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Alternative approach to passive sonar

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NORTH ATLANTIC TREATY ORGANIZATION

Alternative approach
to passive sonar

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Ralph R. Goodman
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Corrigendum

During final preparation the illustrative material of Fig. 1 (page 4) and Fig. 8 (page 9) was accidentally transposed; the caption on the page is the correct caption for that page in each case.

Alternative approach to passive sonar

W.M.X. Zimmer

Abstract: An alternative approach to spatial processing for passive sonar is proposed and discussed. It is considered to offer better performance than conventional and high-resolution beamforming. In particular, the approach makes it possible to construct a broadband beamformer which outperforms high-resolution techniques: it provides better resolution, is sidelobe-free, and allows the detection of rather weak sound sources. The approach is based on the analysis of the statistical properties of the different sound sources of interest and allows controlled extraction of the information of interest. It is also possible with this approach to construct multibeam LOFAR plots which display more than one beam simultaneously without loss of further information. Since the proposed approach abandons the estimation of the cross-spectral matrix, it has no greater requirement viz-a-viz the stationarity of the signals than the conventional approach has.

Keywords: alternative approach ◦ broadband beamformer ◦
classification filter ◦ frequency-azimuth analysis ◦ high-resolution
beamformer ◦ multibeam LOFAR ◦ narrowband beamformer ◦
Wagstaff-Berrou method

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1. Introduction

The development of high-resolution methods plays an important rôle in applications where the physical size of the measurement aperture cannot be increased to provide sufficient resolution for discriminating between two or more signals of interest.

For example, in passive sonar applications one may in principle achieve high spectral resolution by lengthening the time window for the Fourier decomposition of the signals. High angular resolution, however, would need long arrays, and although these are theoretically feasible there are upper limits in practice to the associated large apertures.

When the array aperture cannot be enlarged one may think of using signal processing methods to get higher resolution. However, the requirement of higher resolution has an impact on other performance figures of the beamformer. In particular, it can be shown that [1-4] for a single sound source high-resolution methods do not provide more accurate bearing estimates than the conventional beamformer. Also, when dealing with detection problems, the conventional beamformer is in some sense optimal and the high-resolution methods tend to show decreased performance. This is not surprising, because to achieve a high-resolution sound field estimate it is necessary to extrapolate the hydrophone cross-correlation function beyond the array aperture. This extrapolation may only be done without risk when the cross-correlation function is known exactly (within the array aperture). However, when the cross-correlation matrix estimate is erroneous, its extrapolation may amplify the effect of the measurement errors to yield an increased standard deviation of bearing and peak-level estimation.

Most high-resolution beamforming techniques are based on the inversion of the spectral hydrophone cross-correlation matrix, with the consequence that statistical averaging is needed to provide the necessary non-singularity of this matrix. In the case of beamforming it is a time average which is usually used to ensure statistically independent samples. This means that the signals must be assumed to be stationary in azimuth for a relatively long period of time. The minimum number of independent samples is given by the number of coefficients in the cross-correlation function. It is clear that for high-resolution problems one would try to use the full physical aperture of the array for beamforming. Therefore, the number of time averages should be greater than the number of available hydrophones. A maximum number of averages cannot be defined from a signal-processing point of view since the rule: the more time averages the better the estimate of the correlation matrix, is not applicable due to the possibility of changes within the scenario.

To give a clearer impression of the time requirements some numbers may be useful. On the assumption of a spectral resolution of 1 Hz and an array of 32 hydrophones, more than 32 s are required to provide a non-singular estimate of the cross-correlation matrix. If one increases the number of hydrophones to, say 128, the amount of time required for a non-singular estimate of the correlation matrix will go up to at least 128 s. These figures must be considered as the lower limit, and in fact it can be shown [5] that for an acceptable estimate of the cross-spectral matrix the number of averages should be at least twice the number of hydrophones. However for long arrays this requirement may lead to stationarity problems within the scenario. In particular, when the array is towed one may assume that the target of interest is stationary in azimuth for only a short period of time.

The question is now how to overcome this problem. The apparent answer is to make a better estimate of the correlation function without increasing the time average. This can be done by reducing the aperture to allow spatial averaging. However, this is in contradiction to the needs of high resolution, because to get higher resolution one should first increase the array aperture, and only when there is no such possibility should one try to get high resolution via signal processing. Another answer is to perform some sort of spectral averaging. However such a procedure needs the interpolation of the spectral correlation function, which is not easy to carry out.

The work reported here tries to develop a totally different answer. In accordance with one of the conclusions of [1] the estimation of the spectral hydrophone cross-correlation function will be abandoned and replaced by a method which takes into account the stochastic nature of the sound signals. Similar work has been done at FHP/FGAN, Werthoven (Germany) [6] and at GERDSM, Le Brusac (France) [7]. The method is essentially based on the observation that under normal circumstances two different sound sources will have significantly different statistics. As a consequence, the spectral lines of one source will peak at a different time from the spectral lines of the other source. By exploiting this statistical difference it is hoped to construct broadband methods that have better performance than conventional methods.

2. Derivation of the algorithm

Before the algorithm is derived it may be useful to briefly sketch the general assumptions.

The algorithm should exploit the statistical features of the different sound sources which are present in the measurements; it should avoid time averaging directly after the spectral and angular decomposition of the data; and it should preserve as much of the broadband information of the sound sources as possible.

The following derivation is based on an ad hoc procedure and the author is confident that additional thought will yield further improvements in performance.

The algorithm consists of the following components:

- spectral and angular decomposition of the hydrophone measurements;
- data reduction which ensures that only important information remains;
- the presentation of the remaining information (broadband beamforming and multibeam LOFAR).

2.1. GENERATION OF A FREQUENCY-AZIMUTH SURFACE

The first step is conventional (linear) signal processing, yielding a frequency-azimuth surface. Due to the linearity of the processing all information measured by the hydrophones is still available to the user.

Figure 1 shows an example of such a frequency-azimuth surface. The measurements were taken from a set of at-sea data recorded during SACLANTCEN Sea-Trial SPG 1/85. The number of hydrophones was 32, with an inter-element spacing of 1.96 m (corresponding to an array design frequency of $750/1.96=382$ Hz). The spectral resolution that was selected was 1 Hz.

In Fig. 1 the abscissa represents the steering angle of 512 beams according to a cosine scale (angular decomposition). The ordinate represents the different frequency bins according to a linear scale (spectral decomposition). The colour corresponds to the spectral power and is measured in dB relative to some arbitrary reference level.

One can easily discern that the data were recorded with a high-pass filter with a cut-off frequency of about 100 Hz. The figure shows all the features one may expect from such a frequency-azimuth surface: at low frequencies the different signals are

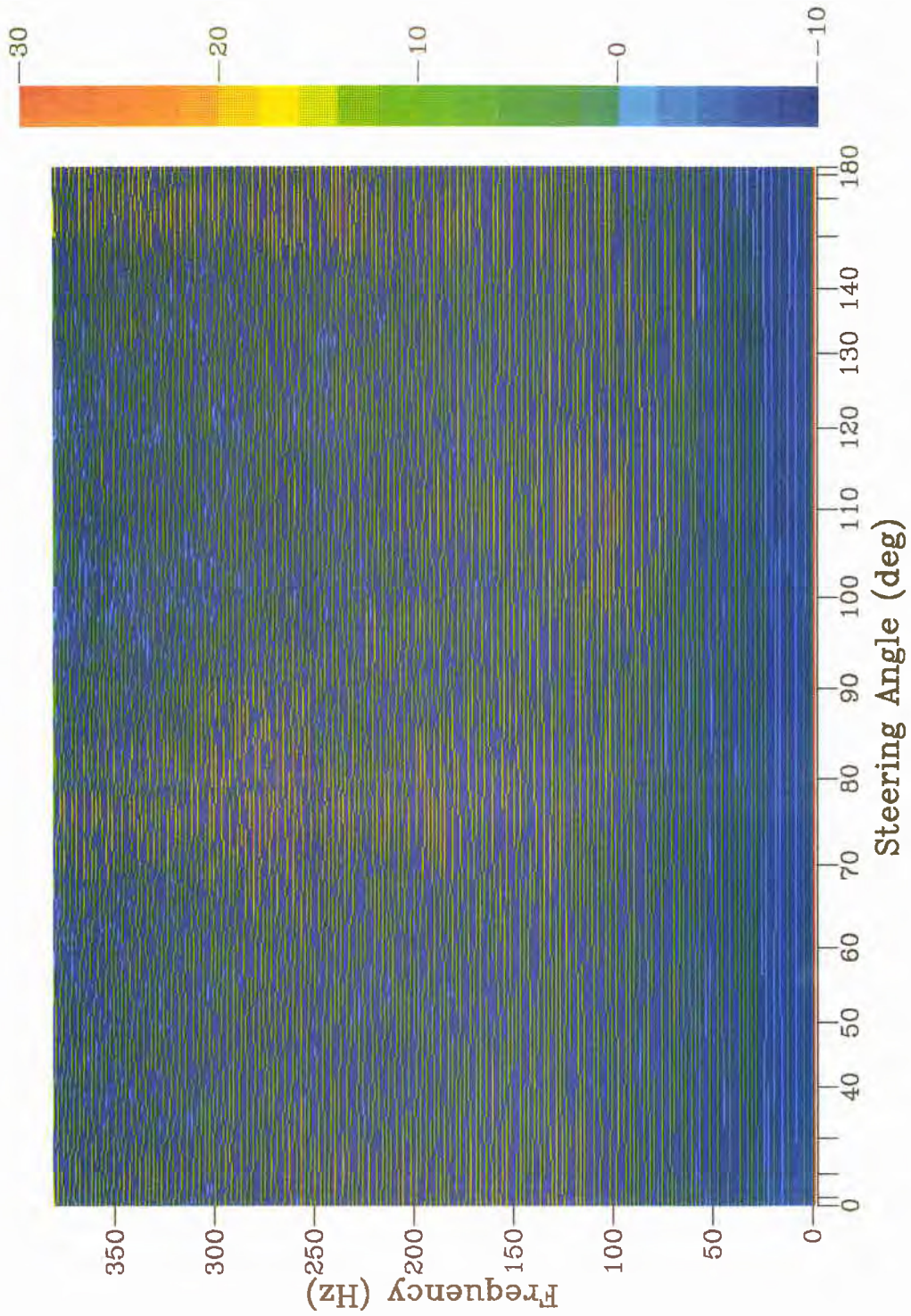


Fig. 1: Conventional frequency-azimuth display.

broadened in angle so that higher angular resolution is found at higher frequencies, and by keeping the steering angle constant (i.e. for a fixed beam) there is evidence of the broadband behaviour of the different sound sources. This means that the instantaneous structures (i.e. lines, local maxima) are not only different between the different targets but also vary independently as time goes on. Consequently there are good reasons to assume that at different times different sound sources will peak up at different frequencies.

A further observation to be made from Fig. 1 is that the inherent angular resolution is insufficient compared to the spectral resolution. In fact it is this lack of spatial resolution that stimulated the research on high-resolution beamforming.

Because the statistical character of the different sound sources is independent of the array aperture, one can expect that through appropriate treatment of the frequency-azimuth surface one will be able to distinguish different sources even if their angular spacing is below the conventional resolution limit. This expectation can be attributed to the observation that when two broadband sources are more or less of equal strength, a certain amount of frequencies can be expected to dominate for one source while other frequencies will dominate for the other source.

What one needs is an intelligent algorithm/strategy which picks out of the frequency-azimuth surface only that information which is necessary for indicating the existence of the different sources; the algorithm/strategy ignores all redundant data.

On the basis of this discussion the next step towards an efficient broadband sonar should be clear, i.e. one applies an intelligent strategy to the frequency-azimuth surface such that redundant information is eliminated without removing important features.

2.2. STRATEGY TO REMOVE REDUNDANT INFORMATION

A series of fairly sophisticated techniques and algorithms may be thought out to clean up the frequency-azimuth surface of Fig. 1. For this report an ad hoc approach has been selected, to allow the derivation of the general principles without complicated justifications.

The ad hoc approach consists of the following rule: From the whole frequency-azimuth surface only select data for further treatment when they are a local maximum in frequency space and a global maximum in beam space. This data-reduction criterion may apparently be criticised as too restrictive, but we will see later on that this is not the case.

To get qualitative control of the algorithm it is convenient to refer to the most important features within Fig. 1. First, we can identify the tow-ship at forward

endfire (i.e. near 0°). Second, at about 75° we have the bottom bounces of the tow-ship. Third, at about 110° we see at low frequencies, around 100 Hz, a strong indication of a sound source which later on will be referenced as the low-frequency source. Finally, at rear endfire (near 180°) we recognise a sound source with dominant high-frequency components. This sound-source will be referenced later as the high-frequency source.

Next a series of figures will demonstrate the impact of this data reduction concept on the original frequency-azimuth surface.

Figures 2, 3 and 4 show a spectral cut of the frequency-azimuth surface at different stages of the procedure. All spectra correspond to a steering angle of 20° . Only frequencies up to the design frequency of the array (about 382 Hz) have been considered.

Figure 2 shows the complete spectrum; Fig. 3 shows the global maxima for this beam; and Fig. 4 shows the remaining local (frequency) and global (beam) maxima. Indeed, Fig. 4 shows that for this particular beam not very much data survived the data reduction process. Clearly, different beams will show different behaviours (i.e. they have more maxima or less maxima).

Figures 5, 6 and 7 show a bearing cut of the frequency-azimuth surface at different stages of the procedure. The selected frequency is 380 Hz and therefore very close to the design-frequency of the array.

Again, Fig. 5 shows the complete beam pattern; Fig. 6 shows the beam pattern when all but the local maxima of the spectra are removed; and Fig. 7 shows the global maximum of the power-bearing plot. By definition of the algorithm, at the most one peak will remain per spectral bin.

All in all, Figs. 2 to 7 show that significant data reduction is accomplished by the ad hoc principle selected for this report.

Because the data reduction is performed in two directions, and because the effects are rather dramatic, it may be of interest to have a global view of the frequency-azimuth surface during the data reduction.

The next two figures (Figs. 8 and 9) give the complete frequency-azimuth surface at the different steps of the data reduction. Fig. 8 is the frequency-azimuth surface in which only the local maxima of the spectra are plotted and Fig. 9 is the final frequency-azimuth surface with local maxima for the spectra and global maxima for the beams. Because relatively few data points survived the procedure it was necessary to magnify the individual points.

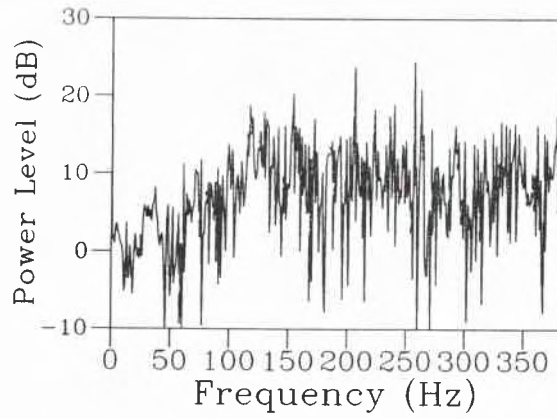


Fig. 2: Conventional spectrum.

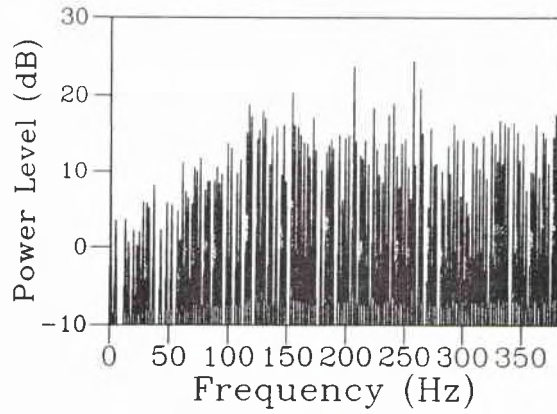


Fig. 3: Spectrum with local maxima only.

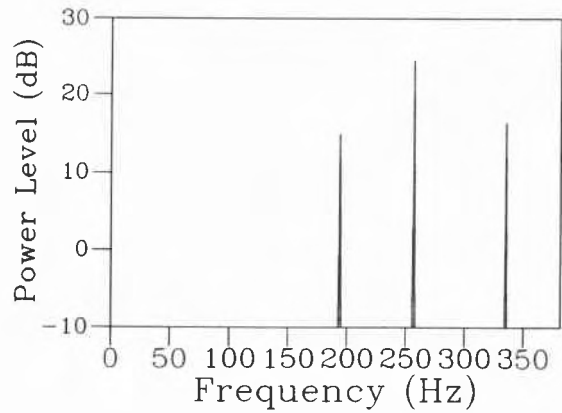


Fig. 4: Reduced spectrum.

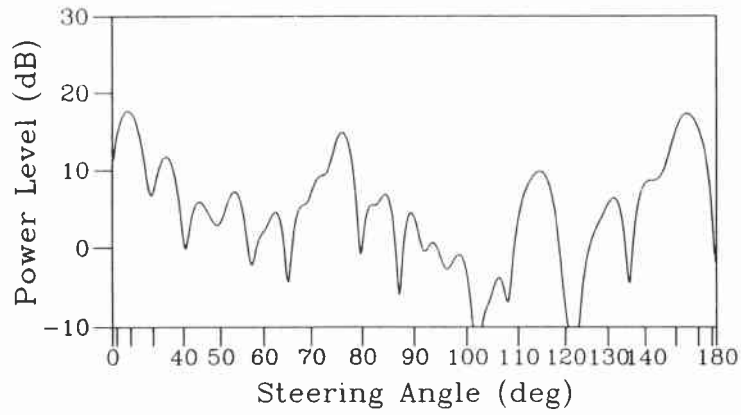


Fig. 5: Conventional beam pattern.

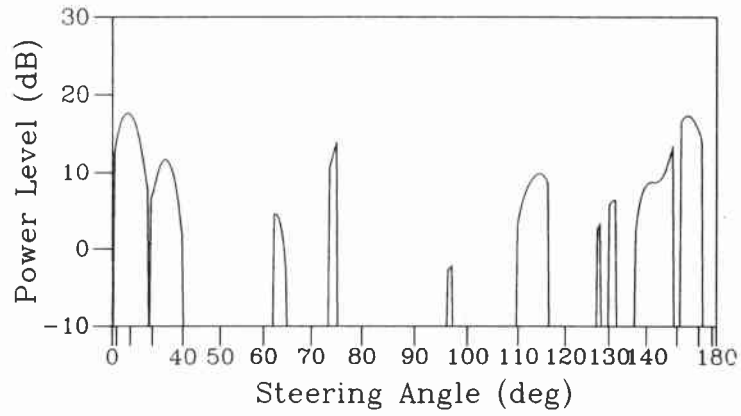


Fig. 6: Beam pattern with local maxima of spectrum.

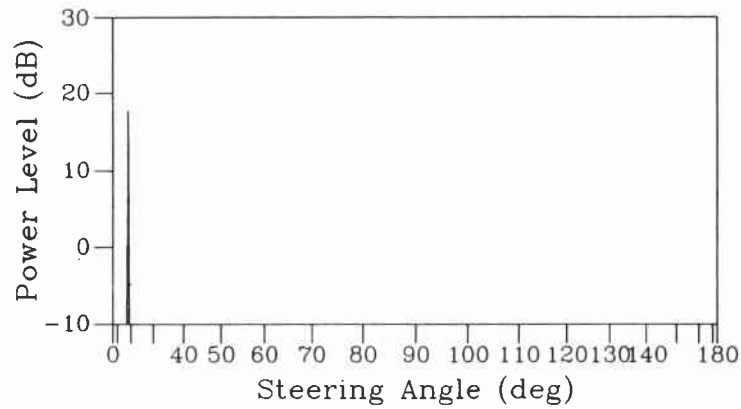


Fig. 7: Reduced beam pattern.

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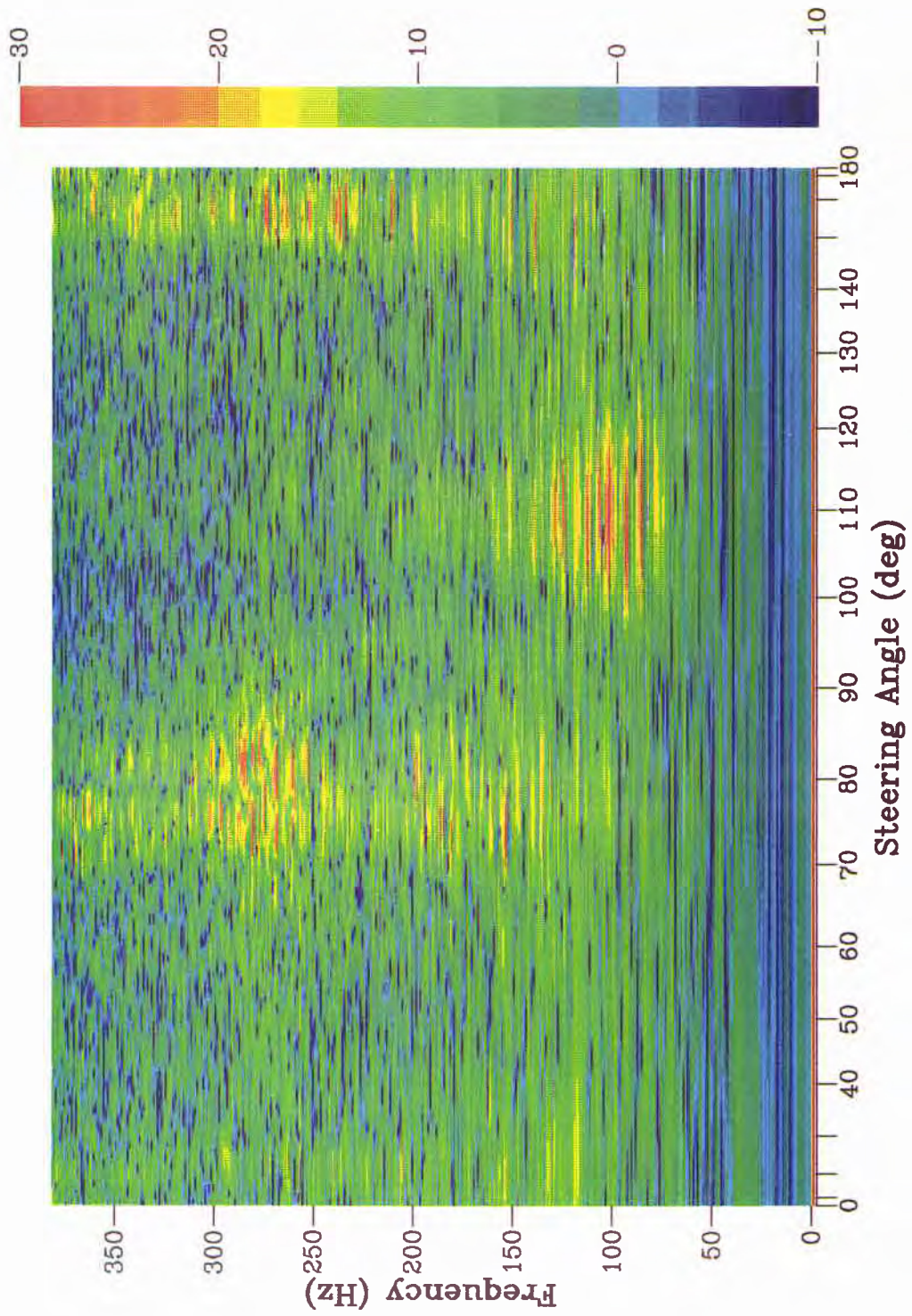


Fig. 8: Frequency-azimuth surface with local maxima of spectrum only.

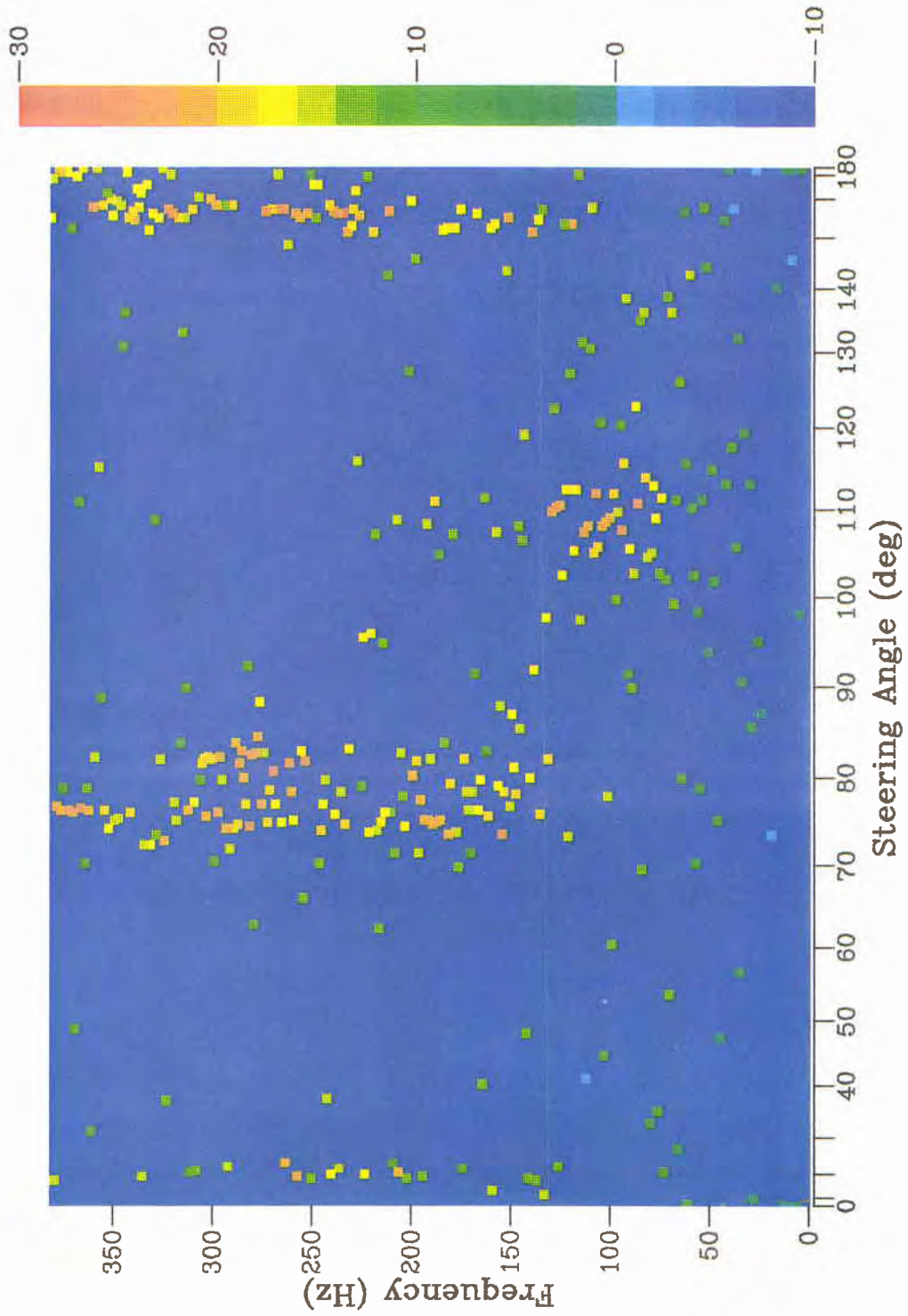


Fig. 9: Reduced frequency-azimuth surface.

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However, a complete assessment of the final frequency-azimuth plot shows that sufficient details are still present to identify the tow-ship, the bottom bounces, the low-frequency and the high-frequency sources as defined above.

3. Presentation of the resulting information

In this section two methods are described for presenting the information which remained after the data reduction procedures. In the first, emphasis is placed on a broadband beamformer; in the second, the possibility of obtaining multibeam time-frequency (LOFAR) plots is discussed.

3.1. BROADBAND BEAMFORMER

Let us assume that beamforming is the task that we intend to carry out on the basis of the hydrophone measurements. In this case the reduced frequency-azimuth surface enables us to construct an interesting broadband beamformer simply by integration of all spectral information remaining within a certain beam. Fig. 10 shows a typical broadband power-bearing plot obtained by this technique.

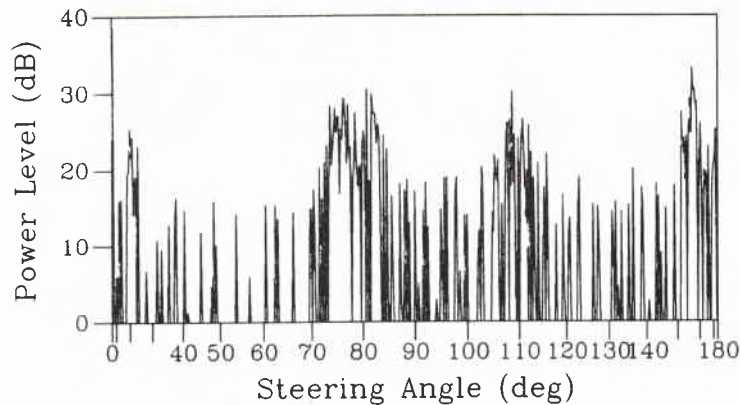


Fig. 10: Broadband beamformer.

Within this figure one can easily recognise the tow-ship at 20° , the bottom-bounces at 75° , the low-frequency source at 110° , and the high-frequency source at 160° . Due to the ad hoc algorithm the overall impression of the power-bearing plot is rather noisy, but it is worthwhile to recall that for every spike there exists a frequency bin where this spike is the global maximum, i.e. the most dominant direction for a narrowband beamformer. However, because the spectral integration also includes very low frequencies, interaction between different sound sources cannot be excluded. This interaction varies in a statistical sense and presents itself as noise.

It seems clear that a single-shot power-bearing plot may not be sufficient for assessing the performance of the broadband beamformer, and therefore a time-bearing plot has been built up to reveal the powerful features of the broadband beamformer (Fig. 11). The following points may be noted:

- One can first of all observe certain tracks, which are distinct like those of the tow-ship at 20° , the bottom bounces at 75° , the low-frequency target at 110° , and the high-frequency target at 160° .
- Secondly one can observe some weak tracks of particular interest. For example, there is a thin track at 62° , which indicates the presence of at least one strong spectral line in this direction. This shows that even generally weak sound sources have a chance of surviving the data reduction procedure as long they have at least one spectral line which peaks up from time to time.
- Thirdly, there are some rather broad tracks which are evidence of wide-angle phenomena (e.g. bottom and surface reflections from the tow ship around 75°).
- Fourthly, there is a wide-angle noise structure which is mostly due to unresolved ambient noise and interactions of the sound sources at low frequencies.
- Fifthly, it is possible to resolve closely spaced sources so that the broadband beamformer shows high-resolution capabilities.
- Last but not least no sidelobes can be observed, which is to be expected from how the algorithm has been constructed.

The most important feature is that due to lack of sidelobes and due to the broadband characteristics of real sound sources this broadband beamformer makes it possible to recognize not only closely-spaced sources but also relatively weak sources. Clearly, it needs an intelligent post-processor, like the human eye, to take advantage of the broadband beamformer.

3.2. MULTIBEAM LOFAR PLOT

Let us now assume that spectral information as a function of time is the item of interest. What one usually does is produce a time-frequency (LOFAR) plot like the one presented in Fig. 12. In this figure the time-scale is plotted on the ordinate, frequency is plotted along the abscissa, and the spectral intensity is colour coded according to a dB scale. In this report, the same reduced information set described in the previous sections is again used (for the same purpose). In Fig. 13 the reduced time-frequency plot is given. Obviously, the overall impression is that Fig. 13 is much more empty than Fig. 12, but some of the important features of Fig. 12 may also be recognized in Fig. 13. These common features are clearly due to the overall statistical behaviour of all of the sound sources which are present in the hydrophone measurements. This means that if one takes time into account there is enough

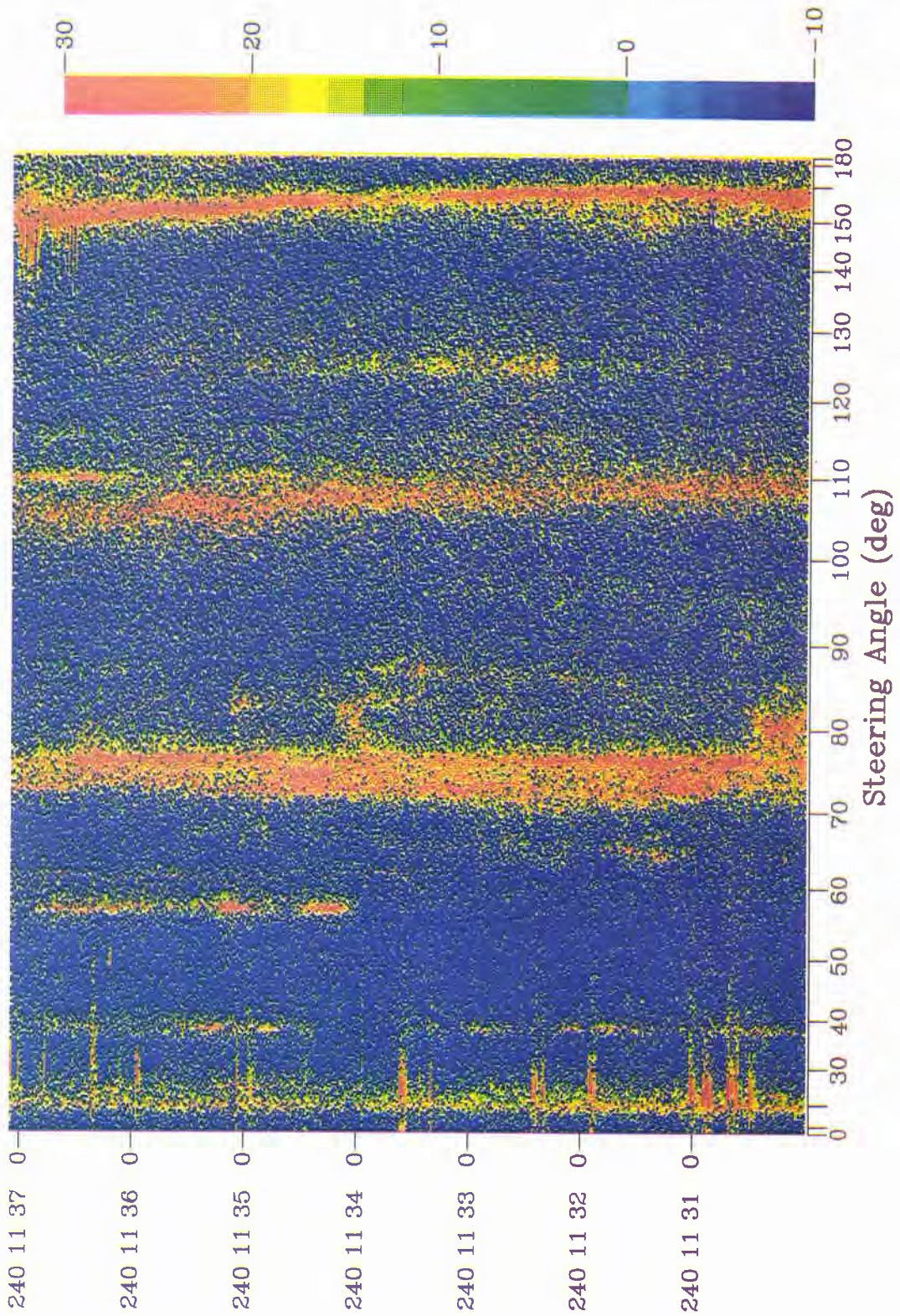


Fig. 11: Broadband time-bearing plot.

information remaining after the data reduction process to highlight important lines and other major features.

While Fig. 12 is a compact image, Fig. 13 is transparent, i.e. it is possible to combine the time-frequency plots of different beams without the overlapping of spectral information. This is due to the fact that for every frequency bin at most one beam direction survived the data reduction procedure.

Displaying more than one time-frequency display at the same time cannot be done simply. A possible method is to give the different beams different colours so that they can be discriminated by inspection (e.g. red corresponds to forward end-fire of the array, green to broadside and blue to rear end-fire and so on). By using colour for coding the different beams, colour is then unavailable for coding of the peak-level intensity, but this turns out to be not a serious problem, as grey-scale coding of the peak-level intensities has been found to be satisfactory.

Such a multibeam LOFAR plot would let all beams, or a part of them, be shown together without losing further information, and would allow switching between the beams by simply manipulating the colour look-up table of the monitoring device (i.e. without further computing power).

Obviously the maximum number of beams one can display in such a way depends on the number of different colours one can put into the look-up table. However, there is the question in how far it is useful to have a lot of colours with only a slight difference between them. Some empirical trade-off is therefore necessary.

At SACLANTCEN an on-line monitoring display of this type has been developed by the Signal Processing Group and successfully tested during the sea-trial SPG/1986. The characteristic features of this '4-dimensional' display are 33 beams, 512 frequencies and 30 power levels every second (over 6 min).

A useful application of this display is the simultaneous monitoring of the different angles of arrival of the sound signal while scanning continuously through all the beams in order to avoid overlooking other interesting features. When testing this technique it was possible by simple manipulation of the display colours and by visual correlation of the spectra of different beams to identify different multipaths of the sound source.

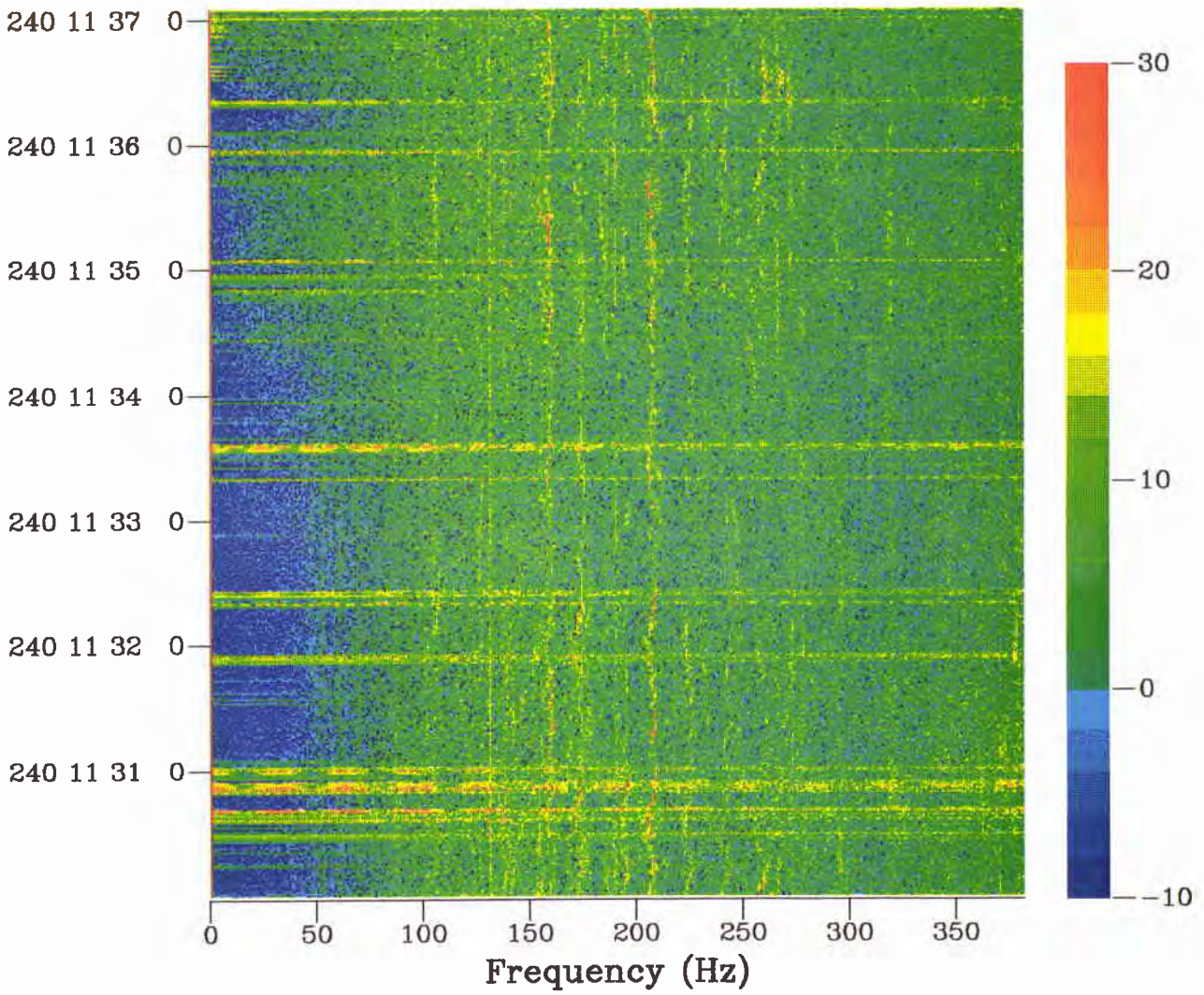


Fig. 12: Conventional LOFAR plot.

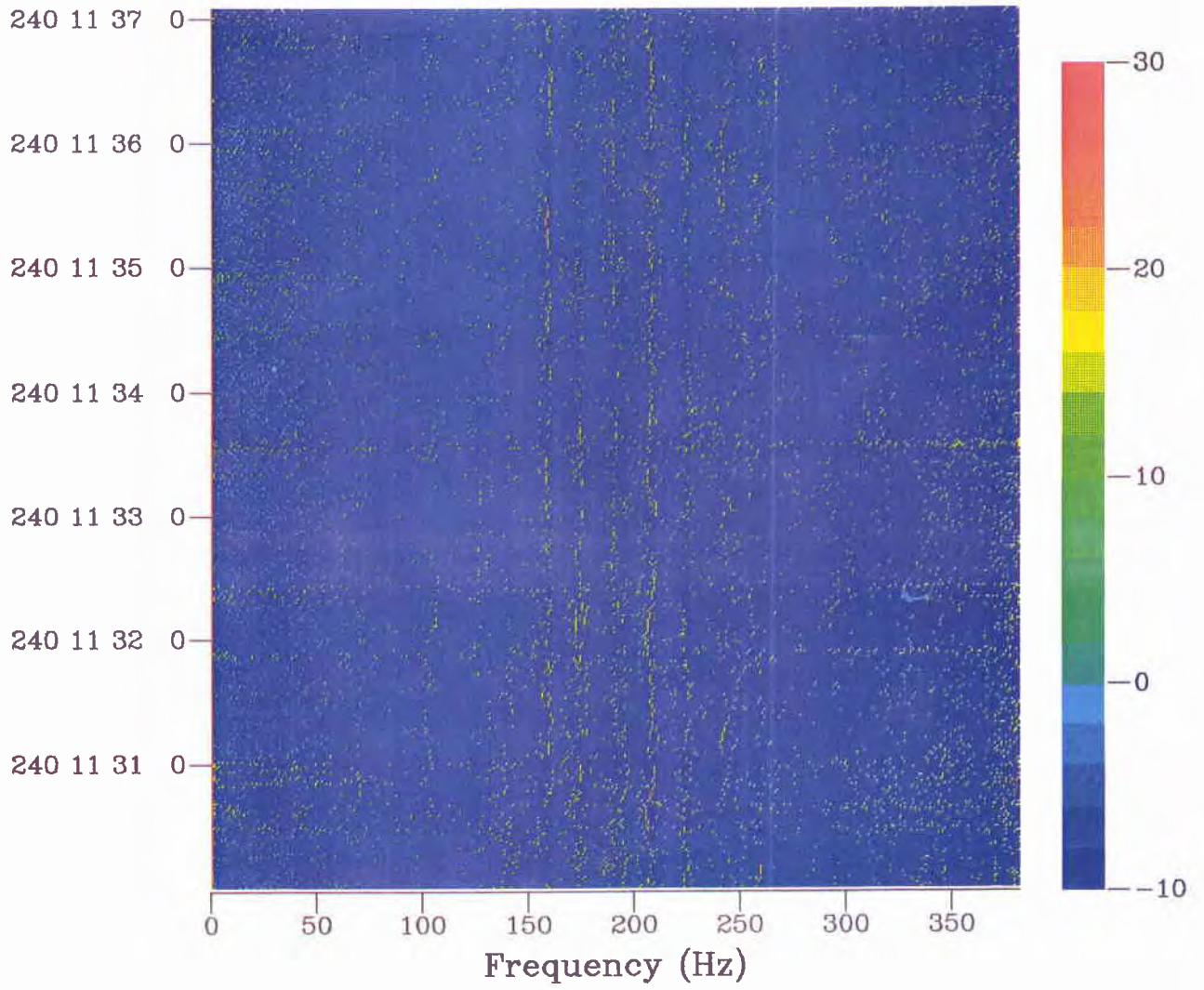


Fig. 13: Reduced LOFAR plot.

4. Comparison of the broadband beamformer with narrowband high-resolution beamforming

In this section an attempt is made to compare the broadband beamformer with a narrowband high-resolution beamformer. The comparison should give an impression of whether it may be useful and desirable to replace the conventional high-resolution concept with the broadband concept as discussed in this report.

In previous reports [3,4] different narrowband high-resolution methods have been discussed, and it has been shown that one of the better performing high-resolution beamformers is the so-called Wagstaf-Berrou (WB) method. Therefore this technique has been selected for direct comparison with the broadband beamformer on the same set of data.

The details of this comparison are as follows: The broadband beamformer is used as described in this report. The narrowband WB beamformer uses spectral data of 380 Hz, which is a frequency near the design frequency of the array, to achieve optimum resolution. The algorithm is identical to the one described in [4] and will not be discussed further: here, it is only of importance to recall that the WB method is a post-processor. The technique has as input the conventional beamformer output and produces a high-resolution power-level estimate of the sound-source distribution by deconvolving the conventional power-level estimate and the single-source beam pattern. The conventional power-level estimate is made via a time average of 40 samples and a spatial forward-backward average.

Figure 14 shows the time-bearing plot of the WB narrowband beamformer. This figure should be compared with that for broadband beamformer as presented in Fig. 11. The superiority of the broadband beamformer is readily recognized. The consistency and clearness of the different tracks is obvious. Clearly, the excellent performance of the human eye plays an important role in the analysis of 2-dimensional colour-coded plots.

The qualitative superiority of the broadband beamformer is no surprise, and in fact one may consider this comparison as unfair. On the one hand, the performance of the WB narrowband high-resolution method is based on the spectral data of a single frequency bin, and therefore a lot of spectral information is missing. On the other hand, the broadband beamformer is based on the complete spectral information and has therefore much more statistical support. This holds true even after the enormous data reduction undertaken on the frequency-azimuth surface.

The unsatisfactory situation in which 'conventional' approaches to high-resolution beamforming yield only narrowband techniques, and therefore ignore most of the

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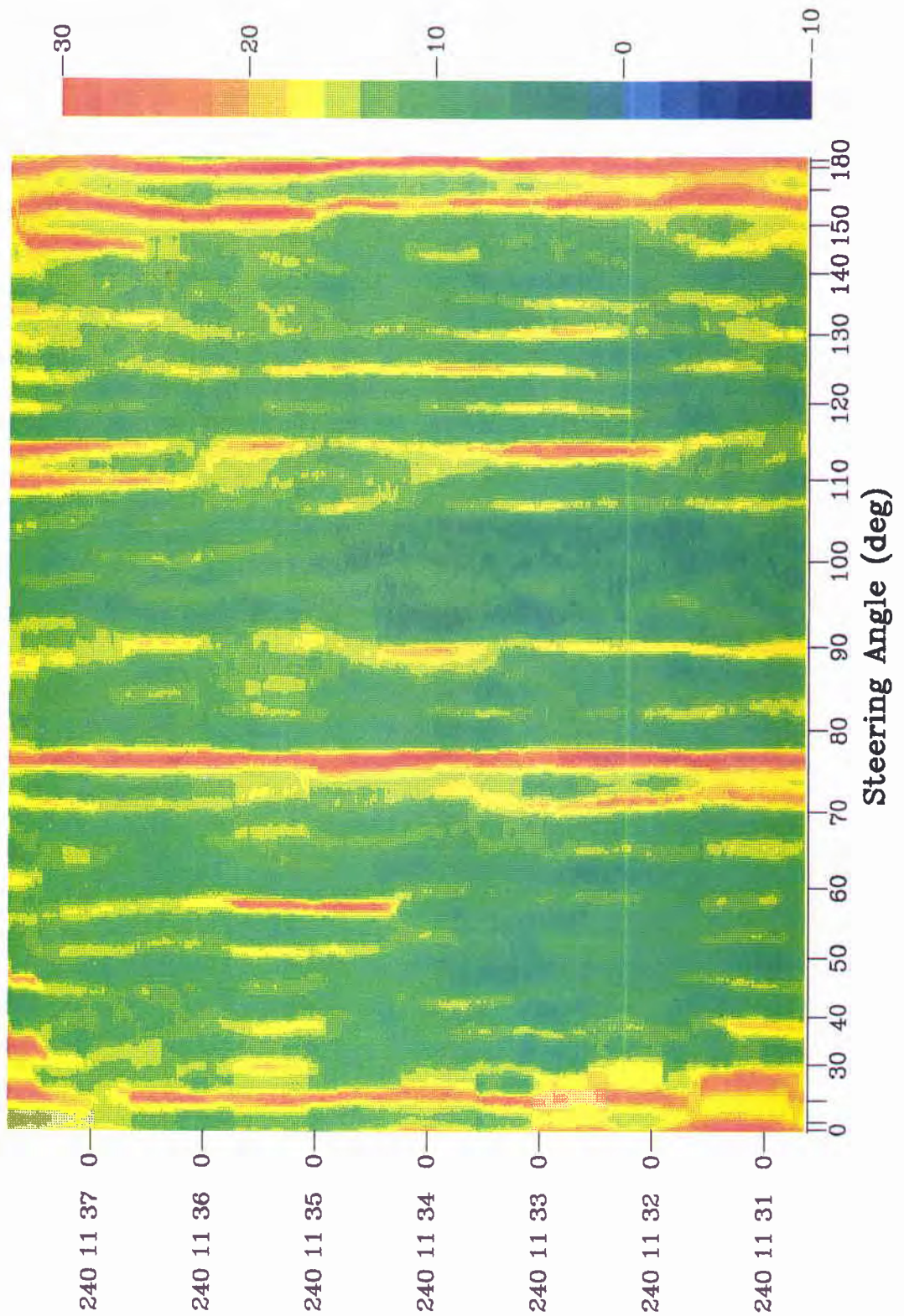


Fig. 14: WB narrowband high-resolution beamformer.

spectral information, convinced the author to try the alternative approach described in this report which exploits the statistics of the whole frequency-azimuth surface.

5. Possible modifications

In this section some modifications to the alternative approach are discussed. In particular, it is assumed that the ad hoc concept used to demonstrate the feasibility of the approach is not satisfactory for all applications of interest.

To start with, it is worthwhile to recall that the alternative approach consists of two steps. First: data reduction of the frequency-azimuth surface; and second: appropriate presentation of the resulting information.

With regard to the data reduction, one can easily recognise that this cannot be done without defining which spectral and spatial information is of importance. This is equivalent to saying that the data reduction corresponds to a 'classification filter' which suppresses all information that is unimportant for the particular (classification) problem. It is clear that the ad hoc rule selected for this report is a very low-level classification concept and there are no objections to more sophisticated classification filters. Further, one can visualize a set of different classification filters being applied simultaneously to the same frequency-azimuth surface to produce useful basic materials for further decisions.

This leads us to the discussion of how the resulting information should be presented. For this report, only the display aspect of the broadband beamformer will be considered. Clearly, the considerations for the multibeam LOFAR plot have to be similar.

With regard to the broadband beamformer, it is the purpose of the beamformer which defines the appropriate presentation of information. It is not really necessary to present the result in the form of the integrated spectral power as a function of steering angle as has been done in this report (for reasons of simplicity). For example, if the data reduction is performed with a classification-filter bank then it may be more appropriate to colour code the different classification hypotheses and in consequence produce direct indications of the presence of various sound sources of particular interest.

There are certainly many more ways of displaying the broadband beamformer output and one should beware of the assumption that the conventional power-bearing plot is in all cases the most efficient solution. This comment is particularly true when one deals with automatic classification concepts. However, with more research one should be able to get an optimal relationship between the purpose (i.e. the task of the beamformer) and the presentation of the beamformer output.

The broadband beamformer is a technique which tries to exploit the statistics of the different sound sources involved. The initial conventional frequency-azimuth surface is therefore based on instantaneous power estimates. This yields a rather noisy time-bearing plot, and to enhance the features of interest and to suppress noise one should consider a statistical treatment. Again, this can only be accomplished when the features of interest and the noise are defined previously. Independent of such a definition, the statistical treatment should not only include simple averaging (i.e. first-order statistics) but should also consider more complicated procedures such as hypothesis testing.

6. Summary

In summarising this report it should first be noted that the alternative approach can be described as a spectral-spatial 'classification filter' of the conventional frequency-azimuth surface.

Contrary to the conventional approach, where the information of the frequency-azimuth surface is simply averaged to get a power estimate, the alternative approach first applies a (nonlinear) 'classification filter' to the conventional frequency-azimuth surface before further treatment, such as averaging. And contrary to the narrow-band high-resolution methods which are based on the information of only a single frequency bin, the alternative approach combines all of the important spectral and spatial information (in a nonlinear way).

The major characteristics of the alternative approach is that it exploits the instantaneous statistics of the different sound sources and does not require time averaging. Nevertheless, statistical treatments after the use of the 'classification filter' may improve the already excellent performance.

The alternative approach may result in a broadband beamformer which has high-resolution capabilities, which is (by definition) sidelobe free, and which allows the tracking of relatively weak sources. The alternative approach may also result in multibeam LOFAR plots which allow the user to display more than one beam simultaneously without further loss of information.

Thus the alternative approach is not simply an additional method of signal processing, rather it is a totally different concept. It provides the user with the possibility of extracting only the information of interest from the measurements. Clearly, this means that the user has to have clear ideas about the information in which he is interested, but this being so the alternative approach translates into a signal processing method that is significantly more powerful than conventional methods.

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