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Letter to the Editor

Visibility-based continuum subtraction in spectral line observations with radio synthesis telescopes

H. J. van Langevelde[1], and W. D. Cotton[2]

[1] Sterrewacht Leiden, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands
[2] N.R.A.O. Charlottesville, Edgemont Road, Charlottesville, VA 22901, USA

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Summary. We investigate the possibilities of subtracting the continuum background from spectral line experiments with radio interferometers by averaging and subtracting ungridded visibilities across the spectrum. We show that in several, astronomically interesting cases this method can be succesful and even more accurate than conventional methods. In the cases where it can be applied our method is a lot faster and more straightforward. We discuss the limits and advantages of this simple, but overlooked possibility.

Key words: Data analysis — Image processing — Radio lines — Radio telescopes — Stars: OH/IR

1. Introduction

In spectral line radio interferometry one hopes to observe either emission or absorption spectra. An interferometer is chosen in favour of a single dish usually to image the spectral line source. Other reasons to use a synthesis telescope are to avoid confusion or to resolve out the strong background (We mention the latter because this is the case for our data, which we will later use as an example). In all cases the final analysis will be on an image-cube, preferably with the contribution from any continuum source in the field removed.

The difficulty associated with subtracting the background can range from relatively easy to extremely difficult. The most difficult cases are clearly these where a weak spectral line is to be detected against a bright extended source. Needless to say that this is the case for a lot of astrophysically interesting sources.

Most, if not all, approaches use data from the same observation to estimate the background. In this paper we will concentrate on this as well. We will also assume that the bandpass of the telescope is properly calibrated and that the background emission has a linear spectrum within our band. Finally we will also assume that the frequency range over which spectral features are expected is known. We thus start off with visibility data across the spectrum (a *visibility spectrum*) of which some channels are "empty" and can be used one way or an other to estimate the contribution of the continuum sources. This is then subtracted from the channels of interest.

There are two ways of subtracting the continuum contribution from spectral line observations: 1) subtraction in the image domain and 2) subtraction in the data (UV) domain. See van Gorkom and Ekers 1989 for a review. Image plane subtraction is usually done by forming a continuum image from the "empty" channel images and subtracting this from the channel images of interest. This can be done using either "dirty" or "CLEAN" (Höbom, 1974) images. UV-plane subtraction has usually been done by Fourier transforming a CLEAN model and subtracting it from the visibility data. This can be an expensive method and, as we will point out in the next section, it can not provide the right solution in all cases. Models based on maximum entropy deconvolutions could also be used, but this technique has not been commonly applied.

We will proceed by pointing out the shortcomings of both methods. Next we will propose a method that will work better in some cases and point out when our algorithm can be used. In section 4 we will present some results on real data. We address the question when to use which method in section 5, though there is no easy way to decide which method will yield the best results in a specific case. This is followed by conclusions.

2. The limits of conventional methods

First we discuss in this paragraph the method to subtract the continuum by "image subtraction". Different schemes to compile the model image can be used, depending on, for example, the relative strength of the continuum and the spectral index of the background source. But in all cases the basic limit originates in the change of the beam over the band. Unfortunately a simple, quantitative statement about the level of the residuals can not be given. The residual image is formed by a convolution of the true image and the changes of the beam with frequency. This last term involves detailed knowledge of the exact shape of the beam, for which no general expression can be given. Clearly "image subtraction" is not to be used in cases of relatively large bandwidth and strong continuum.

The problem of a frequency dependent dirty beam can be overcome by using CLEAN images restored with the same "CLEAN beam". This effectively replaces the frequency dependent dirty beam with a constant beam. This method may be relatively expensive since each channel image must be deconvolved. Apart from that it has the same basic limit as the "CLEAN componenents subtraction", which is discussed in the next paragraph.

In a lot of cases where the change of beam limits the continuum subtraction the "CLEAN component subtraction" method can be used. Because here we subtract the contribution of the model from the visibilities the above described effect disapears. However it has one different basic shortcoming; it requires that we perfectly model the continuum emission. In several cases this assumption breaks down. When the continuum is dominated by extended emission we may need a large number of point sources to represent the background. The number of CLEAN components may be larger than the number of observed visibilities, turning this into an insolvable problem. In the case of extended emission the clean component model of the "empty" channel can be inadequate at some level to model the continuum in the spectral line channel of interest. But even when this is a properly defined problem it may be very difficult and time consuming. The model must be build accurately and Fourier transformed back to the visibility domain before subtraction.

3. Visibility based subtraction

The CLEAN component UV data subtraction method described above suffers from the fact that the deconvolution and Fourier transform of the resulting model may be very expensive operations and are somewhat sensitive to calibration errors. The current implementations of this method implicitly assume that the continuum sources have a flat spectrum across the spectral region of interest. We propose a method of estimating the continuum contribution in each visibility measurment directly from the measurments in the "empty" channels. This technique avoids both the problem of a frequency dependent dirty beam and the need for an accurate model of the continuum structure. It allows for a spectral index of the continuum.

Because all the operations of averaging and subtracting used in "image subtraction" are linear operations, they can also be performed in the UV-plane; we can subtract out the continuum from the visibilities right away. In the image plane we have the data on the same grid and combining them is straightforward. The visibility data are organised in a different way; they come in lists of values for the locus in the UV-plane and the visibility. But as a baseline sweeps through the UV-plane the data for different channels are of course gathered simultaneously. We thus have the data ready for a visibility based continuum subtraction. Our method is to form an estimate of the continuum emission from the channels in each visibility spectrum which are not expected to have spectral features and to subtract this estimate from all channels. Ideally this estimate of the continuum visibility is formed from channels bracketing the channels containing the spectral features of interest. This operation is done independently for each measured visibility spectrum. This way we can subtract the continuum without having any influence from the changes in the dirty beam with frequency.

Obviously we introduce errors of a different nature in this process. An antenna pair measures the visibility at a slightly different position in the UV-plane at a different frequency. We can make a first order approximation of the visibility in the channel of interest at the right position by making a linear interpolation between the two ranges. Such an interpolation is numerically stable, even if individual visibilities are dominated by noise. We are left with the second order and higher terms. The differences with frequency originate then in the changes in visibility with position in the UV-plane. Thus the error ΔV_L is:

$$\Delta V_L \approx \frac{d^2V}{du^2}\frac{L^2}{2c^2}(\Delta\nu)^2 \left(= \frac{d^2V}{du^2}\frac{u^2}{2}\frac{\Delta\nu^2}{\nu^2}\right). \qquad (1)$$

Where L is the baseline length and $\Delta\nu$ is the frequency separation from the average frequency used for the continuum estimation, c is the speed of light in the appropirate dimensions and $\frac{d^2V}{du^2}$ is the second order derivative of the complex visibility with u, the distance from the centre of the UV-plane. This is a measure of the structure of the sources in the field.

It is clear from the formula that the method works best for small bandwidth and short baselines. The term $\frac{d^2V}{du^2}$ gets big when the complex visibility changes rapidly across the UV-plane. Favorable cases are the ones in which the continuum emission is in relatively confined region near the phase tracking center or extended, but relatively smooth. Then the visibility function does not vary strongly across the spectral region observed. On the other hand, a field dominated by point sources will be more difficult, except in the case of a single point source near the phase tracking centre. But in these cases the CLEAN components method works perfectly.

Particulary advantageous in comparison with "image subtraction" is the fact that the result of equation 1 is independent of the strength of the continuum. The requirement is simply that the line strength is larger than the error introduced. This puts no limit on the usefulness of the method in cases of high continuum to line ratio. In fact phase and amplitude errors or poor calibration do not affect the usefulness of the method, as long as they are constant across the spectrum, *i.e.* if the band pass calibration is properly done. Again, we assumed here that the spectrum of the background source is linear (a spectral index is allowed).

4. Results

The visibility based continuum subtraction was implemented in the NRAO AIPS system as task UVBAS. In this implementation two ranges of spectral line channels are specified. For both parts an average is calculated. These two values can then be used to make a first order approximation of the continuum contribution in between the two ranges, where presumambly the spectral feature can be found. We expect no profit from trying to overcome the approximation that all visibilities are taken at the same U,V coordinates by making for instance a higher order interpolation in frequency or by trying to make an interpolation in the UV-plane. Because individual visibility points are usually noise dominated this will be a numerically unstable process.

We were interested in trying the algorithm on observations of hydroxyl (OH) masers at 1612 MHz near the Galactic centre. These masers can be used to measure the distance to the Galactic center if we can monitor their variability accurately (see *e.g.* van Langevelde *et al.*, 1990 or Herman & Habing, 1985 for a review). Several tens of sources near the Galactic center are now known (Lindqvist *et al.*, 1990) and in figure 1a we show a single channel image of OH359.988-0.087, 50″ south

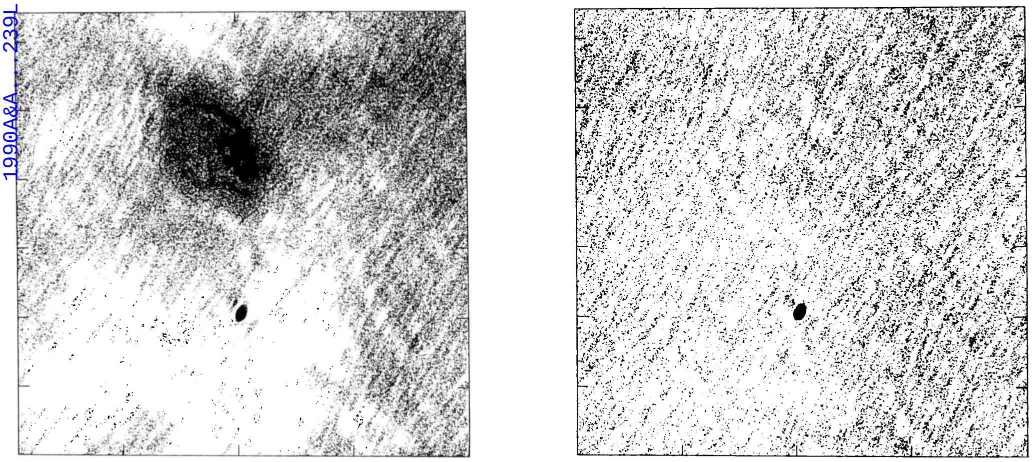

Figure 1. a. A cleaned channel map of OH359.88-0.087 and SgrA. The contours are -0.5, -0.25, 0.25, 0.5, 1.0, 2.5, 5.0 Jy. **b.** The same channel map of OH359.88-0.087, the background was removed with a baseline based subtraction of the visibilities. The contours are the same.

of the strong continuum source SgrA. The bandwidth of the image is only 6.1 kHz. Data were taken with the VLA in a BC hybrid configuration, resolution is $20'' \times 14''$. The image was made with uniform weighting and CLEANed with 2000 iterations.

To measure the flux of the OH source accurately we should have a flat background. This is clearly a problem in figure 1a. Because the Galactic centre is bright and extended (and because we have to do this very often) we have tried to subtract out the background with a visibility based continuum subtraction. We show in figure 1b the results of our algorithm. We used 8 channels on each side of OH spectrum to estimate the continuum. The total separation of these two ranges was almost 200kHz. After the subtraction we made the image in the same way as in figure 1a, using only a small number of components in the CLEAN deconvolution.

Clearly the residual image of SgrA is very weak, surely less than the noise in the maps (30mJy). Comparing this with formula 1 is not straightforward, because an estimate of $\frac{d^2V}{du^2}$ is hard to measure, also because the individual visibilities are totally dominated by noise. But we can approximate the emission by a Gaussian of of size σ displaced from the phase tracking center by x. The residual visibility can be expressed in terms of its original value V_L:

$$\Delta V_L \approx \frac{u^2}{2}\frac{\Delta\nu^2}{\nu^2}(4\pi^2 x^2 + u^2\sigma^4)V_L \qquad (2)$$

where there is a term due to the position offset and one due to the extended nature. We dropped the mixed term, because usually one of the two will dominate.

We can fill in the numbers for the case discussed here. We find that the contribution in a single visibility must be less than 0.5 mJy. So the use of the method is justified here, as indicated by the beautiful result in figure 1b. We have further checked this by creating a noisefree database from with the same UV-coverage as the displayed figures. We have added to this a 3000 CLEAN components model of SgrA and applied the visibility based continuum subtraction to this noisefree dataset. We found residual *images* in the order of 0.1 mJy. So even in this case, which is far from ideal, because the phase tracking center is as far as $4'.6$ away, spectral lines at a level of 0.1% of the continuum could have been easily detected.

We have tested the algorithm for several other cases. We have also data of the same OH/IR stars in A array. Here the result was also satisfying, but we should mention that a lot of the continuum of the Galactic centre is resolved out in this configuration.

Another test was a detection experiment of $H168_\alpha$ at 1.3 GHz seen in emission against the Galactic centre (Pedlar A., Anantharamaih, K.R, van Gorkom J.H., Goss W.M., Longey L., private communication). The line to continuum ratio here was about 0.15%. The data were obtained with the D array. Because of the shorter baselines this data was perfectly suited and as pointed out above the method is not limited in dynamic range. The visibility based subtraction proved to be at least as accurate as point source subtraction and orders of magnitude faster.

An example of a case were the method does not work properly was found in an experiment of HI detection in a field at high galactic lattitude (van Gorkom J.H., Szomoru A., Sancisi R., van Woerden H., private communication). Here the data were also obtained with D-array at a comparable frequency, but the presence of several point sources in the field made these data not suited at all for visibility based continuum subtraction.

5. When to use what method?

Ideally we would present here some rule when to use which of the schemes for continuum subtraction. Unfortunately that is not possible. The limits for "image subtraction" and "CLEAN components subtraction" can not be given quantatively. With simulations we looked into several different types of problems, but it is not possible to cover the whole range of observational parameters since these include relative bandwidth, resolution, source structure, UV-coverage, spectral dynamic range and the signal to noise level of the continuum.

We have performed noisefree simulations to compare our method especially with "image subtraction". We have found no cases where visibility based continuum subtraction works less satisfying than "image subtraction". In several noisefree

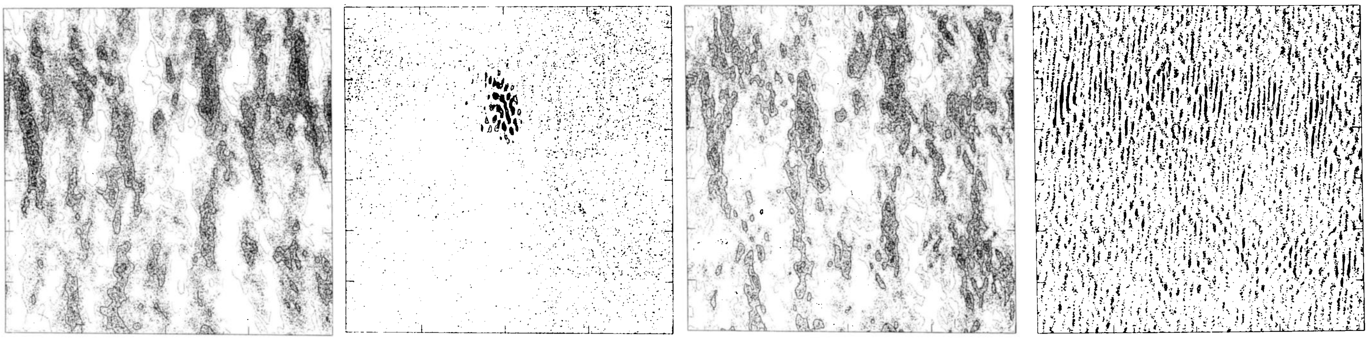

Figure 2. a. The residual map of a 3000 clean components model of SgrA (like in figure 1), of which the continuum was subtracted with "image based subtraction". The contours are -10, -5, -2, 2, 5, 10 mJy. **b.** The same artificial data, but now the "image subtraction" was performed on CLEANed images (1500 iterations). Contour levels are identical to the ones in figure 2a. **c.** Again using the same dataset, we tried a "CLEAN components subtraction", where a 10.000 clean components model was used. Same contour levels. **d.** The same channel map of the artificial data set after visibility based continuum subtraction. Note that the contour levels here are totally different: -1, -0.5, -0.2, 0.2, 0.5, 1.0 μJy.

simulations we found that images formed with the visibility based subtraction had *several orders of magnitude* less residual flux.

We show a comparison of different methods in figure 2. Here we have made a noisefree data cube from the galactic centre, comparable with the continuum emission in figure 1, by adding a model of 3000 CLEAN components to 48 planes of a database in which all visibilities were set to zero. The case we show here is most certainly a worst case for all other subtraction schemes but visibility based subtraction. In figure 2a we show "dirty" image subtraction; the continuum model was made by averaging and combining two ranges of "empty" channels in the same way as in the visibility based subtraction. Figure 2b shows the same procedure, but now with each channel in the data cube CLEANed seperately with 1500 iterations. In this case even clean components subtraction runs into problems. In figure 2c we show the same residual image plane after we modeled the continuum with 10.000 clean components and subtracted this model of point sources in the UV-plane. Even deeper cleaning left this result unchanged. Notice that the final figure (3d) has a completely different scale; the maximum residual is $\approx 10^3$ weaker with UVBAS!

Certainly there are a lot of cases where the "CLEAN componenents subtraction" will yield better results than UVBAS. If the background can be accurately described by a combination of pointsources it can work over large bandwidth.

Finally it is impressing to notice the relative difference in computer resources consumption. We give the amount of CPU seconds the calculation of the 4 images in figure 2 took on the Leiden University CONVEX-C210. Figure 2a, dirty image subtraction, 460 s.; figure 2b, CLEAN image subtraction, 2577 s.; figure 2c, 10.000 clean components UVSUB, 5053 s.; figure 2d, visibility based subtraction, 13 s. Apart from that the amount of diskspace used is also considerably less, because UVBAS can produce the needed visibility data directly.

6. Conclusions

We have shown that a visibility based continuum subtration works in some cases, especially when the channel widths are relatively small and the baselines are short. In all cases this technique can be used instead of *image* based continuum subtraction. It is often superior, especially in the cases of strong extended continuum.

There are also cases where the method gives more satisfying results than a CLEAN components based subtraction, though it will run into problems when run on a field with multiple sources.

An important advantage over both methods is the speed of UVBAS; because it consists of simple operations on each visibility record, it may be faster than the image based continuum subtraction, because no mapping of the "empty" channels is required. Of course it is therefore lots faster than CLEAN components subtraction. Because it directly produces the visibilities of interest it will save disk storage as well.

Unfortunately the decision if it is accurate enough is not always simple. One will just have to try, fortunately it is easy and fast.

We should mention some additional advantages to the method. It directly provides the observer with the visibilities of the spectral line image. It is therefore possible to do, for instance, selfcalibration on the spectral line image. The method does in principal work on uncalibrated data.

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