

Autofocusing a synthetic aperture sonar using the temporal and spatial coherence of seafloor reverberation

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Abstract

An autofocusing algorithm for the compensation of translational motion errors of a sea floor imaging synthetic aperture side scan sonar is presented. The algorithm does not depend on the presence or absence of dominant scatterers in the field of view and is based on the displaced phase center antenna concept. The theoretical performances are studied and the algorithm is shown to perform satisfactorily on simulated data. Preliminary results obtained for a sonar moving on an underwater rail are presented. Sea trials are planned to validate an extension of the algorithm, termed " multibeam interferometry ", to arbitrary motion errors.

1. Introduction

The ideal synthetic aperture is perfectly linear, and the time delays required to form a beam in a given direction can be computed a priori. Synthetic aperture processing then reduces to a straightforward extension of conventional beamforming to multiple pings. In reality, there are deviations of the platform from the specified track, which distort the synthetic aperture. Focusing the synthetic aperture, despite these distortions, is a major difficulty which has up to now prevented operational deployment of such systems in the ocean.

Autofocusing is an adaptive array processing technique which aims at using the sonar signals to focus the distorted array. Similar techniques are been studied for the same purpose in real and synthetic aperture radar [1,2], and for correcting wavefront distortions in radio-astronomy and optics [3]. If proved feasible in sonar, it is obviously a very interesting and cost-effective technique.

It is highly desirable that autofocusing be performed without imposing any condition on the distribution of power in the source field. This independence is seldom achieved by the existing algorithms. Those used in radar often assume the presence of point scatterers in the field of view, which play the part of beacons. They are not suited to sea floor imaging sonar where reverberation is dominant. Others [4] exploit instead the spatial coherence properties of statistically homogeneous reverberation. These suffer then in the presence of features of any kind on the sea floor (highlights, shadows...). This paper discusses a class of algorithms, suited for side scan sea floor imaging with a linear physical array, which achieve the required independence by appropriate sonar design.

The paper is organized as follows. In part 2 the problem to be solved is posed. In part 3, the waveform invariance principle, which forms the basis of correlation navigation sonar, is introduced. In part 4, this principle is used to focus a synthetic array in the presence of arbitrary translational motion errors, using improved correlation navigation sonar techniques to extend previous work by Sheriff [5]. In part 5, results of simulations and preliminary experiments obtained for a sonar moving on an underwater rail are presented.

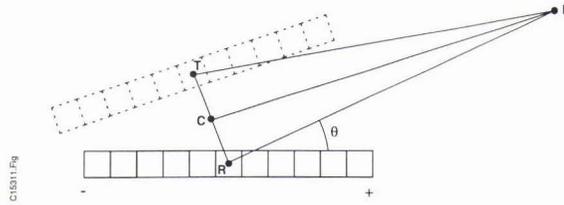


Figure 1 : Array positions at transmission and reception of echo from F

2. Problem description

Focusing a linear array at a point F of the sea floor requires knowledge of the round-trip travel times to the phase center of each hydrophone of the array. For the physical array, assuming far field conditions (or suitable focusing), the travel time to the hydrophone located at abscissa x along the array can be written as $\tau - xu$, where τ is the travel time to the phase center of the array located at $x=0$, and u is proportional to $\cos\theta$, where θ is the bearing (see figure 1). Point F is therefore determined by the two sonar coordinates u and τ in the physical image formed at each ping. Due to the sonar displacement, these coordinates change from ping to ping, and the problem is that of tracking the displacements of F in a sequence of consecutive images with the precision required to coherently register the corresponding physical pixels. For any given pair of adjacent pings 1 and 2, the sonar coordinates of F at ping 2 can be expressed as :

$$u + \Delta u (u, \tau), \tau + \Delta \tau (u, \tau) \tag{1}$$

where u and τ are the sonar coordinates at ping 1. The displacements Δu and $\Delta \tau$ are the necessary and sufficient information required to focus the synthetic array since, by iterating (1), an arbitrary number of pings can be registered.

It is important to note that the corrections to the coordinate displacements derived from ideal-track assumptions will not be the same, in general, for points at different coordinates in the sonar image. Indeed the corrections for F depend on the projection of the motion errors in the radial direction of F, which depends also on the local bottom topography. For example, sway (horizontal across-track displacement) leads to a change in travel time which depends also on the grazing angle at F. Furthermore the shape of the distorted array changes with time and is therefore not the same at the arrival times of echoes at short range or far range. Nevertheless, for the purpose of the estimation, these corrections will be assumed constant or slowly varying in portions of the sonar image, termed "isoplanatic regions". The dimensions of these regions, ideally as small as possible, determine the resolutions in u and τ of the estimation. This concept of isoplanatism comes from astronomy, where it is known that the phase shifts required to correct wavefront distortions are anisotropic, ie, depend on the angle of arrival of the wave. For example, a guide star (beacon) can be used to measure the distortions which affect the source of interest only provided it is sufficiently close for the light rays coming from the guide star to undergo the same propagation disturbances. This condition defines the isoplanatic angle.

In what follows, we consider only the simpler case of purely translational motion errors. The problem then reduces to the estimation of $\Delta \tau (u, \tau)$. The medium is also assumed ideal.

3. Waveform invariance

The use of the correlation properties of signals returned by a diffuse scattering medium, like the sea floor, to measure displacements between two successive transmissions forms the basis of existing navigation sonars termed correlation logs [6]. The main features of such logs may be summarized as follows :

After transmission at a specific location T, and backscatter by the sea floor, the echo received at a specific receiving point R, at a given delay τ after transmission, can be viewed as a realization of a given random variable. The echo results from the interference between an arbitrarily large number of scatterers in the sonar resolution cell. In far field conditions, transmission at T_1 and reception at R_1 after a delay τ is equivalent to transmission and reception from a single spatial location $C_1=(T_1+R_1)/2$, known as the sonar phase center (see figure 1). If the same waveform is transmitted twice from the same phase center, and if the propagation medium and the scatterer geometry has not changed between the transmissions, the same random realization will be received (except for noise) for the same propagation delay, irrespective of the distribution of the scatterers in the sonar resolution cell. This is known as the "waveform invariance" principle.

In the case of interest where transmitter and receiver are on board a moving platform, the second transmission and reception occur at displaced spatial locations T_2 and R_2 . As a result the second phase center C_2 is displaced with respect to C_1 by a vector quantity $\Delta C=C_1C_2$. Then first and second echoes received at delay τ are no longer identical. Due to the displacement, each scatterer undergoes a change in round-trip travel time $\Delta\tau$ determined by the projection of ΔC onto the radial direction to the scatterer. If these changes are identical for all scatterers in a sonar resolution cell, their interference is not affected by the displacement and “waveform invariance” is restored for first and second echoes received at τ and $\tau+\Delta\tau$. If, however, these changes vary, as it will be if the radial direction varies too much within the sonar resolution cell, these first and second echoes will partially decorrelate. Additive noise in the sea or in the receiver will also contribute to this decorrelation.

We will refer to this effect as “baseline decorrelation”, by analogy to a similar situation which occurs in interferometric bathymetry [7]. One seeks there to estimate the depression angle of the rays arriving from the sea floor, using phase comparison between the echoes received by two displaced transducers. These form an interferometer whose angular resolution is given by the receiver separation (or baseline) in wavelengths. In the present application, the baseline is synthetic rather than real but, apart from issues relative to temporal coherence, this difference is unimportant. Baseline decorrelation occurs when the spread in bearing (relative to the baseline) within the sonar resolution cell is no longer small compared to the angular resolution of the interferometer, which can then resolve different scatterers F_1 and F_2 in the resolution cell. An example of such a situation is pictured on figure 2, for a vertical displacement of amplitude P and a non planar sea floor.

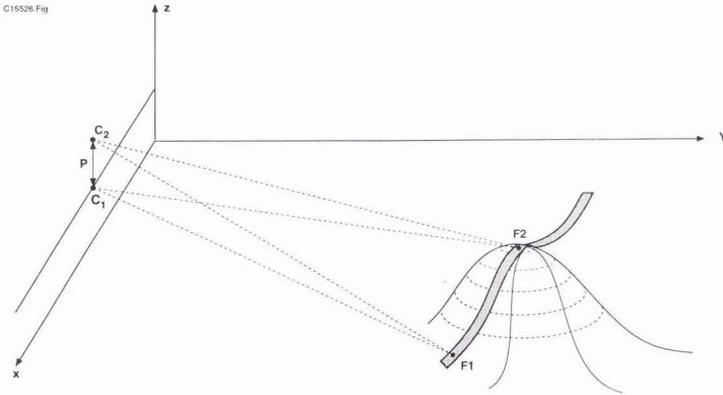


Figure 2 : Influence of bottom topography on baseline decorrelation. Are shown an interferometric baseline C_1C_2 , and two points F_1 and F_2 in a sonar resolution cell (shaded).

The most important decorrelation occurs when the displacement is colinear to the array. In the case of statistically homogeneous reverberation, and for an along-track displacement of D , the resolution of the interferometer is $\lambda/2D$ (where the factor two is because the baseline is synthetic) and the spread in bearing is λ/L , where L is the length of the physical array, since the baseline is colinear to the array. It can be then shown that the field correlation is $1-(\lambda/L)/(\lambda/2D)=1-2D/L$. Independence of two looks of the same scene (which is the effect sought for in incoherent synthetic aperture) is achieved for $D=L/2$. Even for $D<L/2$, which appears as a basic condition for autofocusing on reverberation, the speckle in the pixels which correspond to F remains weakly correlated. This makes the estimation of (1) from direct cross-correlation of the physical images difficult.

A correlation log attempts to restore waveform invariance despite platform motion by displacing the receiver between the first and second receptions. Such a displacement can be achieved very simply by using at least two identical receivers R and R' . Use of R' instead of R at the second reception displaces the second phase center from $C_2=(T_2+R_2)/2$ to $C'_2=(T_2+R'_2)/2$. The condition to restore waveform invariance is $C'_2=C_1$, which occurs when $R_2R'_2=-2C_1C_2$ as in figure 3.

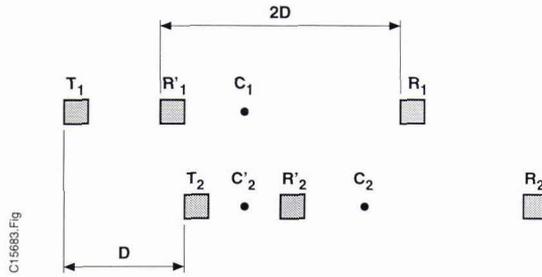


Figure 3 : Achieving waveform invariance by displacing the phase center

At ping 1, (2) transmission occurs at T₁ (T₂) and reception at R₁. (R₂). Motion between pings is D.

In practice, one uses an array of hydrophones and computes the cross-correlation at all the possible discrete values of the hydrophone separation vector. One then uses appropriate interpolation to estimate the best separation vector, ie, the one at which the cross-correlation is maximum. This vector provides an estimate of the displacement projected along the array, whereas the correlation delay provides an estimate of the displacement in the look direction. It is desirable to have as many hydrophone pairs with distinct separation vectors as possible in the array and correlation logs often use planar rather than linear arrays. In many cases of application with a linear array, it is not possible to achieve strict waveform invariance. Then the correlation log limits baseline decorrelation as much as possible by shortening the baseline, so as to coarsen the resolution of the interferometer. It will also orient the baseline in space so as to minimize the angular spread in bearing (relatively to the baseline) within the sonar resolution cell.

It must be cautioned that, although correlation logs have been around for a long time now, few systems exist (compared to the number of Doppler logs). With few exceptions, the theory has focused on the measurements of translations alone, ignoring possible errors introduced by rotations or the possibility of measuring both translations and rotations by suitable extensions.

4. Application to autofocusing

Sheriff proposed to use the physical linear array as a simplified correlation log to measure translational motion errors. His algorithm can be described as follows :

Choose a hydrophone pair of the physical array with vector separation 2D, where D is the ping-to-ping displacement derived from ideal-track assumptions, to play the part of R and R' of part III (the existence of such a pair requires D<L/2, where L the length of the array). Measure next the phase shift between the echoes received by R at ping 1 and R' at ping 2 in the same range bin, ie, at the same delay τ after first and second transmissions. Finally, apply the opposite phase shift, range bin by range bin, to all the hydrophones of ping 2 and then register ping 2 with ping 1 using ideal track assumptions.

Sheriff recognized that further (unspecified) processing may be necessary to correct possible residual phase errors. Nevertheless the method is reported to have performed successfully in tank experiments with rods used at point targets. However it does make some simplifications with respect to existing correlation log techniques. First correlation is reduced to phase comparisons on the basis of a single pair of measurements. Next the hydrophone separation vector is fixed a priori. Finally it is also seen that the phase shift corrections are assumed isotropic (not to depend on u). These assumptions limit rather severely the precision and the angular resolution of the autofocusing, as shown below.

4.1 Precision of the estimation

It is well-known in bathymetry that, due to the baseline decorrelation, the estimation of interferometric phase shifts on the basis a single pair of measurements is noisy. This measurement is a random variable which is by no means constrained to remain some kind of average of the phase shifts of the unresolved scatterers within the resolution cell. This is true for the ensemble average but, for individual realizations, large deviations may occur, in particular in the range bins where the reverberation fades. This effect is known in tracking sonar as the "glint" of an extended target. Maximal glint occurs when the target highlights interfere destructively. Glint is reduced by averaging over K range bins, after which the standard deviation of the phase estimate is given by :

$$\frac{1}{\sqrt{K}} \sqrt{\frac{1-\mu^2}{\mu^2}} \tag{3}$$

where μ is the field correlation coefficient. This formula is established by Goodman in [8].

Furthermore the estimation of time delays, rather than only phase shifts, is necessary when $\Delta\tau$ is no longer small compared with $1/B$, where B is the sonar bandwidth. This time delay estimation can be carried out using standard interferometric techniques, which may be summarized briefly as follows. One first estimates the correlation phase at the position of the maximum of the correlation envelope. This provides an ambiguous estimation of the time delay because phase measurements are modulo 2π . Amongst all the ambiguous time delays, which correspond to time delays which differ from the true time delay by an integer number of carrier periods, the one which is closest to the maximum of the correlation envelope is chosen.

It must be emphasized that precision is an important issue since the price to pay for processing only adjacent pings, as in the class of algorithms studied here, is a build up of errors, analogous to a random walk. The precision required on the ping-to-ping correlation delay increases with the total number N of pings to be coherently registered. For a given value of μ , determined by the physics of the backscatter and the level of additive noise, the precision can be increased by increasing K . The required values of K to limit the loss in synthetic aperture array gain to 1dB is plotted on figure 4 as a function of μ for different values of N . This follows from (3) and a calculation similar to the one presented in [1].

It is also preferable to choose the hydrophone separation vector adaptively, as in a correlation log, rather than to base this choice on ideal-track assumptions. In particular along-track motion errors introduce time delay errors for all image points off boresight. It is then elementary to show that, on the time window for which the correlation is performed, $\Delta\tau$ is given by :

$$\Delta\tau = \alpha u + \beta \quad (4)$$

where α is the best separation vector and β the correlation delay.

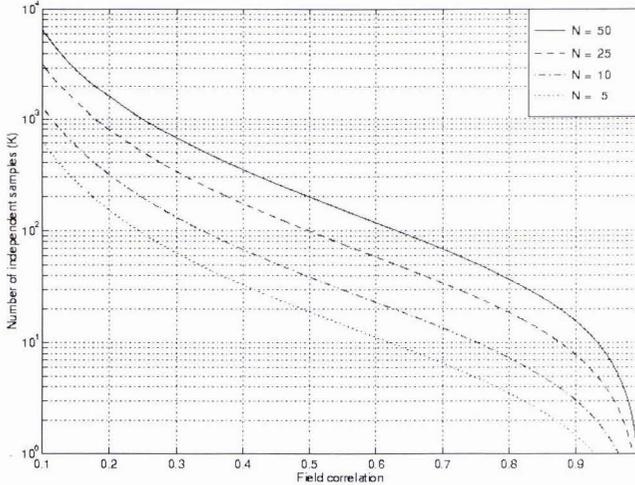


Figure 4

4.2 Resolution of the estimation

The length of the time window upon which the correlation is performed determines the temporal resolution of the estimation of (1). The maximal value of K is determined by the condition that the variations with τ of $\Delta\tau$ remain a small fraction of the carrier period (isoplanatic condition). For instance, $K=100$ allows coherent registration of 25 pings for $\mu > 0.5$. With a 20kHz sonar bandwidth, this corresponds to a time window of 5ms. Platform dynamics on this time scale can be neglected but it is necessary to assume that variations of the line of sight over slant range intervals of 3m to 4m are small enough. This condition is easier to satisfy at small grazing angles.

It is seen from (4) that the time delay correction now varies linearly with u in the field of view. Thus both the precision, and to some extent the angular resolution, of the estimation have been improved. Further increase in precision and resolution is possible by using $M \geq 2$ hydrophone pairs with redundant separation vectors. M can be increased by reducing the ping-to-ping displacement D to a smaller fraction of $L/2$ (see figure 5). The redundancy can be used to increase the temporal and angular resolutions. Since spatial redundancy increases by M the number of points in the correlation, K can be reduced by M which leads, if required, to an improvement in temporal resolution by a factor of M . The improvement in the angular resolution, which is more critical, can be obtained by processing the M hydrophone pairs as a displaced sub-array. One can take benefit of the angular resolution of the sub-array in the autofocusing. In the example of the 400kHz sonar considered above, distinct piece-wise linear corrections (4) could be estimated in subsectors of 0.1° , by choosing $D=L/4$, assuming $L=3m$.

The isoplanatic angle is then reduced from 5° to 0.1° which should significantly relax constraints, in particular on the bottom topography.

The use of $M \geq 2$ redundant hydrophone pairs is not new. It was proposed by Raven [9] for the purpose of estimating the phase corrections in the presence of both angular and translational motion errors. He used the M pairs to estimate separately M phase shifts by the algorithm discussed by Sheriff. He then adjusted a linear law to these M phase shifts. The autofocusing consisted in applying the opposite phase shift law, range bin by range bin, to all the hydrophones of ping 2 prior to registration with ping 1 using ideal track assumptions. This extension is interesting, because it shows that autofocusing in the presence of arbitrary motion errors is possible, in principle. However Raven's method suffers from the same limitations in precision and angular resolution as Sheriff's.

5. Results

Simulated synthetic aperture images (3mx5m) autofocused using both Sheriff's method and the method presented here are shown on figure 6. The scene consists of a spherical target on a flat uniformly reverberating sea floor. The reverberation is generated using a standard point scatterer model. The target is a sphere of 1m diameter at 150m range for a sonar at 30m above the sea floor. The central frequency is 400Khz with a bandwidth of $B=30\text{kHz}$. The physical array length is $L=1\text{m}$, and the ping-to-ping displacement $D=L/4$. The motion error was a bias in sway velocity of 3mm from ping to ping. The total number of integrated pings was 11. It is seen that Sheriff's autofocusing fails by far to achieve the required precision. The improvements proposed here solve the problem.

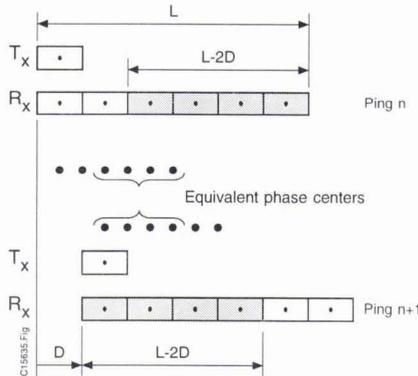


Figure 5 : Hydrophone pairs with redundant separation vectors

Images were formed (cf figure 7) for a sonar constrained to move on a rail which guarantees an ideal track. The physical array length is $L=3 \times 19.5\text{cm}$ and the ping-to-ping displacement is $D=L/3$. The sonar operates at 53kHz with a 15° tilt and the rail is at 6m80 above the sea floor. In this case the phase errors where not due to motion errors but to electronic jitter. This situation is, however, only partially representative of the one which will be encountered at sea. This is first because the time delay corrections due to jitter are isotropic (so that autofocusing does not require angular resolution) and second because the causes of baseline decorrelation in the case of jitter differ significantly from those in the case of motion errors. Nevertheless this example illustrates that the autofocusing algorithm is not limited by its principle to the compensation of motion errors alone. By analogy with astronomy, it can be anticipated that the compensation of medium induced wavefront distortions require an autofocusing algorithm which accounts for anisoplanatism. The method presented here should therefore be capable, in principle, to correct both array and wavefront distortions. However the effect of medium inhomogeneities on baseline decorrelation requires more attention.

6. Conclusion

An autofocusing algorithm for the compensation of translational motion errors has been presented. The algorithm is based on a local isoplanatic assumption, that is, the redundancy of the time delay corrections in small portions in range and bearing of the physical sonar image. The estimation makes use of correlation sonar techniques : the decorrelation of speckle in pixels of adjacent looks, termed "baseline decorrelation", is reduced by phase center displacement. Improvements which allow order of magnitude gains of precision and resolution on the previous work by Sheriff, such as the use of range averaging to combat "glint", or sub-array processing with multiple redundant hydrophone pairs, have been proposed. The theoretical performances of the algorithm have been studied, in particular the build up of errors due to the processing of only adjacent pings, and

promising results have been obtained on simulated data and on experimental data obtained for a sonar moving on a rail. An extension of the algorithm to arbitrary translational and angular motion errors, termed "multibeam interferometry", has been defined by Thomson Marconi Sonar. The extended algorithm, which exploits two-dimensional correlations of sonar images formed with a displaced sub-array, estimates both displacements in (1), with order of magnitude improvements in precision and resolution over the method proposed by Raven. GESMA and Thomson Marconi Sonar are planning sea trials in June using the PVDS (Propelled Variable Depth Sonar) of Thomson Marconi Sonar.

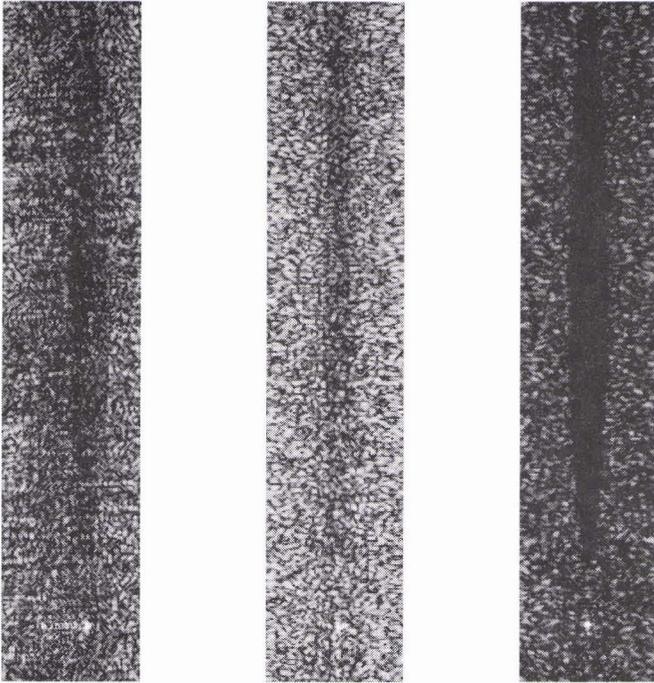


Figure 6 : Simulated images before autofocusing (left) and after autofocusing by Sheriff's method (middle) and the method presented here (right).

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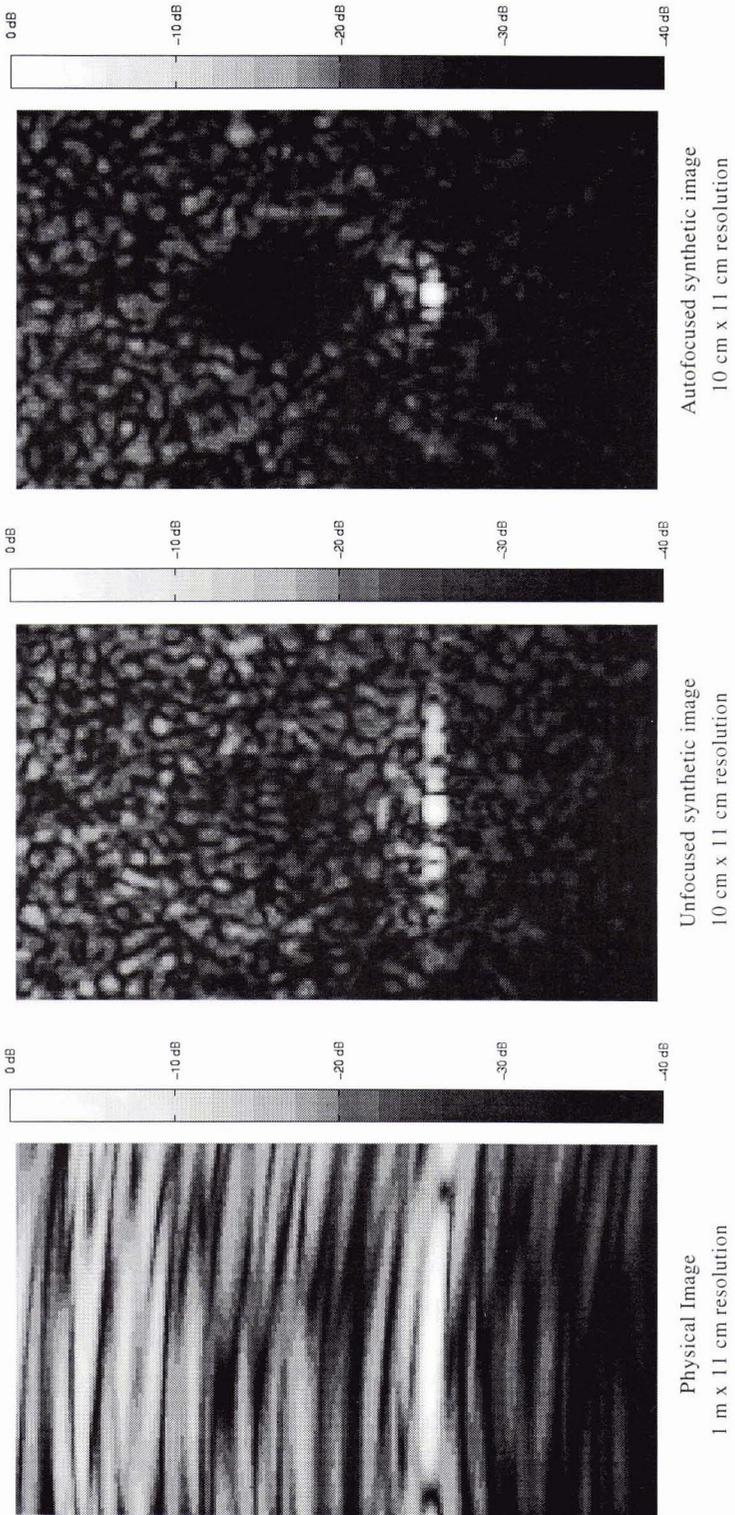


Figure 7 : Target sphere at 53 kHz. Image sizes 3 m x 6 m