CHAPTER 8
CONCLUSIONS

A number of ideas are new to this work. While they have served to answer a number of questions about diffraction tomography there remains much work to be done. This chapter, therefore, reviews the state of the art of diffraction tomography as presented by this work and indicates directions for future research.

Chapter 2 reviewed the wave equation and its integral solution. While this material is well known among people doing research in diffraction tomography and inverse scattering its presentation here emphasized the common mathematical problems in acoustic and electromagnetic scattering. For this reason all distances were expressed in wavelengths and the object function represented the (complex) refractive index variation of an inhomogeneity for either acoustic or electromagnetic waves. Researchers more concerned with experimental work will want to use the relationships presented in Chapter 2 to convert the results presented in the remainder of this work to more physical quantities.

Finally Chapter 2 also presented two approximations, the Born and the Rytov, which allow linearized versions of the wave equation to be written. These two first order perturbational approximations are important because they allow simple inversion algorithms to be derived. Since these approximations are so critical to first order diffraction tomography the mathematical limitations of each approximation are also discussed.

The Fourier Diffraction Theorem relates the scattered field measured on a line to the Fourier transform of the object and is presented in Chapter 3. This theorem is only true when either the Born or the Rytov approximation is valid but it has generated much excitement in the research community.

The Fourier Diffraction Theorem was derived by two different methods in this work. Both approaches to the Fourier Diffraction Theorem lead to the same relationship between the scattered field and the object's Fourier transform. The conventional approach is to decompose the Green's function, the field scattered by a point scatterer, into plane waves and simply substitute this result into the integral solution to the wave equation. A second, new approach, is to consider the Fourier Diffraction Theorem entirely in the Fourier domain. This method points toward a more natural computer implementation and was exploited in Chapter 6 for computing better approximations to the scattered field.

The remainder of Chapter 3 discussed experimental methods for collecting enough scattered data so that a unique estimate for the object can be formed. The potential methods described include using a plane wave to illuminate the object, synthesizing plane waves much like what is done in phase array antenna design and broadband (in time) incident fields.

Chapter 4 discussed two mathematical algorithms for inverting the scattered data to estimate the object's (complex) refractive index. Much like conventional (straight ray) tomography there are two approaches that can be used to invert the scattered data. These two algorithms, often described as interpolation in the space domain and frequency domain, were presented here and their algorithmic complexity was discussed.

In addition several signal processing concerns were examined in Chapter 4. By calculating the Mean Squared Error between the object and the reconstruction it was concluded that zero padding each projection is a good way to reduce the interpolation error in the frequency domain. On the other hand, using a Hamming window to shape the projection and reduce the effect of the finite aperture severely attenuates the high frequency information in the projection and increases the error.

The limitations of first order diffraction tomography were discussed in Chapter 5. Two types of errors limit the quality of the reconstruction: mathematical limitations caused by the approximations used to derive the Fourier Diffraction Theorem and experimental limitations caused by the ability to only collect a finite amount of data. The mathematical limitations are the most severe. In deriving the Born and the Rytov approximations it was necessary to assume that the scattered fields were small compared to incident fields. This is equivalent to saying that the object must be weakly scattering for the first order diffraction tomography algorithms to hold and if this condition isn't met then the reconstruction will have serious artifacts.

The limits of first order diffraction tomography are easily described in terms of the magnitudes of the scattered fields but a more meaningful measure is to study the range of objects where the approximations are valid. This was done in Chapter 5 by calculating the exact scattered fields from a large number of cylinders and then making an estimate of the object assuming that the first order diffraction tomography algorithms are valid. Thus it was concluded that the Born approximation is valid when the product of the diameter of the cylinder (in wavelengths) and the absolute value of the refractive index change is less than 0.5. On the other hand the size of the object is not as critical to the Rytov approximation. Instead the refractive index change is the limiting factor and reconstructions based on the Rytov approximation are good as long as the refractive index of the object is less than a few percent.

The experimental limitations, on the other hand, can always be minimized by collecting more data. Thus it is clear that interpolation error can always be reduced by increasing the number of projections or the number of samples per projection. Another, less obvious, limitation is the finite aperture of the projection. Unlike conventional (straight ray) tomography where the projection of a finite sized object has a finite length, the same is not true for scattered fields. With diffraction tomography the scattered field never goes to zero and the sampling interval for the projection must be carefully balanced to prevent aliasing but yet large enough to measure the high frequency information far from the center of the projection. An expression for this relationship was derived in Chapter 5 and several reconstructions were presented with different sampling intervals to confirm the optimum sampling interval.

The limitations of first order reconstruction algorithms were addressed in Chapters 6 and 7. The most severe limitation is caused by the first order perturbation models assumed in deriving the Fourier Diffraction Theorem. Thus Chapter 6 discussed several approaches to more accurately model the scattered fields. With one of these more accurate models it should then be possible to invert the relationship and derive a better reconstruction algorithm. A survey of several possible approaches to inverting the scattered data is presented in Chapter 7.

Since better reconstructions will be based on more accurate models of the field inside the object two approaches to more accurately model the scattered field were presented in Chapter 6. The most severe limitation of first order algorithms is the assumption that the field inside the object is approximately equal to the incident field. Thus when this condition is not valid the Born and the Rytov approximations are no longer valid.

The simplest technique is to assume that the perturbational model used to derive the Fourier Diffraction Theorem is approximately correct and simply include more of the higher order terms. The result is a series of terms much like a Taylor series. This is an iterative procedure and was applied to both the Born and the Rytov approximations.

An important measure of any series is a description of its region of convergence. In this case the region of convergence is a function of the entire object and the results presented in Chapter 6 were simplified by considering the convergence as a function of size and refractive index of simple objects. Thus the region of convergence can be described by two parameters and all objects outside this region (because they are larger or have a greater refractive index change) will cause the series to diverge.

The series described in Chapter 6 were calculated by sampling the object and the fields and then using an efficient algorithm based on Fourier transforms. In each case the scattered field was calculated by multiplying a function of the object by a field and then convolving this "scattering potential" with the Green's function. The convolution represents the most expensive part of the algorithm and can be efficiently calculated using FFT's.

The convergence properties of the Born and the Rytov series were determined by a binary search procedure. Thus for a given size the refractive index of the object was varied till a point was found were the series converged for all refractive indices that were smaller and diverged if the refractive index was larger than this point. By varying the size of the object it was possible to show a region of convergence as a function of both object size and refractive index.

The simulations of the Born series showed it to converge only when the first iteration is an accurate estimate of the field inside the object. Thus the phase change of the field as it travels through the object is a good indication of not only the quality of a first order Born reconstruction but also describes the region of convergence of the Born series.

The convergence of the Rytov series is more surprising. For all cases studied the Rytov series' region of convergence includes the region of convergence for the Born. This is especially surprising since the first order Born and Rytov approximations have different regions of validity.

In addition Chapter 6 also presented a study of the effects of attenuation on both the Born and the Rytov series. A key part of this work is the idea that attenuating plane waves can be described either in terms of a solution to the wave equation or in the Fourier domain. In a non-attenuating media the two approaches are identical since plane wave solutions to the wave equation are also Fourier waves.

Considering an attenuating plane wave in the Fourier domain makes it possible to calculate the higher order Born and Rytov series for attenuating media. While the algorithms remain the same there is a significant difference in its convergence properties. Since the energy in the field is attenuated as it travels away from the scattering site the region of convergence for both the Born and the Rytov series is increased as the attenuation of the media is increased. Thus the attenuation of the media balances the extra field caused by a larger scattering potential.

A second approach to calculating the scattered fields from a known object was also discussed in Chapter 6. By sampling the object and the fields a set of discrete equations can be written that relate the field and the object. Without using any approximations it is then possible to express the field as the solution of a linear matrix equation.

While the form of the matrix equation is simple, the large amount of data makes this problem difficult to compute directly with today's computers. Instead it was necessary to use an iterative technique known as the Kaczmarz approach to solve the matrix. While the iterative technique used can be shown theoretically to always converge, numerical errors limit the range of objects to those that have a refractive index change of less than 20-40%.

The rate of convergence of this method is only a function of the orthogonality of the defining equations. Thus when the object has a small refractive index the defining equations are nearly orthogonal and the Kaczmarz approach quickly converges to the correct field. On the other hand as the refractive index is increased the hyperplanes defined by the equations become nearly parallel and convergence is much slower. Since the Kaczmarz approach treats each equation for the field separately faster convergence is often possible by sequencing the equations so that each equation is nearly parallel to the one before it.

Finally Chapter 7 presented a survey of several techniques for reconstructing an object without using first order approximations. The most difficult part of this problem is that it now necessary to actually compute the field inside the object. In first order diffraction tomography the field inside the object is assumed to be a plane wave but this can't be true with higher order approximations. Since it is necessary to illuminate the object from a number of different directions to perform the reconstruction a calculation of the field is necessary for each view. The large number of equations makes this a difficult and expensive process.

A straightforward approach is to write a system of equations that describes both the field inside the object and the refractive index of the object. It should then be possible to solve this system of equations for both the field and the object. Unfortunately it is a non-linear system of equations because the defining equations are a function of the product of the two unknowns. For this reason it is necessary to use some type of search procedure to solve for both the fields and the object.

A second approach, first used in high energy physics and described in Chapter 7, is to do a perturbation expansion for the object. This is similar to the Born and the Rytov series described in Chapter 6 but now the object is assumed to consist of a series of components.

The convergence of this approach is a function of two series. Since this approach is based on a Born series expansion for the scattered field it is only valid when the field inside the object can be described as a converging Born series. As seen in Chapter 6 this is a rather severe limitation. In addition the object is expressed as a separate series expansion and for this approach to converge it is necessary for both the Born series and the object series to converge.

Finally a third approach, described in Chapter 7, is to make a first order estimate for the object and then use this object to calculate a better estimate for the field inside the object. Like the Born and the Rytov series described in Chapter 6 this is a fixed point algorithm. This approach is made even more difficult than first order reconstruction algorithms since it is necessary to calculate an estimate of the object given an arbitrary illuminating field. Since each projection is no longer independent the Fourier Diffraction Theorem is not valid and a reconstruction procedure will need to look at all the scattered data simultaneously. This can be easily done using a matrix formulation but there is a severe performance penalty.

The convergence properties of this particular series is not known although it is probably reasonable to assume that the region of convergence will be a function of the quality of the first order estimate of the field. If using the first order estimate of the field is not better than the original assumption to use the incident field then certainly the series will diverge. This condition represents a severe limitation for the technique.

Future work on this problem could continue in several areas. The perturbational approach has a limited range of convergence but for objects that fall within this range a better quantitative estimate of the object should be possible than that which is possible using first order algorithms. The same is also true for the fixed point approach but more work is needed to determine the range of convergence.

Certainly the only guaranteed approach to solve the inverse scattering problem is to find a solution to a non-linear set of equations. There are a number of algorithms that can be used but the large number of equations (a 128x128 reconstruction has over 2 million unknowns and equations) makes this a very difficult problem.

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