Review of radio image recovery methods

V L Khmelev¹, A F Fominykh²

¹ Research engineer, Tomsk State University, Tomsk, Russia
² Bachelor student, Tomsk State University, Tomsk, Russia

E-mail: alexandrafedorovna02@gmail.com

Abstract. Radio-wave image restoration techniques are now intensively being researched at the Radiophysics Faculty of Tomsk State University. Key methods of radio-wave image reconstruction are examined in this paper. We describe the mathematical basis of adapted methods in the single scattering approximation. These methods are used at the Department of Radiophysics in the developed safety systems. The technique of differential hyperboles and Stolt’s method, for instance, were adopted from acoustic seismology. Mainly, geotomographic systems use these methods for imaging objects under the surface. Safety systems have close task, they are to detect prohibited items under the passengers’ clothing and in the luggage at railway stations or airports. Radio-wave tomography methods can reconstruct images of prohibited objects in the same way as X-rays safety system, but without X-ray radiation, so without harm for a human biology tissue.

1. Introduction
There are on the market many devices allowing you to capture an optical image of objects. The basic physical principle of image acquisition is registering an intensity of reflected optical waves with using one and more semiconductor matrices. Besides the cameras, a man able to capture images in memories of surrounding objects with the help of his own eyes. Human perception has a limit, ultrasonic and electromagnetic radiation goes out this limit. However, this radiation obeys the same physical law as visible radiation. A recovered image based on the ultrasonic or electromagnetic radiation calls the wave image. The first to develop methods for obtaining acoustic images in acoustic seismology [1] As sources of seismic waves was an explosion or series of explosion. After it, an explosive wave goes through the soil reflects from solid layers, going back and registered by a seismograph. The processing of seismograms allows us to determine the depth of different layers because each layer has a different density, which affects the reflection coefficient of the layer. An acoustic image based on the density of the reflecting layer, for a radio image, the basic physical characteristic is the dielectric constant of the scattering inhomogeneity. Figure 1 shows an optical image of an object, and 2 shows the radio wave image of the same object.
The direct task of the propagation of radio waves writes as follows [2]:

$$U_n(t) = \iiint_V \rho(r) S\left(\frac{t - |T_n - r| + |r - R_n|}{c} \right) \frac{1}{|T_n - r| - |r - R_n|} \, dr,$$

where $U_n(t)$ is the signal recorded in the n-th receiver, $S(t)$ is the signal emitted by the transmitter, $R_n$—receiving antennas position, $T_n$—transmitting antennas position, $\rho(r)$ is the distribution of scattering inhomogeneities. The direct task is calculation of the field $U_n$ at the specified point, at time moment $t$. However, getting data on the distribution of scattering inhomogeneities in space and restoring their shape based on the registered data of the electric field is the inverse problem. We mostly use in our prototypes [3],[4] two methods: the wave migration method [2] and the Stolt method [3]. The first method works in the time domain, and it is more demanding in computational terms, and the same time, it is able to recover the radio image in real time. The second one is much simpler to compute and performs the calculation in the frequency domain. It works in post-processing. I.e. Before getting radio-image you have to perform a full scan with radio wave measurements, save data and then the processing recovers image.

2. Wave migration method, diffraction hyperbole method

Real-time scanning systems use the migration method. The specific task is obtaining radio images, during scanning and improving refinement by using additional radio measurements. In addition, this method is calling the diffraction hyperbole method, because moving a transceiver along the axis received signal from a point source has the form of a hyperbola. Figure 3. gives an example of a hyperbola from a point source, and figure 4 shows the sum of two hyperbole obtained by scanning of two point sources.
As mentioned above, the migration method solves an inverse problem. This problem is unstable and can get a solution in special cases. This problem is solving in the single scattering approximation. Considered, that all waves which are a result of secondary reflections from scattering surfaces will have a much weaker amplitude and can be ignored. As well effects of self-Eclipse not taken into account. Instead of distribution of inhomogeneities \( \rho(r) \), the migration method finds an approximate \( p(r) \) which are not always equal but close enough. Math record is:

\[
\rho(r) \approx p(r) = \sum U_n \left( \frac{|T_n - r| + |r - R_n|}{c} \right).
\]

A problem of this algorithm is that for each point of calculated space has a necessary to sum all the received oscillograms. In the moment of receipt nth oscillogram, it has to recomputed all points of the space under research.

Usually such systems used in geotomography because a research object has to be static. An operator moves geogramonogram in a scan surface. During moving process, the algorithm recovers radio wave image. If the result of image reconstruction has the object of interest, then he can perform additional radio wave research to improve the quality of the radio image. Such systems use in archaeology, biological research of underground animals, and mine clearance.

3. Stolt Method

As mentioned above, the Stolt method works in post-process radio image reconstructed systems. Therefore, for the image reconstructing process, you have to the collect data and after use the methods. The main distinguishing feature of this approach is the transition to the frequency domain. Seismology acoustic, also, has developed Stolt method and subsequently it adopting to radio tomography. This method has a limitation in the sensing scheme. Suppose that all point of a sensing trajectory lies in the one surface, and all receivers and transmitters combined, i.e. geometrically located at the same point. In the case of movement of the transeiver pair, a point lying in the sounding plane and equidistant from them is the transeiver pair position. You also have to carry out phase correction of the received signal. This point lies in the sensing plane between the receiver and the transmitter and is equidistant from them. It is also necessary to make a phase correction of the received signal. In systems with large antenna arrays, consisting of a large number of receivers and transmitters, the calculation of phase corrections becomes an unobvious task. This problem reviews here [6][6].

In the classic case, radio wave data recorded at a point \( x, y \) the scan surface \( S(x, y, t) \) decompose into a flat-wave spectrum \( S(x, y, \omega) \). Then the transition to the spatial frequency space by using the direct Fast Fourier transform:

\[
\hat{S}(k_x, k_y, \omega) = \int_{-\infty}^{\infty} S(x, y, \omega) \cdot e^{-ixk_x - iyk_y} dx dy,
\]
The next step is replacement $\omega = c \cdot \sqrt{k_x^2 + k_y^2 + k_z^2}$, and transition to a coordinate system of spatial spectra. We assume that at the meeting points of the wave and scattering inhomogeneities, the inhomogeneities replaced by common-mode point sources. Each wave travels from the transmitter to the inhomogeneity and from the inhomogeneity to the receiver, these paths are equal for the monostatic scheme. Therefore, the wave receives a double phase incursion, and then point sources produce wave with a double frequency and in the opposite direction back to receivers. The basic assumption could formulate more simply. We believe that only waves reflected from inhomogeneities were obtaining, the rest of them went so far that after reflection their amplitude could neglect.

$$P(k_x, k_y, k_z) = S(k_x, k_y, k_z)^2,$$

where $P$ spatial spectrum of point sources located on inhomogeneities surface. Then their location is possible to found by using the inverse Fourier transform.

$$P(x, y, z) = \iiint_{-\infty}^{\infty} P(k_x, k_y, k_z) e^{ixk_x+iyk_y+izk_z} dk_x dk_y dk_z,$$

where $P(x, y, z)$ is the distribution of inhomogeneities. Using FFT algorithms instead of classical summation reduces the computational complexity of the algorithm for a large amount of radio wave data exponentially. Despite its high speed computing, the limitation of the monostatic scanning scheme and post-processing makes the algorithm ideal for fast mechanical scanning schemes. For example, systems for safe scanning of aircraft passengers at airports, engineering communications scanners.

4. Conclusion
The radio image recovering is the inverse problem. In practice for solving this problem, we use the single scattering approximation, which simplifies the recovery image processing. This article represents two basic methods for solving the problem: the migration method and the Stolt method. Each of these methods has advantages and disadvantages.

The migration method is a versatile approach and it can work in both schemes: monostatic and bistatic. This approach is suitable to work with three dimensional antenna arrays. On the other hand, the price for versatility is a high computational complexity.

The Stolt method transforms calculations to the frequency domain, speeding up and facilitating computing. The method adds restrictions to the scheme of sounding. It works in the monostatic scheme and with two-dimensional antenna array.

In this paper, we investigated basic schemes for radio wave image reconstructions. The authors hope that this paper will be useful for students and master’s students, who do their research in the field of radio-vision systems.

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