PAPER 87

A COMPARISON OF AN INTERFEROMETER AND TOTAL-POWER SURVEY OF DISCRETE SOURCES OF RADIO-FREQUENCY RADIATION

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A fundamental limitation to the number of radio sources observable with a given aerial system is set by the finite solid angle of the aerial beam's reception. In any survey, whether it be a total-power survey or an interferometer survey, errors tend to occur whenever two sources are present simultaneously in the aerial beam. If the receiving system is a total-power system the contributions from the two sources will add, and either they will be interpreted as a single source of greater intensity than each of the individual sources, or the sources may be resolved but their intensities and positions may be subject to considerable errors.

With an interferometer, beating will occur between the fringe patterns of each source and the record's appearance will depend on their relative phases. Thus, the interpretation of the record in a confused region will in general be different from the interpretation that would be placed on a total-power record covering the same region. It is therefore to be expected that an interferometer survey of a given region of sky will give rise to different results from a survey made with total-power equipment of the same resolving power at the intensity level at which the confusion effects become serious. A comparison of the results obtained from a total-power and an interferometer survey of similar resolving power should enable us to make an estimate of the reliability of a survey that is resolution limited. This paper summarizes the results of such a comparison.

1. THE TOTAL-POWER AND THE INTERFEROMETER EQUIPMENT

The total-power equipment was similar to the one used at 158 Mc/s by Brown and Hazard [1]. The aerial system is a paraboloid 218 feet in diameter and 126 feet in focal length, and at a frequency of 92 Mc/s the beamwidth is 3 degrees between half-power points and the power gain is 1390 over a half-wave dipole. Allowing for feeder loss and the factor of 2 in sensitivity because of the switching system, the equivalent power gain is reduced from 1390 to 415. The beam is directed to different declinations by tilting the mast that supports the primary feed in the north-south plane.

The interferometer was a phase-switched instrument, the paraboloid being used as one of its elements while its second element consisted of an array of dipoles, the beamwidth of which, between half-power points, was 80 degrees

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in declination and 4°.5 in right ascension. The zeros in the right-ascension plane fall on the first subsidiary maxima of the paraboloid polar diagram, and the side lobes in this plane are negligible. In the declination plane the resultant polar diagram is effectively the voltage polar diagram of the paraboloid, and the first side lobes are 12 per cent of the peak intensity in the main beam.

The secondary aerial was at a distance of 156 wavelengths from the paraboloid, which gives a lobe separation of 22 minutes of arc and about four lobes within the half-power points of the envelope of the resultant interference pattern which was approximately 3°.5 wide in right ascension and 4°.6 in declination.

The gain of the dipole array was 96 over a half-wave dipole and the resultant gain of the interferometer in the vertical was 580. Because of the array's large beamwidth in the north-south plane it was possible to cover different regions of the sky, as in the total-power survey, by merely tilting the mast of the 218 foot paraboloid.

2. METHOD OF ANALYSIS

The sets of records obtained with the total-power equipment and with the interferometer were analyzed separately and two independent lists of sources were obtained. For the purpose of this analysis a source on the total-power records was defined as an increase in intensity corresponding to the aerial beam shape and on the interferometer survey as a fringe pattern with an envelope approximating the envelope of the interferometer-response pattern. The total-power list will therefore include enhanced regions of emission of angular diameter less than the aerial beamwidth. The interferometer list, however, will include only those sources with angular diameters much less than the lobe separation of 22 minutes of arc.

A source was included in the total-power list of sources only if it was observed on at least two records. As a further check on the reliability of this list a number of records obtained at 92 Mc/s were compared with the corresponding records obtained at 158 Mc/s in an earlier survey by Hanbury Brown and Hazard [2]. Fig. 1 shows a comparison obtained at declination 52°30′ N. It can be seen that although these records were taken at an interval of several years, there is very good agreement between them when allowance is made for the smoothing produced at 92 Mc/s by the larger aerial beamwidth. In no case was any disagreement found between the two sets of records. It was concluded from this comparison that the majority of the sources derived from the total-power survey genuinely represented enhanced regions of intensity although they may represent not only single sources but blends of two or more too close together to be resolved by the aerial beam.

The interferometer records were less disturbed by interference than the total-power ones and in general two records at each declination setting were sufficient to establish that a feature was genuine. In all, about 150 records were obtained covering most of the region included in the total-power survey.

On all the records a continuous lobe pattern, probably due to faint sources below the resolving limit of the aerial, was visible above the noise. The interferometer was therefore clearly not limited by noise fluctuations, but resolution limited.

The right ascension of any source was found from the time it was observed to transit the aerial beam. The declination was found by plotting the intensity observed at transit against the declination and noting the declination at which the maximum intensity was received, this measurement also giving the intensity of the source.

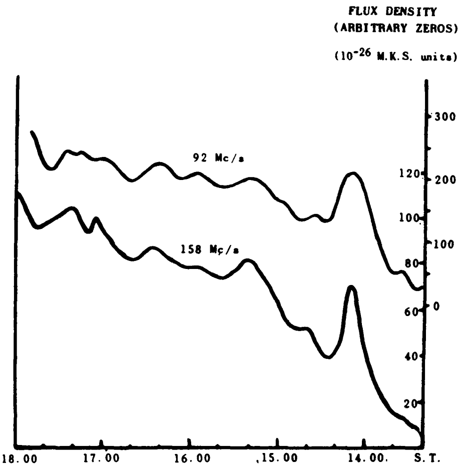

FIG. 1. Profiles of the same declination taken at 158 Mc/s (2-degree beam) and 92 Mc/s (3-degree beam) showing correlation of unresolved structure. The prominent source at 14^h10^m S.T. is HBH 18 (IAU 14N5A).

In the case of the interferometer survey the declination of each source was also estimated from the lobe speed of the observed fringe pattern, and the declination thus derived was used to check that the source was genuine and not caused by the presence of one of the intense sources in a minor lobe of the aerial beam. The main side lobes, which are most serious to the north and south of the main beam, are only important near the more intense sources observed in the survey and, since their positions are known, should not introduce any errors to the survey.

3. COMPARISON OF OBSERVATIONS

The positions and intensities of 116 sources were derived from the total-power records and of 134 sources from the interferometer records. These lists of sources are to be published in the Jodrell Bank *Annals* together with a detailed comparison of the observations. The results of this comparison will now be summarized.

In the region of sky common to both surveys there are 81 sources in the total-power list (list *T*) and 102 sources in the interferometer list (list *I*). A direct comparison of the lists shows that there are 40 positional agreements within the limits of experimental error. On the basis of the estimated errors in position only 11 coincidences would be expected if the lists were completely random; therefore the majority of the above coincidences must be genuine. This is confirmed by a comparison of the intensities of the sources in the two lists. In all cases there is no evidence of any deviation from unity that cannot be accounted for by random errors in the measurements.

In the region of sky common to both lists there are 40 sources on list *T* and 60 sources on list *I* that do not coincide with sources in the other list.

These discrepancies are divided into flux-density groups in tables I and II and it can be seen that for sources of intensity less than 60×10^{-26} watts $m^{-2}(c/s)^{-1}$ the agreement between the surveys is very poor.

TABLE I

Intensity $\times 10^{-26}$ watts $m^{-2}(c/s)^{-1}$	$\geqq 19$	20 to 39	40 to 59	$\geqq 60$
No. of list *T* sources covered by interferometer	14	35	14	18
No. of list *T* sources not on list *I*	9	22	5	4

TABLE II

Intensity $\times 10^{-26}$ watts $m^{-2}(c/s)^{-1}$	$\geqq 19$	20 to 39	40 to 59	$\geqq 60$
No. of list *I* sources covered by total-power survey	1	51	34	16
No. of list *I* sources not on list *T*	1	35	24	0

In order to investigate the discrepancies in more detail the sets of records obtained in the two surveys were compared directly in the regions of the missing sources. Interferometer sources were found in the position of a further five of the total-power sources, and total-power sources were found in the position of four of the interferometer sources. All of these sources were comparatively weak and had been considered doubtful in the original analysis.

However, in the positions of the majority of the missing interferometer sources there were no visible total-power sources, and similarly in the positions of the missing total-power sources there were no visible interferometer sources. It is possible that the total-power sources that were not observed on the interferometer records have large angular diameters, but there is no analogous possibility to explain the absence of the interferometer sources on the total-power records.

It is possible that some of the weaker interferometer sources lie in depressions in the background radiation which mask their presence on the total-power records, but is improbable that this can account for all the discrepancies. It therefore appears that some of the sources on the interferometer survey are spurious, a number of which probably arise owing to beating effects of weaker sources that are present simultaneously in the aerial beam. This effect is illustrated in Fig. 2, which shows a comparison of the total power and interferometer records for declination 32 degrees N. The correlation between these records appears to be poor, the most striking feature being that the clearly defined interferometer source at right ascension $12^h\ 30^m$ lies in a minimum on the total-power record. This phenomenon is a characteristic feature of the records and clearly suggests that at least some of the interferometer sources are spurious, produced by beating between two sources on either side of the apparent interferometer source.

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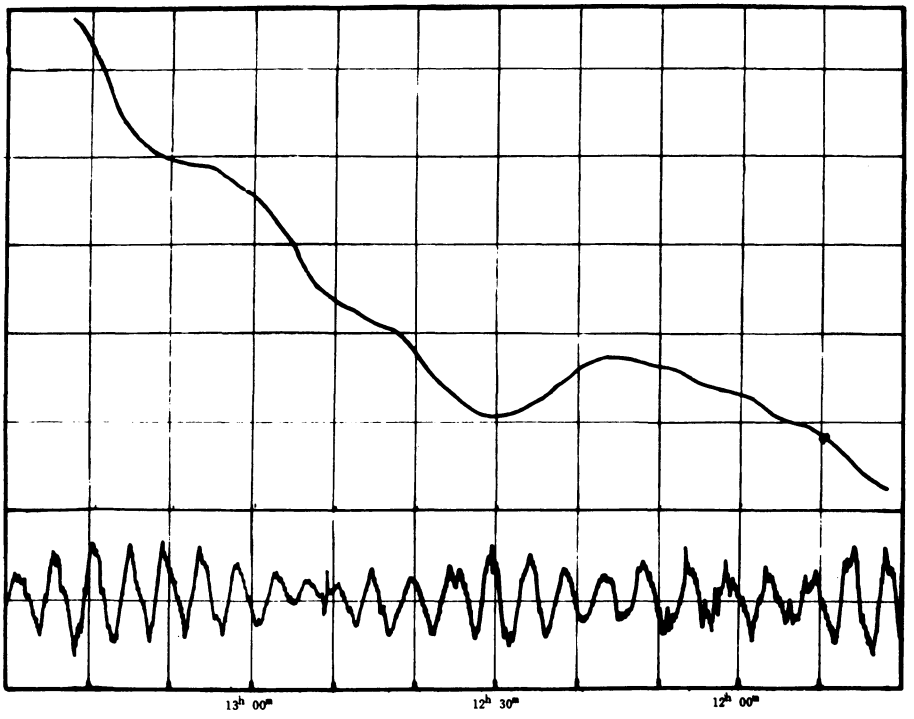

FIG. 2. Total power and interferometer records over the same region (aligned accurately in time). The obvious interpretation of the interferometer record is clearly at variance with the total power. One division represents 30×10^{-26} watts m^{-2} $(c/s)^{-1}$.

For the present purpose, however, it is sufficient to note that there are discrepancies between the interferometer and the total-power records and it seems certain that the sources that are observed in the interferometer and not in the total-power survey are the results of confusion.

4. THE RELIABILITY OF A CONFUSION LIMITED SURVEY

The intensity level at which discrepancies appear between the total power and the interferometer surveys enables us to estimate the source density at which confusion effects become important in the interferometer survey. For this purpose the analysis is restricted to the region of the sky between right ascensions 05^h and 17^h. Outside this region the majority of the interferometer sources are strong sources found on isolated records and are therefore not a representative sample, but inside these limits the interferometer survey is complete. In this region there are 3500 square degrees of sky common to both surveys in which 96 interferometer sources were observed. Above an intensity limit of 60×10^{-26} watts $m^{-2}(c/s)^{-1}$, there are 11 interferometer sources that were observed on the total-power survey, below this level there are serious discrepancies between the two surveys. Thus, when the observed number of sources in area of 3500 square degrees exceeds 11 errors begin to appear in the interferometer survey. The area covered by the interferometer beam between half-power points is 12.5 square degrees, which corresponds to a source density of about 1 per 25 beam areas. Since these errors are probably caused by weaker sources in the beam this observed density corresponds to a higher density of confusing sources.

5. CONCLUSIONS

It has sometimes been stated that the maximum number of sources that can be resolved in a radio survey is equal to the number of beamwidths in the sky. The observations presented in this paper show that the number of sources that can in fact be reliably catalogued is very much less than this. The actual density at which serious errors occur in a survey will depend on the instrument and the method used to reduce the observations. It seems that if this simple type of analysis, which is commonly employed in radio astronomy, is adopted then errors will occur at an observed density of about one source per 25 beam areas. This limitation must be borne in mind in drawing conclusions from source counts, and it places a severe restriction on the number of sources that can be reliably observed by existing aerials operating on meter wavelengths where most surveys have been carried out. In order to extend the investigation to the spatial distribution of the localized sources to greater distances, surveys with much greater resolving power must be used, or more reliable methods of analysis must be devised.

REFERENCES

[1] Hanbury Brown, R., and Hazard, C. *M.N.R.A.S.* **111**, 357, 1951.
[2] Hanbury Brown, R., and Hazard, C. *M.N.R.A.S.* **113**, 123, 1953.

Discussion

Ryle: Dr. Hazard has stressed the importance of making instruments of sufficient resolving power to restrict our observations to sources for which there is only one source per 20 beamwidths. We could say that the method developed by Dr. Scheuer (*Proc. Camb. Phil. Soc.* **53**, 764, 1957) allows one to work to above one source per beamwidth; this technique of course enormously increases the power of existing instruments, and makes it possible to draw conclusions about sources that could only be reliably observed individually with instruments that must at present be regarded as impracticable.

Brown: Dr. Scheuer's *paper* method of investigating the distribution of sources by means of the probability distribution of the interferometer record was based on an idealized model of the sky. How is this method affected by the actual type of distribution we are likely to encounter, and in particular what are the errors introduced by a dispersion in the angular diameters of the sources?

Scheuer: Since there is not time to explain the statistical method for

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analyzing confused records, I think it would be best if I asked for questions, which I shall try to answer. Hanbury Brown has already asked about the effect of a dispersion in angular diameter. A source whose angular diameter is comparable with the lobe spacing of an interferometer produces a pattern on the record similar to the pattern from a point source, but of reduced amplitude; hence its contribution to the resultant deflection on a confused record is identical with the contribution of a weaker point source. The effect of angular diameter is therefore the same in the statistical method as in a source count on unconfused records, no more and no less. The question of angular diameters arises only in interferometric observations; sooner or later one must impose a limit on the size (or, ideally, on the brightness temperature) of features that one is willing to count as "discrete sources." Perhaps others would like to comment on this question.

The other source of error, which is also substantially unchanged whether one uses source counts or the statistical method on a given set of records, is the possible clustering of sources. The evidence on clustering is not yet entirely conclusive, but perhaps Dr. Mills will have more to say on this subject.

Lovell: It seems to me that the great difficulty in applying these statistical counts to models of the universe is the lack of homogeneity in the sources to which the observations refer. For example, the results would show the Perseus cluster as a single source NGC 1275, whereas in fact the cluster itself, which is neglected, contains a very large number of galaxies.

Scheuer: As I have said, the angular diameters of sources introduce the same errors, whether one uses source counts or counts of deflections. These effects are a property of the aerial system, not of the statistical analysis. The effects of clustering are roughly these: A pencil-beam system resolves nearby clusters into separate sources; a more distant cluster appears as an extended source whose apparent flux is the total flux of the cluster; the most distant clusters appear as point sources. An interferometer of the same size also resolves nearby clusters into separate sources; a more distant cluster appears as a source whose apparent flux is intermediate between the total flux and the flux of one of the sources in the cluster; only clusters so distant that they do not fill one interference lobe appear as point sources with the total flux of the cluster. In order to allow for the effects of clustering, either in source counts or in counts of deflections, it is essential to know a great deal about the kind of clustering that is present. Clusters such as the Perseus cluster are unlikely to have an appreciable effect on the 81.5-Mc/s or 159-Mc/s Cambridge results, but on a more general basis the question must remain open.

Mills: Dr. Scheuer has brought to light one of the serious weaknesses of an interferometer survey. Strong sources of large angular size are either eliminated or counted as weak sources, thus affecting both the source counts and the envelope statistics in such a way that an apparent excess of faint sources is produced. As shown later in paper 91 the number of large sources is significant.

It is illuminating to consider the information provided by interferometer and pencil-beam surveys in terms of the spatial Fourier components accepted by the instruments. An interferometer accepts a band of high frequencies that depends on the aerial spacing and size of the individual aerials. A pencil-beam instrument accepts lower frequency components extending to zero frequency. The latter are required to measure the flux densities of large sources. When faced with a complex brightness distribution involving a complex distribution of the Fourier components, it is not surprising that interferometer and pencil-beam instruments give different results. In particular, the envelope statistics of an interferometer can never yield definite information when a complex distribution is involved.

Scheuer: Measurements of angular diameters by Baldwin and Archer suggest that angular diameters as great as 5 minutes are rare among Class II sources; measurements at Manchester and Mills's own recent measurements suggest that a large proportion have diameters of seconds of arc. I would agree entirely with Dr. Mills that we should have more complete information about sources. A picture with resolution approaching that of an optical photograph is very desirable, but does not appear to be within reach at the present time. Until such a time comes, one must be content with information in a part of the Fourier spectrum, and I do not believe that information in one part of the Fourier spectrum is necessarily more valuable than the same amount of information in another part; that to omit some of the middle of the Fourier spectrum is more dangerous than to have no sample of the higher components.

Gold: Whether large-area antennas are genuinely required to investigate the distribution in depth or whether some other device of analysis can suffice to extract the information from the results with a smaller area, clearly has to be settled. The output of any receiving system is known not to relate uniquely to the actual radiation pattern in the sky, but to be compatible with a variety of patterns in each case. If one were entitled to assume certain characteristics of this actual pattern, then the antenna output would enable one to deduce others. The total information content goes up with antenna size, and therefore the range of possible patterns in the sky compatible with the record diminishes. So long as we are unclear about the nature of the actual pattern we shall require the information from the large antenna, and we cannot make do with the information given by sampling at a few places within this size. Scheuer's type of analysis cannot overcome the genuine lack of information, and if we cannot trust a particular assumption about the pattern in the sky we cannot derive any benefit from it. We therefore are left with a clear case for larger aperture antennas and we could not get the same information "on the cheap" by any device of analysis.

Vitkevich: I should like to say that if we intend to investigate now any one problem of radio astronomy we have to consider two questions: first the resolving power and second the sensitivity of the radiotelescope we intend to use. If we investigate the problem of the distribution of weak sources at meter wavelengths, the problem of resolving power is the more difficult and the more important one. Using an interferometer at 3.5 m wavelength with a surface of 4000 m^2, Ryle could detect about 2×10^3 radio sources, but if the resolving power of his radiotelescope were higher, this number would probably be increased. The reason is that the resolving power (the directivity) of his system was poor. He could not use the full sensitivity of the instrument. As the surface increases, difficulties of this kind also increase. Ryle's new system is very intesting, but it does not have good resolving power. In my opinion, the best system is one combining the principles of the cross and interferometer. This kind of system is now under construction in the U.S.S.R. (V. V. Vitkevich in *A. Zh.*)

Dewhirst: The question whether all discrete sources in high latitude have angular diameters small enough to be consistent with the assumption that they are galaxies is in every respect an extremely important one. The present radio evidence is incomplete and conflicting. At present we seem to distinguish three situations: (1) The radio diameter is quoted as 12 seconds or less; we infer that the optical diameter of the galaxy would be of the order of 3 seconds, i.e., about a 22^m galaxy, and it is not surprising that there is no identification. (2) The radio diameter is about one or two minutes and the source is identified with a galaxy of this order of size. (3) The radio diameter is quoted as about 5 minutes: we should expect the optical object to be about one minute in diameter or about 16^m, yet we can make no certain optical identification even with a much fainter galaxy. Three such latter situations are suspected at present and urgently require detailed investigation: if such situations are confirmed we may be obliged to infer that there are objects in high latitude that are features of the galactic halo rather than of the distant metagalaxy. They would have to be condensations one order of magnitude smaller in size than the unidentified large-diameter sources (or background irregularities) which are at present thought to belong to the galactic halo.

Jennison: An aperture of given size, whether or not divided as an interferometer system, produces the same quantity of information, though the particular sample of information is different in each case. Though Mr. Ryle inferred that the interferometer has the *added* advantage of phase information, this information is not additional but alternative to the phase information inherent in the envelope of a pencil beam. The latter contains the lower frequency Fourier components in place of the group at higher frequencies contained in the interferometer pattern.

While there exists a disagreement between surveys by the two types of instrument it is evident that the only satisfactory solution lies in a completely filled aperture or a synthesis that is extended to fill the corresponding area completely. Otherwise we assume a priori conditions for the distribution and structure of the sources, which may not be justified in view of more detailed study of individual sources or very localized regions. No applications of statistical analysis can fill in the gaps in the Fourier components, and while the present anomalous position exists, I do not consider that readings taken with an interferometer at a single spacing or at a very small number of spacings can necessarily be correlated with readings taken with a single aperture.

Ryle: As Dr. Scheuer has pointed out, we have never claimed that the statistical method could supply Fourier components not present in the aerial! In fact, as those who have read our survey papers will know, the aerial system was used in three different ways: as an interferometer of high resolving power; as an interferometer of intermediate resolving power; and as a pencil-beam system. The range of angular frequencies covered therefore covers several bands in the total range out to the greatest resolving power of the system. Any model of the sky that contains components only in the gaps in the angular frequency spectrum we used, seems to be rather special!

Field: If I understand Mr. Hazard correctly, it is necessary to utilize phase data to get the same amount of information from an interferometer as would be given by a pencil-beam system with the same resolution. Has this phase information been utilized in the Cambridge survey? If not, does this not explain at least partially the discrepancies between the Cambridge and Sydney surveys? Perhaps Dr. Scheuer would comment on this.

Smith: The probability distribution must of course use the phase information. It is inherent in the method. You will hear from Dr. Shakeshaft of the most recent Cambridge survey (3C at 160 Mc/s), in which phase information has indeed been most rigorously used.

Pawsey: It should be recognized that the Cambridge conclusions depend on the application of the inductive method. The observations are in themselves incomplete, cf. the restrictions of the Fourier components of the distribution of brightness as discussed by Mills. But a plausible hypothesis is advanced relating source distribution in space, source sizes, degree of clustering, and so forth, and from it and the observations a conclusion is drawn. It is the essence of the inductive method that the hypothesis must conform with *all available observations*, and the present controversies strongly suggest that this is not true in this case. Hence it is imperative to resort to the most direct means for determining the distribution of radio brightness in the sky. This implies the use of pencil-beam techniques of a resolution adequate to resolve the existing uncertainties.