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# Data Acquisition by Switching

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**Abstract.** In an attempt to cancel large, time-variable signals from receivers and the atmosphere, observers frequently choose switching methods for their data acquisition. The receiver is switched rapidly between two nearby frequencies or spatial directions and the two signals differenced to cancel most of the non-astronomical signal. The resulting difference must be deconvolved to recover the desired astronomical spectrum or image. Methods for performing the deconvolution are considered, all of which appear to have stringent requirements and serious limitations.

## 1. Introduction

Radio-frequency observations are contaminated by time-variable signals from receivers and the atmosphere that exceed the astronomical signals by large factors. One of the traditional methods of cancelling these unwanted signals is to switch rapidly between two nearby frequencies or spatial directions, differencing the result. If one of the two frequencies or directions is free of astronomical signal while having the same instrumental and atmospheric signals, the differencing method can produce a measurement of the celestial signal by simple methods. Unfortunately, the variation of instrumental and atmospheric signals with frequency and direction is significant and forces the distance of the chop to be fairly small, frequently leading to astronomical signal in both switch positions. The difference spectrum or image is the convolution of the astronomical spectrum or image with a positive and a negative delta function separated by the distance of the switch (or "chop" or "throw"). The deconvolution of this difference is the subject of this paper.

## 2. Direct Deconvolution: the EKH Method

Emerson, Klein, & Haslam (1979) noted that the convolution with the plus and minus delta functions in the image plane is a multiplication by a sine function in the Fourier plane. The EKH method is then a division in the Fourier plane by this sine function, which is equivalent to a convolution in the image plane by the Fourier transform of this cosec function (an infinite set of delta functions separated by the beam throw, positive on one side of the origin and negative

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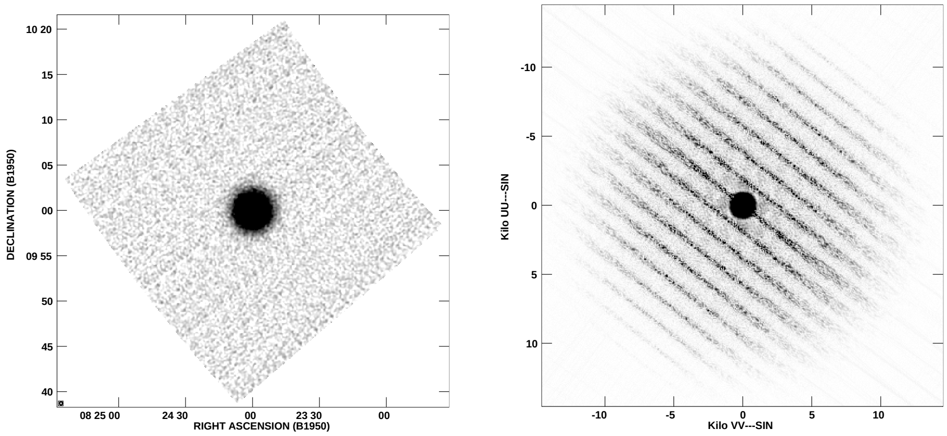


Figure 1. EKH restoration of simulated data: image plane (left), Fourier plane (right) illustrating EKH sine-wave pattern of noise.

on the other). Liszt (1997) pointed out the these delta functions are actually convolved with a $\sin(x)/x$ function since the multiplication by the cosec covers only a limited area in the Fourier plane. This smoothing allows evaluation of the convolution for beam throws which are not an integral number of pixels.

In effect, this direct deconvolution averages the plus-beam and minus-beam observation of an object at its correct position and differences them at positions integer multiples of the beam throw away from this position. Differencing is very sensitive to any instrumental error. A difference in pointing of 6% of the beam width will, for example, make a difference image 1% of a point source. The EKH algorithm provides simple methods for correcting the length of the beam throw and the relative gains of the two beams. Any error in the angle of the beam throw requires a relative shift of the plus and minus images (not rotation) before application of the EKH convolution. This shift is accurate only if the image has been well sampled. The EKH algorithm cannot correct for differences in the shape of the plus and minus beams.

At each pixel, the EKH algorithm combines the plus and minus samples of the flux at that pixel with $N$ samples of the noise, where $N$ is width of the field measured in beam throws. As pointed out by EKH, the resulting noise is $\sqrt{N/4}$ times that obtained by the traditional Dicke method. Therefore, if the field is small, the EKH technique actually improves the noise, but if the field is large, the noise is degraded due to the inclusion of non-signal samples at each pixel. Unfortunately, to reduce the effect of variations in the atmosphere and the instrument, one wants to reduce the length of the throw which raises the noise. This noise is not entirely random, but is strongly enhanced at spatial frequencies corresponding to the beam throw. This is illustrated in Figure 1 which shows an EKH restoration of simulated NRAO 12m-telescope data and its Fourier transform. A four Gaussian artificial source at the illustrated celestial coordinate was "observed" in on-the-fly mode for 15 minutes beginning at hour angle $-1.5$ hours. The telescope is tracked in azimuth at a set of constant elevations and switches in azimuth. The image is deconvolved with the EKH

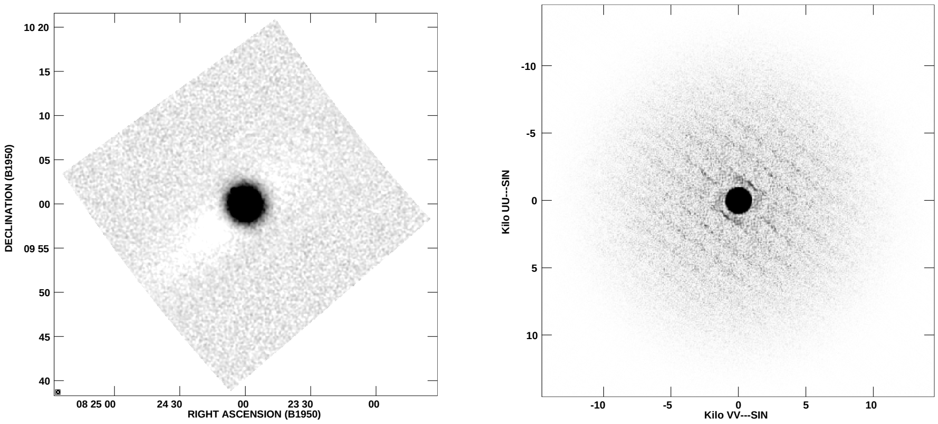


Figure 2. 100000 iteration Clean restoration of simulated data: image plane (left) with negative defect, Fourier plane (right) with EKH noise pattern appearing at lower levels.

method and then re-gridded in celestial coordinates. Note that the sine wave of noise in the Fourier plane becomes blurred away from the center due to the rotation of the throw direction (in these coordinates) across the image.

## 3. Band-Limited Deconvolution: the Clean Method

Hogbom (1974) first described the "Clean" deconvolution method which he applied to synthesized images from radio interferometers. In that application, the method searches for the maximum pixel value in the current residual image and then subtracts a scaled "dirty beam pattern" centered on that pixel from the residual image. After enough iterations, each of the components found is convolved with a Gaussian "Clean beam" and added back to the residual image. For switched difference images, a point source would appear as a positive signal in one location and a negative signal a beam throw away from that location. Therefore, a variant of the Hogbom Clean has been used in which the search cycle looks for the maximum in the difference of the pixel value and that one beam throw away. Simple Gaussians have been used, in tests to date, for the plus and minus dirty beams. Even these allow for corrections to all of the basic instrumental parameters including differences in width between the two beams. A carefully measured point-source response image in the plus and minus throws could be used instead for more detailed correction of instrumental parameters.

With interferometric data, Clean is found to work well with complexes of small-diameter objects, but to have some problems with objects significantly larger than the synthesized beam width. The switched-data Clean has similar successes and failures with two additional problems. First, the source components found in the switched case must be restored not on the pixels at which they were found, but at pixels half-way between the pixels of the plus and minus responses. Therefore, if the Clean does not reduce the residual to pure noise, ghosts of the difference image will appear in the output which will not be covered over by the restored components. Second, it is found that the switched Clean begins in early iterations to deviate systematically from the correct result, often with negative regions surrounding the source. If the Clean is continued long enough, these regions can be corrected at the cost of additional noise which appears primarily at the spatial frequency of the throw. This is illustrated in Figure 2 for the same simulated observation.

## 4. Discussion

Clean can correct for certain instrumental problems for which there are no remedies in the EKH technique. Barring such problems, the EKH method is to be preferred for its simplicity and absence of systematic defects. Both of these methods require the observer to record data on all sources in the field with both beams. If any object is observed with only one of the beams, major defects will be created in the deconvolved image. One of the manifestations of this error is the presence of large negative "sources" in a field that should be all positive.

If a field is observed with multiple throw lengths and/or directions, then the images may be averaged directly or by a technique suggested by Emerson (1995) and now known as "Emerson 2." Images after deconvolution and, if needed, regridding onto a common coordinate system are Fourier transformed and averaged with a weighting (by a sine square function) appropriate to each throw length and direction.For images deconvolved by EKH, this technique produces an image with noise that is about the same as found with a simple average but with a more random distribution. For Clean images, Emerson 2 is found to reduce but not fully remove the systematic problems and it actually can raise the noise over that in a simple average since the data are not fully utilized. Note that the Emerson 2 technique requires the beam throw to be constant over an image. This condition is violated when observations are made in relative azimuth-elevation (to reduce the effects of the atmosphere), but then, of necessity, re-gridded into celestial coordinates before averaging.

Maximum entropy deconvolution has been tried as well on switched difference images. Since MEM deals with image-wide statistics, it is tolerant of systematic deviation over small areas. As a result, it was found to have the same problems with small-diameter sources in switched images as it does in interferometric images. New non-negative least squares methods appear promising, but remain to be tested.

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