the optical picture (and theoretical dynamical models of an interacting pair) one would expect radiation in a filament running partly E-W. Due to the characteristics of this particular beam, the amplitude of any elongated E-W structure is strongly reduced. He showed that CLEAN can only partly reconstruct the missing information, using a realistic model with superimposed noise.

Somewhat disappointed by this result, I started to make similar experiments, using the same data, but a more simple model, namely a thin bar lying exactly in an E-W direction which gives, from the point of view of CLEAN, the strongest effects. I systematically varied the amount of noise superimposed and the loop gain. The results from these experiments can be summarized as follows:

i) The ability of CLEAN to reconstruct the true distribution is strongly affected by the S/N ratio. There is a rather sharp transition, where CLEAN starts to fail.

ii) The S/N ratio at which the true distribution can be reconstructed showed in some cases to be dependent of the loop-gain. For a bar of constant amplitude (thus with sharp edges) a high loop-gain, up to 1.5, was more successful than a small loop-gain. On the other hand a Gaussian amplitude (smooth edges) distribution along the bar showed no great differences in the results for various loop-gains.

The conclusion is that a small loop-gain is in general advisable, especially if one has a dirty beam with significant positive sidelobes. Ambiguities in CLEAN, due to different loop-gains, number of iterations, etc. can occur at too low a S/N ratio.

3.2 Increase of Resolution

It is tempting to use (or misuse) the method CLEAN to achieve higher angular resolution than one would obtain by the usual techniques. I would like to distinguish two categories:

i) First category: One would like to extrapolate the visibility to higher spatial frequencies than are contained in the observation. In Paper I application of the error theory shows clearly, that this is only possible for very high signal-to-noise ratios. But even in such cases one should keep in mind, that non-statistical errors of the observations then can play an important role.

ii) Second category: In Fourier transforming the observations, one usually applies a weighting or taper function, in order to reduce the side-lobe level of the dirty beam, resulting in prettier looking maps. As already mentioned in Section 1.1-(ii) CLEAN does recover these artificially degraded high spatial frequencies. Ron Harten used CLEAN to increase the resolution of maps, where such a taper function has been applied. He could demonstrate that the undoing of the taper function is possible, but any further increase in resolution leads to unrealistic maps. – But this method looks rather a cumbersome way to begin with; this is however not true, since the cleaned map is restored with a clean beam, therefore one gets higher resolution and a pretty looking map.

3.3 Some Pitfalls

a) CLEAN of smoothed maps: There is no objection using smoothed maps, if the dirty beam is smoothed as well, and if the FT of the smoothing function is non-negative. This condition can sometimes be violated however, if the smoothing is done in the map (e.g. in a small region of interest to save computing time), since the truncation of the smoothing function can in fact introduce negative weights in the UV-plane, which will lead to divergence during the CLEAN process.

b) CLEAN of extended sources: A basic assumption we made in earlier sections was that the sky is essentially empty. Suppose we sampled the visibility including a zero-spacing, which picks up a general background. We could use CLEAN in a restricted area, keeping the number of points W in the window smaller than the number of observations, R. In this case we obviously cannot expect to reconstruct the true distribution correctly. On the other hand if we were to use the whole map for CLEAN (thus violating the condition $W < R$) strange things can happen. Figure 2 shows a case where an artificial map of constant amplitude has been cleaned with loop-gain $g = 1$. The result is a sinusoidal looking wave, a perfect artifact.

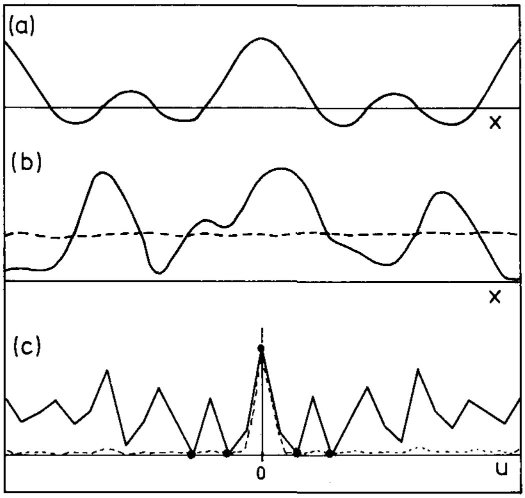

Figure 2. Experiments with a continuous brightness distribution in one dimension. (a) dirty beam, (b) clean map (the clean beam is equal to the dirty beam to the first zero), (c) FT of components. In (b) and (c): full lines, loop-gain = 1; dashed lines, loop-gain = 0.01, 1000 iterations. The dots give the assumed 'observation'. One sees that CLEAN with $g = 1$ gives rise to artifacts.

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In the UV-domain, one sees that CLEAN has done its job perfectly well, the FT of the components - although wavy - equals exactly the 'observed' visibility at the positions of sampling. Another experiment was made, using a loop-gain g = 0.01, for 1000 iterations. The final residuals are at the 10% level of the dirty map. In Fig. 2 the components are shown by the broken line; one sees they are almost uniform. This demonstrates that a small loop-gain does not turn a smooth background into pronounced artifacts.

The above example gives a possible explanation of some features in a controversial map of the galactic centre made by Balick et al. (1974), based on observations with the NRAO interferometer. This map showed lobes which were not present in a more completely sampled map by Ekers et al. (1975). The odd orientation of the baseline of the NRAO interferometer, combined with the effect of low declination, results in projected short spacings, which are sensitive to the extended source. If one applies CLEAN to the map (what has been done by Balick et al.) in a restricted area, one can expect artifacts similar to those in above example, especially if a high enough loop-gain is used. Using the original data it can be shown that these lobes can be avoided with a small loop-gain.

The main question is how to avoid this effect? The most safe method is to clean an area with less points than the number of observations ($W < R$) and if an extended source may be present, which exceeds the size of the area to be cleaned, the corresponding short spacings should be excluded. The use of a small loop-gain helps to avoid difficulties as above experiments and also those of other users of CLEAN have shown.

4. VARIATIONS AND OTHER APPLICATIONS OF CLEAN

4.1 Limited Phase Information

In VLBI observations the phase cannot be measured absolutely, only relative phases. In recent years a new reduction technique has been developed, using the concept of closure phase. In simultaneous multi-interferometer observations phases must add up in some simple way to zero. Assuming some phases one can calculate the remaining phases from these conditions. The resulting map is then processed using CLEAN in an iterative way (Readhead et al., 1978). I do not intend to describe this method in detail, but I would like to make a remark related to the previous section. Due to the erroneous phase, the calculated 'true' source may extend over a large part of the map. If CLEAN is used in a restricted area one can also introduce artifacts by using a high loop-gain and by continuing the iteration-process too long.

I have tried a different approach to a similar problem, by using the CLEAN concept in its original form. Suppose one has observations with partial phase information. Putting the unknown phases to zero, one gets by Fourier transforming the data a dirty map. If we search this map for the maximum and subtract a beam at this position, we have to keep in mind, that due to the missing phase, the beam cannot simply be shifted to this position, but has also to be calculated for this particular position, setting the phase to zero at those sample points where no phase information is available, because in this case the shape of the beam depends on the position in the map. This is the only difference from the usual CLEAN. The analogy with the normal CLEAN is evident, because one also puts non-measured samples of the visibility to zero (amplitude and phase), whereas the described method puts only the phase to zero, since the amplitude is observed. As in the normal CLEAN the missing information is interpolated.

4.2 Other Applications of CLEAN

To my knowledge CLEAN has not been used much outside the field of radio synthesis observations. An example of another possible application in astronomy I would like to explain concerns the interpretation of beam-switching observations, used in radio-astronomy, but also extensively in a.o. infra-red observations. Two beams observe the brightness distribution and the differential output is recorded. This is equivalent to the observation with a beam of the form 1, -1. This results in a differentiated brightness distribution. A standard method of analysis is to integrate the signal. This method has the disadvantage that it relies on the model beam to give a really differentiated distribution and integration can only be done in small pieces, otherwise the statistical fluctuation leads to large excursions of the baseline. Could one apply CLEAN? The conditions of convergence of CLEAN are that the dirty beam has to be symmetric and its FT non-negative. In both senses the beam-switching beam is not conform to these requirements. Already Temple (1938) mentions the possibility in order to be able to apply his relaxation method (essentially CLEAN) to convolve the data with the asymmetric beam and to use the self-convolution of the beam as the 'dirty' beam. Obviously one then gets a symmetric dirty beam, whose FT is non-negative (being squared). Now it is possible to apply CLEAN, in the idealized case with a dirty beam $-\frac{1}{2}$, 1, $-\frac{1}{2}$. The matrix B will be positive definite, the resulting components are a linear combination of the convolved data (the coefficients being the elements of the inverse matrix, B^{-1}). This makes an error analysis possible; note that it will be different from the case of FT data.

I tentatively tried this method with real IR data of a high altitude flight, published by M. de Muizon, 1978. The dirty beam is based on the observations of Saturn, see Figure 3, and the data is sampled at a 2' interval. In Figure 4 the result of the integration by Muizon of the source M17 is shown, together with the results of a tentative CLEAN with 15 components, which are convolved with a 4!5 Gaussian.

There are other potential fields of application of CLEAN, such as seismography, tomography etc. But I think the method is only then successful, if one can assume that the 'true' map is almost empty.

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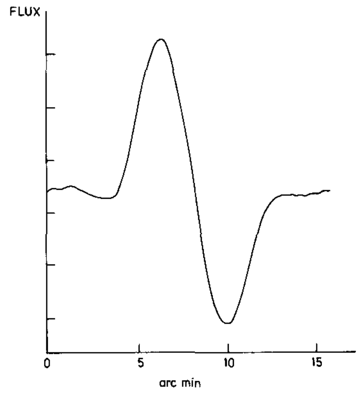

Figure 3. Profile of the beam-switching IR observations of Saturn (Muizon, 1978). The self-convolution gives the dirty beam, which is used in CLEAN shown in Figure 4.

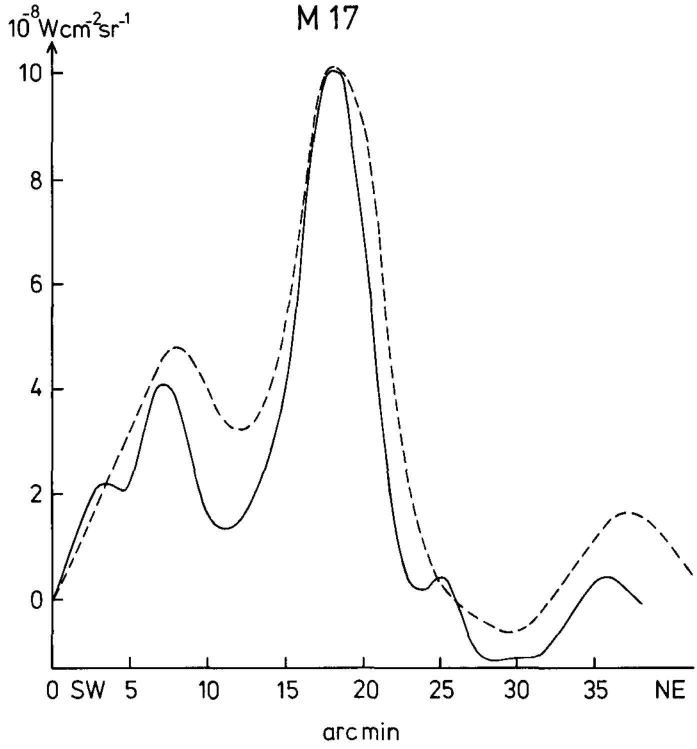

Figure 4. Results of the standard integration method (full line) and experimental CLEAN (dashed line) for the IR-observations of M17 (Muizon, 1978).

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DISCUSSION

Comment E.B. FOMALONT
Is it always better to use a small loop gain in cleaning a map?
Reply U.J. SCHWARZ
Mostly yes, but not always, see reply by Ron Harten.
Reply R.H. HARTEN
The high gain factor can be of use for sources with high negative side-lobes. Generally only the first few components need to be cleaned with a high gain factor.

Comment J.P. HAMAKER
In section 3.1 you discuss the mapping of a structure containing a bar. The only reason why you prefer the solution including the bar is that you have a priori information making it likely for something to be there. The u-v area that contains the pertinent information is not accessible in this case. Without your a priori knowledge you would most probably have accepted the two-component picture without a bridge as a reasonable one. The preference for the outcome using a high loop gain in this case is purely fortuitous.
Reply U.J. SCHWARZ
This is not completely true. There is no confined brightness distribution which is completely unaccessible by any sampling. But if one has noisy data, such a bar-like structure as above can stay undetected. My point is to show that for sufficient S/N one can recover the true distribution, and the quality measure can give an indication of the reliability of the reconstruction.

Comment L.R. D'ADDARIO
You said very little about the clean beam. Would you comment on the fact that the final map, after convolution with the clean beam, disagrees significantly with the available visibilities?
Reply U.J. SCHWARZ
As shown in my paper, CLEAN fits the FT of the components to the unweighted visibility of the true distribution. The components contain the most information, which can be used directly to calculate for instance moments. But in order to suppress the highly uncertain large spatial components, which can be disturbing in some applications, one can convolve the components with a clean beam. If one doesn't like to degrade the good reliable part of the fitted visibility but still likes to depress the large spatial components one can use the FT of a box function (method used by Rogstad and Shostak, A&A, 1973, 13, 99). But in general one uses a clean beam similar to the FT of the taper or weighting function, having the same motivation as in making maps by the simple FT.

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