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Research Note

Complementing Aperture Synthesis Radio Data by Short Spacing Components from Single Dish Observations

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Summary. A method is described for supplementing aperture synthesis observations with short spacing data from single dish observations. These are necessary to complement the observations done with correlation interferometers when the sampling near the origin is incomplete. The method is illustrated with two examples which show results obtained by this procedure for two galaxies.

Key words: aperture synthesis – radio telescopes – short spacings

I. Introduction

The aim of interferometric observations as done with modern correlation interferometers such as the Westerbork Synthesis Radio Telescope (WSRT) is the determination of the brightness distribution on a part of the sky through the measurement of the complex function that describes its Fourier transform (*FT*) in the (U, V) (spatial frequencies) plane.

A complete description of such brightness distribution can only be obtained through its inverse Fourier transform if the measurements have been done over the entire (U, V) plane. There are two main practical limitations that make this impossible.

First, it is obvious that there will be always a largest base line in use and this fact limits the size of the observed (U, V) region. The result of this is a finite angular resolution in the obtained maps.

The second limitation is on the side of the short spacings. There is a minimum spacing between two elements of an interferometer because of their physical sizes. This means that measurements are seldom done with baselines shorter than about 1.5 times the size of the elements.

When transformed to the sky plane the gap around $U=V=0$ will produce a broad negative feature (a bowl) in the synthesized antenna pattern surrounding the main lobe. The effect of this feature will be quite serious when the observed object is extended since then a large part of the flux coming from broad components will be lost.

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A method now widely used in radio astronomy to eliminate the effect of undesired features in the antenna pattern is the clean and restore procedure. In this procedure a set of delta functions is found which reproduces the uncleaned map when convolved with the synthesized antenna pattern (SAP). This set is then convolved with a specified antenna pattern, producing a map without the effects of the sidelobes and without features that an SAP can show as a consequence of missing observations.

This method implies an interpolation or extrapolation, since it cannot provide by itself the information that is missing. It means that it can be applied in the case of the missing short spacings only when the objects are of small extent (not larger than about half the size of the bowl). For larger objects the approximation is not valid and the problem can be solved only by introducing the missing information. Single dish observations can be a source for that information, provided that the dish is large enough.

In this paper we describe a method for obtaining such information in the form that is required in order to complement correlation interferometer observations, from single dish data.

In Sect. II we shall describe the theory and in Sect. III the adopted procedure will be outlined. In Sect. IV two examples are shown in which results of this procedure can be seen and finally in Sect. V some warnings are given about the application of this method.

II. Theory

For the description of the procedure to derive the short spacing components from single dish observations it will be assumed that a sky brightness distribution map, B_{obs} (l, m) has been obtained and that the single dish antenna pattern, $A_{sd}(l, m)$ is known. It will also be assumed that the frequency band pass has been the same for both instruments. The sky coordinate system (l, m) and the associated spatial frequencies (U, V) system must be defined in the same way as for the aperture synthesis data. In the case of the WSRT these systems have been described by Högbom and Brouw (1974).

The map produced with the single dish antenna represents the convolution of the true brightness distribution $B_{tr}(l, m)$ with the single dish antenna pattern.

$$B_{obs}(l, m) = A_{sd}(l, m) \times B_{tr}(l, m). \quad (1)$$

The *FT* of the convolution gives

$$b_{obs}(U, V) = a_{sd}(U, V) \cdot b_{tr}(U, V), \quad (2)$$

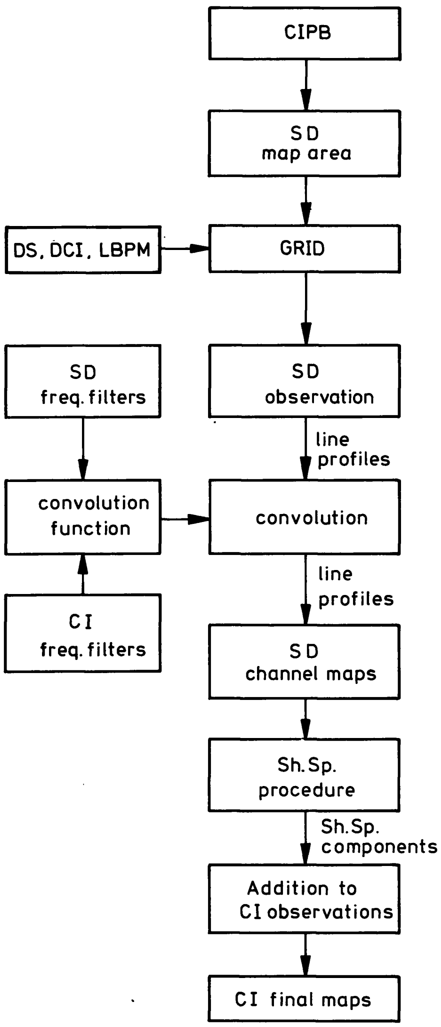

Fig. 1. Block diagram of the steps required to derive short spacing corrections from single dish data. For the meaning of the abbreviations refer to the text (Sect. IV)

where b_{obs}, a_{sd}, and b_{tr} are the *FT* of B_{obs}, A_{sd}, and B_{tr} resp.

The function $a_{sd}(U, V)$ is different from zero only within a certain region around $U=V=0$. The extent of this region depends on the size of the single dish and on its illumination. For those values of U and V for which $a_{sd}(U, V)\neq 0$ we can deduce the values of b_{tr}:

$$b_{tr}(U, V)=b_{obs}(U, V)/a_{sd}(U, V). \qquad (3)$$

Care must be taken not to use this expression for (U, V) values for which a_{sd} is very small. The useful extent of a_{sd} is determined by the amount of noise allowed in b_{tr}.

The limitation to the U, V values for which (3) can be applied and b_{tr} determined means that we can, in fact, only determine a function b'_{tr} defined by

$$b'_{tr}(U, V)=b_{tr}(U, V)\cdot P(U, V), \qquad (4)$$

where $P(U, V)$ is a cylindrical function whose value is equal to unity for U, V points within the region where (3) is valid and zero outside.

In order to obtain from b'_{tr} the required short spacing components we must calculate the response expected from a two-element interferometer with a baseline equal to the missing spacing.

The complex output $w(U, V)$ of a correlation interferometer can be written as (Högbom and Brouw, 1974).

$$w(U, V)=C\iint A_{ci}(l, m)\cdot B_{tr}(l, m)\exp\left(-2\pi i(lU+mV)\right)dldm \qquad (5)$$

where C is a constant that depends on the receiver characteristics (bandwidth, gain, etc.) and $A_{ci}(l, m)=(A_1(l, m)\cdot A_2(l, m))^{\frac{1}{2}}$ is the primary antenna pattern of the correlation interferometer deduced from the antenna patterns A_1 and A_2 of both elements.

The integral expression in (5) is recognized as the *FT* of the product $A_{ci}\cdot B_{tr}$, so we can write:

$$\begin{aligned} w(U, V)&=C\cdot FT\{A_{ci}(l, m)\cdot B_{tr}(l, m)\}\\ &=C\cdot a_{ci}(U, V) * b_{tr}(U, V), \end{aligned} \qquad (6)$$

where a_{ci} is the *FT* of A_{ci}.

Using b'_{tr} as obtained from (3) instead of b_{tr} we find:

$$\begin{aligned} w(U, V)&=C\cdot a_{ci}(U, V) * \{b_{obs}(U, V)/a_{sd}(U, V)\}\\ &=C\cdot a_{ci}(U, V) * \{b_{tr}(U, V)\cdot P(U, V)\}. \end{aligned} \qquad (7)$$

This expression shows that if the single dish is large enough, so that $P(U, V)$ contains the whole extent of a_{ci} when centered on a given (U, V) point, the value obtained for w for that point is correct (except for the noise).

The constant C must be obtained from calibration procedures. The results can be checked by examining the zero level of the final maps and by comparing the values derived from spacings that have been measured with the interferometer with those actually observed (provided that the single dish is sufficiently large).

III. Outline of the Adopted Procedure

Figure 1 shows a diagram in which the steps are indicated that have to be followed to derive the short spacing components for the line observations using the elementary theory described above.

The primary beam of the correlation interferometer (CIPB), the sky brightness distribution $[B(l, m)]$ and the desired dynamic range together determine the size of the area of the sky that has to be mapped with the single dish (SD) radio telescope. If no unusually strong sources occur in or near the area of interest it generally means that for a dynamic range of x *db*, the single dish map must cover the area enclosed by the x *db* contour of the CIPB. It is, however, not useful to map more than the area of the well-known part of the CIPB.

Let DS be the diameter of the SD instrument, DCI that of the CI elements and LBPM the length of the longest desired projected base line, all measured in wavelengths. The minimum necessary grid-point spacing Δg is then given by:

$$\Delta g=(\mathrm{DS}+\mathrm{DCI}+\mathrm{LBPM})^{-1}\ \mathrm{rad}. \qquad (8)$$

The SD line profiles must be convolved with a function determined by the SD and the CI frequency filters, such that the resultant profiles are those which would have been obtained with the CI filters. These profiles are used to produce single channel maps to which the short spacing procedure described in Sect. II is applied.

The output of the procedure is in the form of simulated interferometric observations which may be combined with the real observations prior to transformation into final maps.

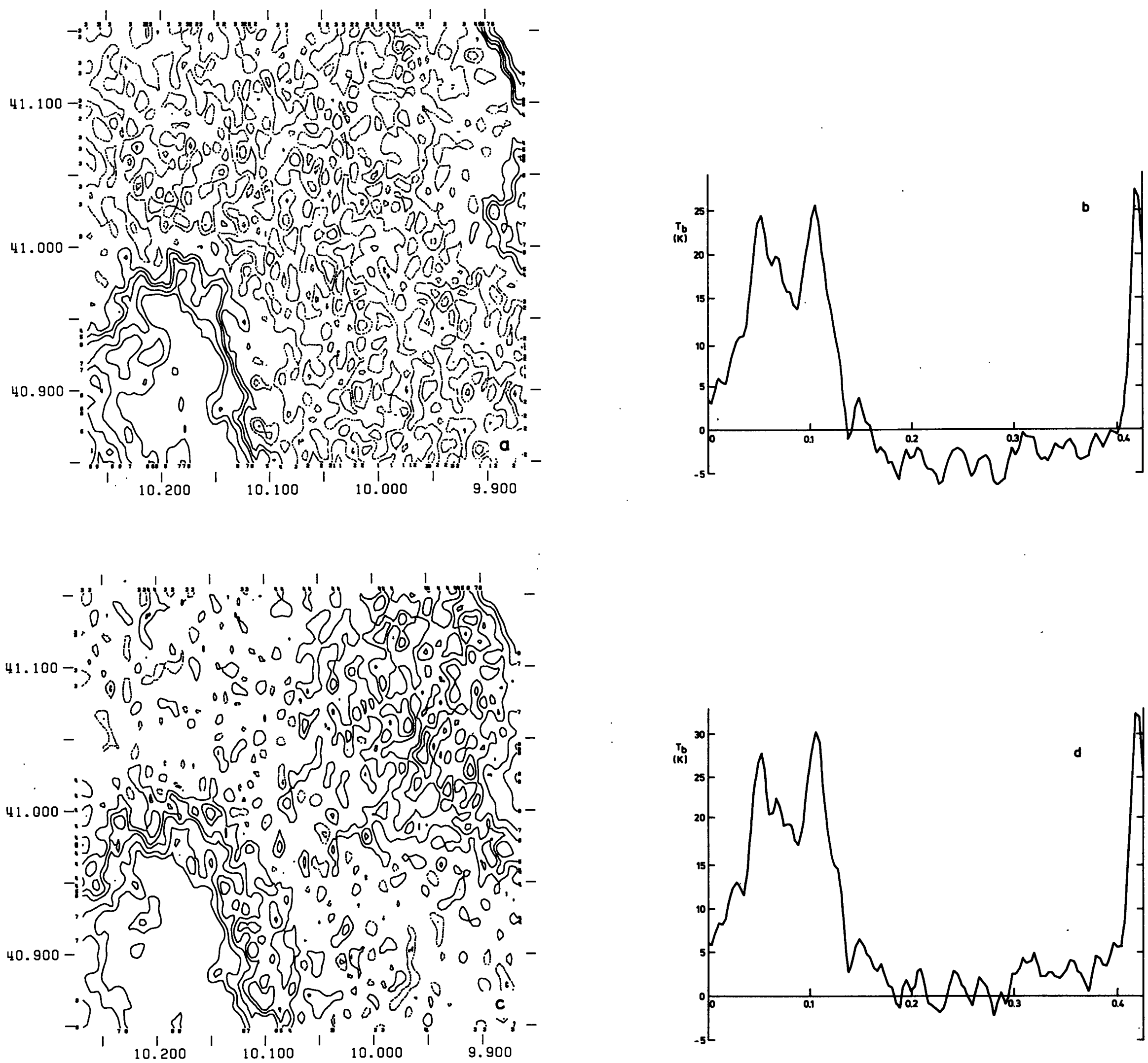

Fig. 2a. H I channel map for the central part of the field at $-320\ \mathrm{km\ s^{-1}}$ for M 31 without short spacing correction. Contours have been plotted between -6 K and $+14$ K brightness temperature. Negative contours were plotted with broken lines (alternate contours with short and long dashes). The 0 K contour has been omitted. **b** Cross-cut of the map shown in **a** along the diagonal from the lower left to the upper righthand corner. **c** The same as **a** but with short spacing correction included. **d** Cross-cut of **c** made in the same way as **b**

IV. Examples

In this section we shall show examples of the results obtained on two galaxies, M 31 and NGC 4258. Both galaxies were observed with the WSRT in the H I 21 cm line. The WSRT has been described by Baars and Hooghoudt (1974), Casse and Muller (1974). and Högbom and Brouw (1974), and the spectrometer by Allen et al. (1974). The baselines used for these observations were from 36 to 1458 m at 18 m intervals. The primary half power width for the WSRT at 21 cm is 36′. The channel filters were $27\ \mathrm{km\ s^{-1}}$ wide to half power.

M 31: For the WSRT, M 31 is a very extended object. The problem caused by the absence of the 0 and 18 m spacings in the observations was quite severe in this case as can be seen in Fig. 2a. This map shows the central part of the field for the channel at $-320\ \mathrm{km\ s^{-1}}$ (heliocentric velocity) as obtained without any short spacing correction. Figure 2b is a cut across the map diagonally from lower left to upper righthand corner. The negative region between the extended hydrogen features shows an average brightness temperature of -5.3 K.

Figures 2c and 2d show the same map and cross-cut after applying the short spacing correction. The single dish data were derived from the Jodrell Bank observations published by Gottesman and de Jager (1970). A description of the data processing is given by Bajaja and Shane (1979). It can be seen that the hydrogen structure has been raised because of the elimination of the negative bowl and that the broad low level features have become visible.

NGC 4258: Though this galaxy is not as large as M 31, it was necessary to include short spacing observations also in this case. The single dish observations, which were obtained with the 100 m Effelsberg telescope of the Max-Planck-Institut für Radioastronomie in Bonn, have been described extensively by van Albada (1978). Figure 3 shows how well the short spacing procedure has

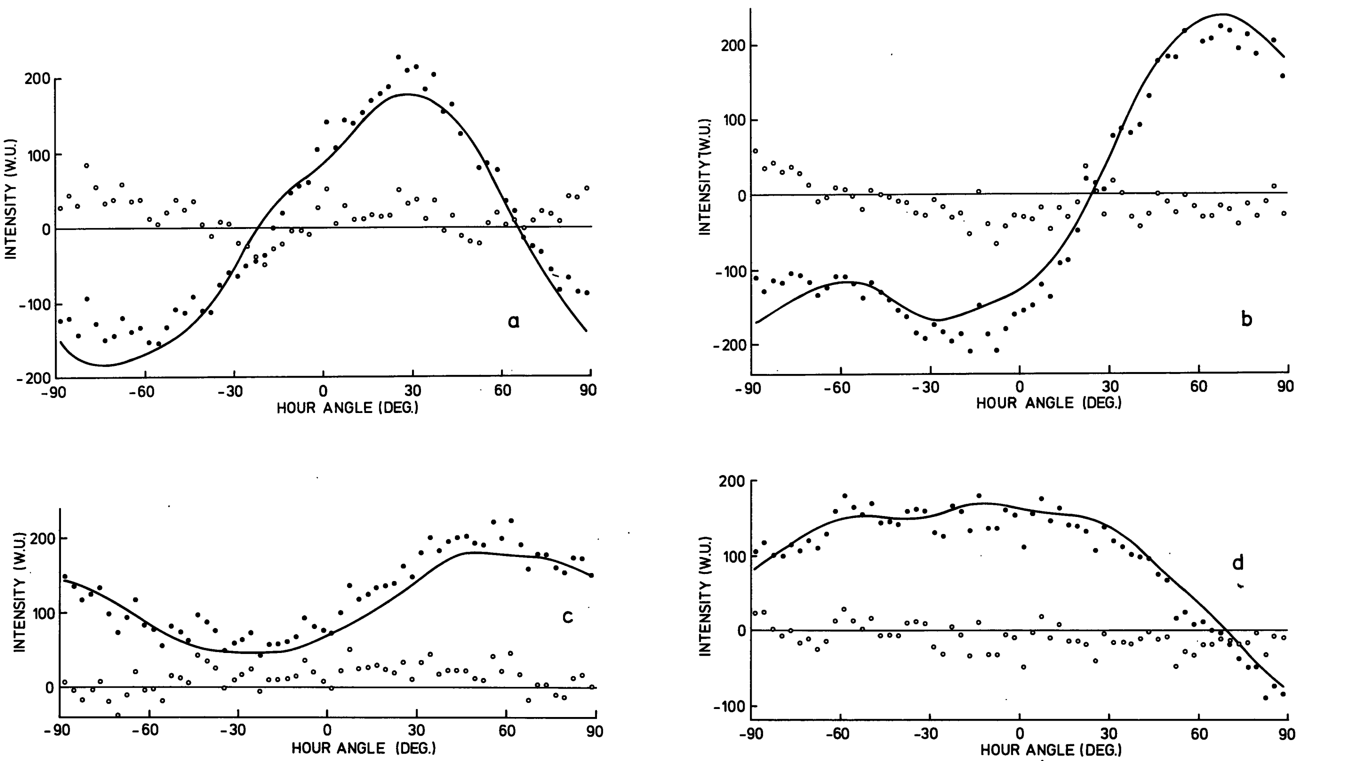

Fig. 3a. Cosine components for the channel at $+280\ \mathrm{km\ s^{-1}}$ for NGC 4258. Dots: WSRT data smoothed to 3° in HA; smooth curve: correlation function obtained through the short spacing procedure described in this paper; circles: differences between WSRT data and the correlation function from the SD. Ordinates are in Westerbork units (1 WU = 5 mJy). **b** As **a** for the sine component. **c** As **a** for the channel at $+600\ \mathrm{km\ s^{-1}}$. **d** As **c** for the sine component

worked in this case by comparing the cosine and sine components from WSRT observations and those derived from the single dish observations for the 36 m baseline of two velocity channels (at $+280$ and $+600\ \mathrm{km\ s^{-1}}$).

In order to make this comparison possible the continuum contribution has been removed from the WSRT data. Both the WSRT data and those obtained with the SD have been smoothed by a function 3° wide in hour angle and have been sampled every 3°. The much larger smoothness of the results from the SD is due to the fact that in these the noise is strongly correlated while all WSRT points are independent.

V. Cautions

In applying the procedure described above, one must be aware of the peculiarities of the (l, m) and (U, V) coordinate systems. For the WSRT observations (Högbom and Brouw, 1974), at low declinations and for large fields, the (l, m) coordinate system differs strongly from, for instance, the rectangular coordinate system on a photographic plate. The consequence is that the primary beam of the interferometer is distorted in these (l, m) coordinates and if it intersects the celestial equator, it even becomes two-valued.

The same problem appears with the SD beam but since it must be smaller than the interferometer primary beam, the effects will be smaller too.

The calibration of the SD data must be done very carefully and in all cases it is recommendable to check the results of the short spacing procedure in the way it has been done in this paper in the examples of Sect. IV.

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