Modified Cross-Correlation Back Projection for UWB Imaging: Numerical Examples

R. Zetik, J. Sachs and R. Thomä

***Abstract*—The article presents a modification of cross-correlated back projection algorithm for UWB imaging. The modification concerns its improved performance in sense of better quality of reconstructed 2D or 3D images of the propagation environment. The performance of the new imaging algorithm is demonstrated on numerical examples.**

***Index Terms*— back projection, migration, ultra wideband imaging**

I. Introduction

Imaging performed by electromagnetic (EM) waves plays an important role in various applications in non-destructive testing, ground penetrating radar, through-wall radar, medicine and others. Imaging methods are based on the scattering of EM waves in an unknown medium and involve some form of back propagation, back projection, or time-reversal for image re-construction.

There are numerous techniques that are used to solve this inverse problem in order to get images of an unknown medium [1], [2]. Each of them supposes a certain measurement arrangement and data acquisition schema as well as some specific stimulation signal. According the measurement arrangement we can distinguish between techniques with monostatic or bistatic data acquisition.

The group of imaging techniques with bistatic data acquisition assumes separated source and receiver of EM waves. This group can be further subdivided into following categories [1]:

- one fixed source using narrowband stimulating signal and moving receiver,
- multiple sources using narrowband stimulating signal and moving receiver,
- one fixed source using broadband or ultra-wideband (UWB) stimulating signal and moving receiver.

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An imaging algorithm that solves inverse problem in the case of the first category is referred to as holography. Diffraction or projection tomography algorithm delivers images in the case of the second category and time domain back propagation solves inverse problem according to the third category. There exist also various combinations of these categories, however, they only add a redundancy to the collected data [1]. This redundancy is reduced if the source and receiver are moved coherently with a constant mutual distance. Another way to reduce this redundancy is the modification of the measurement arrangement from a bistatic to a monostatic data acquisition.

In case of a monostatic data acquisition the same terminal is used as source and receiver of the EM waves. The best known imaging algorithms belonging into this group are the SAFT (Synthetic Aperture Focusing Technique) and the SAR (Synthetic Aperture Radar) algorithm. They are known from non-destructive testing by ultrasound or from microwave imaging.

Imaging methods (bistatic or monostatic) using broadband or UWB stimulation signals are usually referred to as migrations [3]. A well-known time domain imaging method is the Kirchhoff migration. It was developed using ray theory and assumes only Rayleigh- or specular scattering of EM waves from the objects. These assumptions are fulfilled only if the size of the objects is much larger or much smaller than the wavelength of the stimulating signal. Otherwise, objects give rise to a structural resonance or a geometric induced dispersions of waveforms and the ray-tracing model is no more valid. Furthermore the imaging method assumes a constant wave velocity, which must be a priory known. Despite of these restrictions, the Kirchhoff migration is widely used due to its relatively low computational complexity comparing to other imaging methods.

The aim of this article is to introduce a new method for UWB imaging. It is based on cross-correlated back projection algorithm [4], which improves the standard back projection scheme used for the Kirchhoff migration. The new algorithm preserves low computational complexity of the Kirchhoff migration and overcomes some disadvantages of the cross-correlated back projection.

The article starts with the description of the standard back projection algorithm and its improved cross-correlated version. It discusses advantages of the cross-correlated back projection algorithm over the standard scheme. Then, the modified cross-correlation back projection algorithm is introduced. Its performance is compared with other imaging algorithms by a few numerical examples.

II. Cross-correlated back projection and its modification

The basic image formation process in heuristical back projection methods is illustrated in Fig. 1. Here, we assume a 2D bistatic measurement arrangement with one fixed source stimulating the medium with an UWB wave and a moving receiver. The receiver observes the EM field along a line at different positions (Rx1, Rx2, ..). The captured signals represent a 2D data set, in which the first dimension represents the traveling time and the second one refers to the position of the receiver. If we assume for simplicity only a single point scatterer within the whole medium than the train of the scattered EM waves appears as a hyperbolic trace in measured data (see Fig.1 bottom).

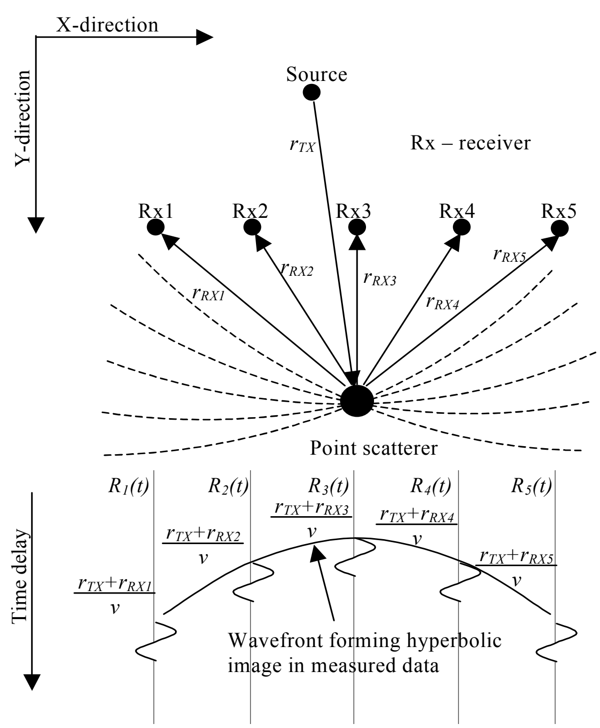

Fig. 1 Migration for bistatic measurement arrangement

The imaging methods map a point response from each measured signal as an arc (a section of an ellipsis) in the migrated image. Here, the contributions of all captured signals are superimposed. Since the arcs follow slightly different paths and intercept only at the position of the point scatterer they add coherently only at this position. The migration can be described by the following equation

$$o(x,y) = \frac{1}{N}\sum_{n=1}^{N} R_n\left(\frac{r_{TX}+r_{RXn}}{v}\right). \qquad (1)$$

Here, R_n refers to the measured signal at the receiver position Rx_n, r_{TX} is the distance between the source and the object, r_{RXn} is the distance between the receiver and the object, v stands for the propagation velocity and $o(x,y)$ represents the migrated image. The quantity $(r_{TX}+r_{RXn})/v$ is the round trip time of the EM wave to propagate from the source to the object and back to the receiver.

The arcs sum only completely at the position of the point scatterer. That’s why there will be the largest peak in the image. However, the summation also causes some artifacts, which are distributed over the whole migrated area. These artifacts influence the image in two ways. Firstly, they decrease the spatial resolution. This results from the fact that the summing is also at least partially coherent in a vicinity of the point scatterer. With increasing distance from the scatterer the degree of coherence between the different measurement signals of course decreases. Secondly, the artifacts provoke side lobes in image regions where the traces do not overlap but still individually contribute to the image. This results in an increased noise floor of the migrated image.

The question is, if there are simple means to reduce the side lobes in order to improve the resolution and noise suppression. In [4], such a method was proposed. It was named as cross-correlated back projection method. The idea is to reduce the side lobe level by suppression of the signal levels within the sum if the considered image point (x,y) is away from the actual location of the scatterer. This is done by a joint migration of two signals – one gathered by the moving receiver ($Rn(t)$) and another by an auxiliary reference receiver ($R_{ref}(t)$) as follows

$$o_j(x,y) = \frac{1}{N}\sum_{n=1}^{N} R_n\left(\frac{r_{TX}+r_{RXn}}{v}\right) R_{ref}\left(\frac{r_{TX}+r_{RXref}}{v}\right). \qquad (2)$$

Since two different delay terms in conjunction have to match the actual scattering scenario, the probability to add “wrong” energy to an image pixel, which does not coincide with the point scatterer, will be drastically reduced. This effect is demonstrated in Fig. 2. The two signals only contribute to the pixel energy if the base lines of the appropriate receivers coincide i.e. intersect. On the one hand, this is at the location of the scatterer. These contributions are added coherently and finally represent the image of the object. On the other hand, some (unwanted) intercept points appear in the upper half plane. They do not contribute to the object image. Since they are scattered through the migrated image, they slightly increase the noise level. If however the imaging is restricted to the lower half-plane, as e.g. for Ground Penetrating Radar, they do not interfere.

A further improvement can be gained by averaging the signal product over the duration T (e.g. effective width of the impulse) of the stimulating impulse[1] i.e. to determine a correlation coefficient between both signals. This finally leads to the cross-correlated back projection method described by

[1] For arbitrary UWB signals use width of auto correlation function of the stimulus instead of impulse duration.

further equation

$$o_c(x,y)=\frac{1}{N}\sum_{n=1}^{N}\int_{-T/2}^{T/2}R_n\left(\frac{r_{TX}+r_{RXn}}{v}+\xi\right)R_{ref}\left(\frac{r_{TX}+r_{RXref}}{v}+\xi\right)\mathrm{d}\xi \tag{3}$$

The best results will be achieved if the point response of both receivers $R_n(t)$ and $R_{ref}(t)$ are orthogonal..

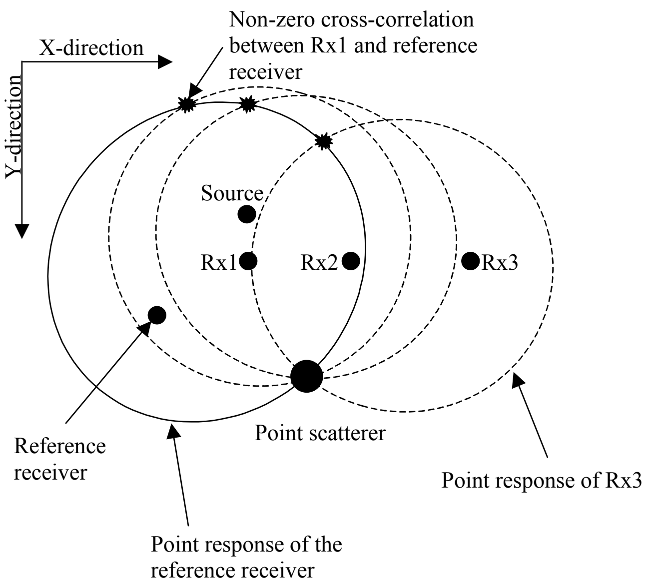

Fig. 2 Cross-correlated migration for bistatic measurement arrangement

In order to remove the remaining ambiguity within the whole 2D-plane, it is proposed to exploit a further reference antenna and to migrate the average of a threefold product as follows

$$o_{\mathrm{mod}}(x,y)=\frac{1}{N}\sum_{n=1}^{N}\int_{-T/2}^{T/2}R_n\left(\frac{r_{TX}+r_{RXn}}{v}+\xi\right)R_{ref1}\left(\frac{r_{TX}+r_{RXref}}{v}+\xi\right)R_{ref2}\left(\frac{r_{TX}+r_{RXref}}{v}+\xi\right)\mathrm{d}\xi \quad . \tag{4}$$

The modified cross-correlation method actually leads to the intersection of three ellipses. If the receivers are not aligned in a straight line then there exist only one contribution in 2D as well as in 3D migration, which is coherently added to the image of the object.

III. SIMULATION EXAMPLES

In what follows, the performance of three imaging algorithms described by (1), (3) and (4) will be compared using simulated data. On this occasion, the effect of more complex scanning tracks as a simple linear one will be investigated. Let us assume a monostatic measurement arrangement, which means that receiver and source coincides. The source transmits an UWB stimulation impulse modeled as Gaussian-modulated sinusoidal pulse. The pulse is centered at 10 GHz frequency having a fractional bandwidth of 100 %. The aim of the imaging algorithms is to deliver a 2D image of an area of 3 by 3 meters. Within this area, there is only one object – a point scatterer- situated at the position [1.25, 0.25]. Its position and also the number of scatterers is not a priory available for imaging algorithms. Thus, it is not possible to select a priory some optimum track for the sensors that should scan the area. Let as move in a first example the sensors with a constant speed along a regular track, which forms a rectangle of 1 by 1 m centered in this area. During the movement, the receiver captures (simulated) 100 impulse responses. These impulse responses in conjunction with the appropriate sensor positions represent the input dataset for the imaging algorithms.

The result of the standard back projection computed according (1) is illustrated in Fig. 3. Note, that the migrated image data are displayed in a dB-scale. The horizontal axis is related to the X-direction and the vertical axis is related to the Y-direction. The bold solid line represents the rectangular track of the sensors. The point responses form circles in the migrated image. They all intersect inside the rectangle at the actual object position forming a smeared object image. But obviously, the circles do not intersect only at the position of the object. The regular movement of sensors along the 4 sides of the rectangle creates 4 additional phantom images of the object and 4 striking circular side lobes. This is caused by the fact that the sensors movement along one line represents actually a synthetic uniform linear array, which causes this ambiguity. The side lobes and especially the phantom images restrict the dynamic range of the migrated image to about 11dB.

Let us now investigate the performance of the cross-correlated back projection considering the same scenario. The migration is computed according (3). This algorithm needs for the cross-correlation a reference receiver. This arises a question concerning its useful location. There are two basic criteria to be respected. The first one imposes orthogonality of the point responses from the reference receiver and the other ones. The second criterion requests a similar angle of an object observation by the reference receiver and the cross-correlated receiver. This is prompted especially in real measurements where the response of the objects is usually strongly angle dependent and the algorithm assumes that all antennas receive nearly the same point responses. Therefore, it seems to be a good choice to use for the reference receiver previous measurements of the moving receiver and to reject an additional one. Fig. 4 illustrates the results of the cross-correlated back projection. Here, the reference signals were

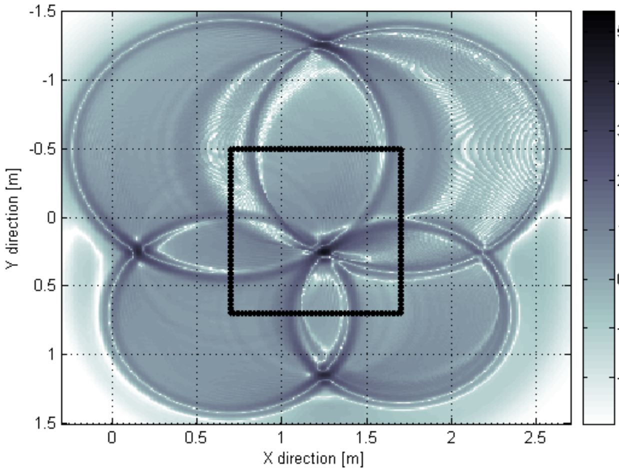

Fig. 3 Standard back projection

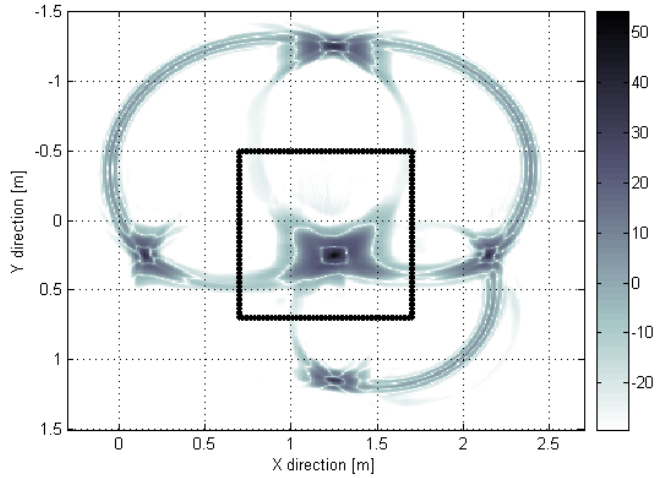

Fig. 4 Cross-correlated back projection

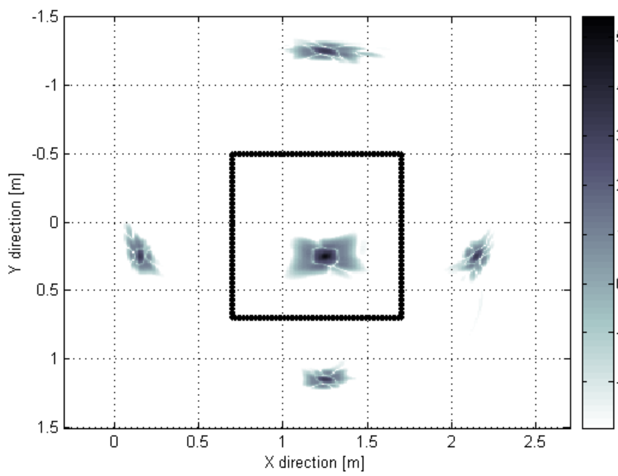

Fig. 5 Modified cross-correlated back projection

gained from signals measured 30 positions before the current receiver position. Thus, the distance between the locations of the two receivers was about 30cm. The cross-correlation within the migration algorithm significantly removes the side lobes compared to the standard migration. But they were not completely suppressed. The 4 phantom images remain nearly at the same level (-13 dBc).

Further improvements with respect to the side lobes can be achieved by using the modified cross-correlation back projection described by (4). The results are illustrated in Fig. 5. Here, the image is almost free of side lobes and the level of the phantom images degreased to about –18 dBc which still gives some space for further improvements.

The phantom images can be removed in a better way by a proper selection of the track for the sensors movement. The previous numerical examples shown that the right sensor track plays an important role for the imaging algorithms. Finally, this track forms the aperture of the synthetic array, which is created by the sensors movement. If the track is linear or partially linear then its linear parts form linear synthetic array. This initiates an ambiguity in the migrated image, giving rise to the phantom images. With respect to this fact it is better to deal with a chaotic track that removes the ambiguity and significantly suppresses the phantom images. This is demonstrated by next numerical examples. Here, we assume the same scenario containing only one point scatterer. But now, the track used for the movement of the receiver and the source is modified from the rectangular form to a quite more irregular course. The new track was created by adding a sinus component and some uniform noise to the former rectangular scanning path.

The resulting form of the track is depicted in Fig. 6 together with the results of the standard back projection algorithm. The phantom images disappeared completely and the side lobes have been reduced from – 12 dBc to – 23 dBc (compare with Fig. 3). These improvements only result from the better choice of the scanning path. A comparable effect can also be observed in the case of the cross-correlated back projection and its modified version. The phantom images are removed and the dynamic range is significantly increased. In case of cross-correlated back projection (Fig. 7) the dynamic range achieves 40dB. In case of modified back projection (Fig. 8) the range is about 48dB. It is limited only by the side lobes that arise sometimes due to the un-orthogonal point responses from reference receiver and the cross-correlated receivers.

I. Conclusion

The article presented a new modification of the cross-correlated back projection for UWB imaging. It demonstrated its performance by numerical examples. It was shown that the modified algorithm improves significantly the image quality. Accept its improved performance it still preserves low computational complexity of the standard back projection algorithm.

The developed algorithm can be advantageously used for example for on-line visualization of the propagation environment in communication systems or cooperative sensor networks. System terminals may gain by that way information

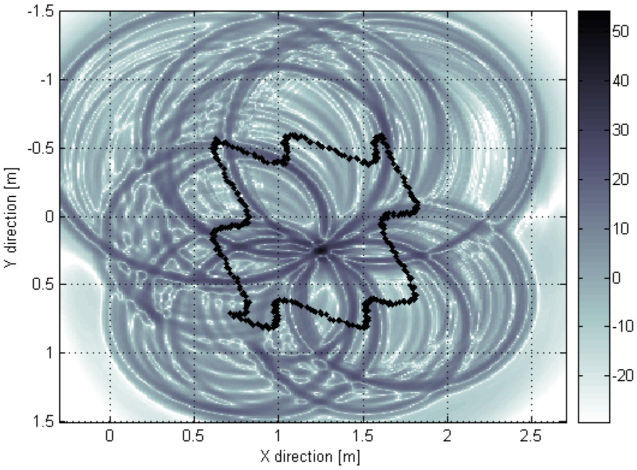

Fig. 6 Standard back projection

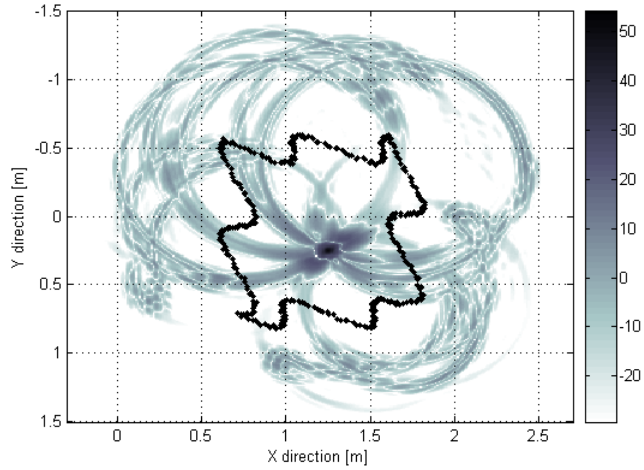

Fig. 7 Cross-correlated back projection

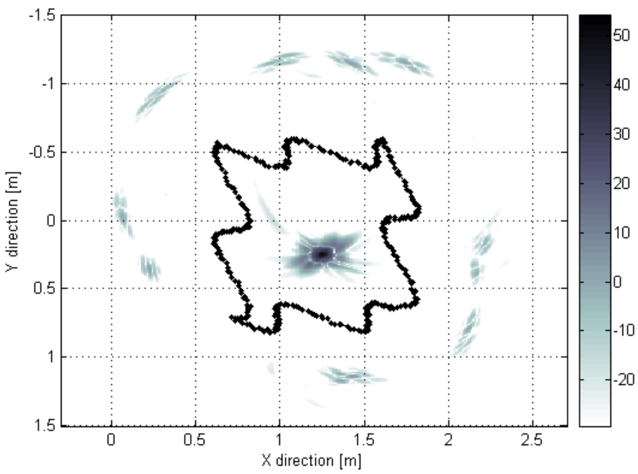

Fig. 8 Modified cross-correlated back projection

about the geometric and electromagnetic structure of the propagation environment. In combination with high-precision positioning algorithms it allows to the system terminals of some sensor network or communication system to be position aware or even self-organized. This can considerably extent capabilities of these systems. The first measurement examples demonstrating this kind of application can be found in [5].

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REFERENCES

[1] P.C. Sabatier, “Basic methods of tomography and inverse problems,” Adam Hilger, Bristol and Philadelphia, 1987.

[2] L. Borcea, G. C. Papanicolaou, C. Tsogka, and J. G. Berryman, “Imaging and time reversal in random media”, Inverse Problems 18, pp. 1247–1279, 2002.

[3] D.J. Daniels, “Ground penetrating radar - 2nd edition,” IEE, London, 2004.

[4] S. Foo and S. Kashyap, “Cross-correlated back projection for UWB radar imaging,” IEEE Antennas and Propagation Society Symposium, Piscataway, NJ, USA, Vol. 2, pp. 1275–1278, 2004.

[5] R. Zetik, J. Sachs, R. Thomä, “Imaging of propagation environment by UWB channel sounding,” COST273 Temporary Document TD(05) 058, Bologna, Italy, January 2005.