SUBSURFACE RADAR EXAMINATION OF AN AIRSTRIP

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ABSTRACT

Increasing intensity of air traffic and growing take-off mass of passenger and cargo civil airplanes leads to the growth of a loading on airstrips, taxiways and aircraft parking places of airports. It results in an increased wear of concrete pavement and requires a continuous monitoring of their state and supporting power with the object of ensuring the flight safety. Subsurface radar can be used as one of the means for non-destructive testing of reinforced concrete airfield [1]. Taking into account large areas of airfield pavements and their constructive features, the carrying out of these jobs will probably require the creation of dedicated equipment and software.

1. INTRODUCTION

The main tasks which can be solved by using subsurface radars, include:

- Detection of airfield pavement defects (cracks, voids and delaminations inside reinforced concrete slabs, etc.)
- Revealing of under-pavement cavities, formed because of washing away of the sand bed by ground water
- Determination of rebar laying places, fuel mains, and cable channels in airfield pavements.

First experiments on the sounding of reinforced concrete constructions by means of subsurface radars were, evidently, carried out in the late 1980s in Canada. The subsurface radar PS-24 [2] was used in these experiments. However, an unsuccessful form of the results presentation did not allow the obtaining of any convincing conclusions. Later, both the equipment and signal processing techniques were improved [3]. As recognizes today, to search non-uniformities in construction it is necessary, as a minimum, to obtain the images of reflected signal profiles over the paths of movement of radar antennae. But, 3D-representation of sounding domain, which lies below the examined site, is most informative.

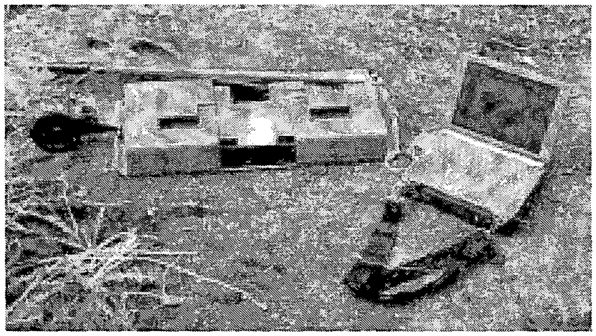

Fig. 1. Subsurface radar of OKO-M1.

2. GPR DATA

The paper describes algorithm of quality improvement of the image, obtained at airstrip sounding. The experiments on airstrip sounding were carried out with help of the OKO-M1 subsurface radar (Russia), which had impulse length about 1 nc, see Fig. 1. In experiment the reinforced concrete slabs of an airstrip were sounded. Fig. 2 shows the initial radar images of a metal rebars in concrete cover of airstrip obtained by the impulse time-domain subsurface radar with a spatial resolution of the order of 0.1 m. The horizontal axis at the image corresponds to the airstrip surface, and the vertical axis corresponds to a time axis, which is related to the depth of search.

The rebar images are seen as reflections of the transmitted impulse signal at the relatively uniform background with phantom images in the radar shadow zone behind a metal rebars. The presence of the phantoms is caused by multiple reflections of the radar pulse signal between the antennas and rebars in a ferroconcrete slab of the airstrip. The reflected impulses themselves form at the image segments of arcs that are accounted for the sufficiently wide antenna-beam pattern (up to 30°) of the OKO-M1 subsurface radar.

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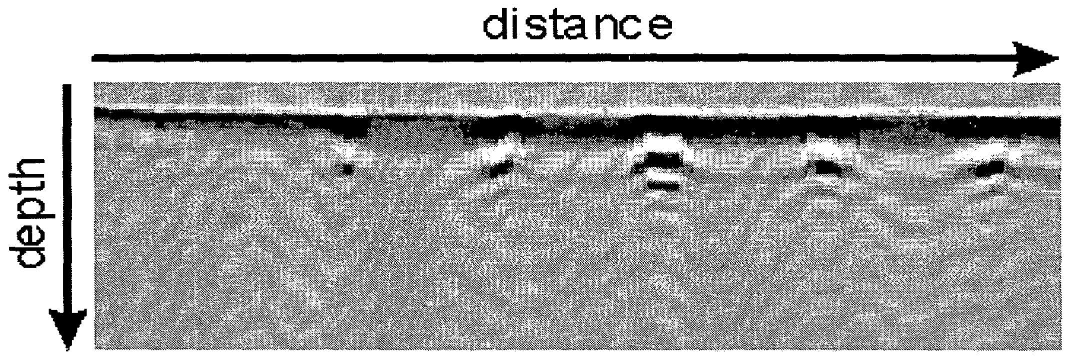

Fig. 2. Initial radar image of metal rebars in airstrip.

2. SYNTHETIC APERTURE TECHNIQUE

To improve the quality of the obtained images the migration technique was used [4]. The analogue of this technique, widely used for air and space deployment radars, is known as synthetic aperture technique. However this technique lacks versatility at subsurface sounding of condensed mediums (soils, building constructions, etc.) In general, this is connected with the peculiarities of electromagnetic wave propagation in lossy medium.

First of all in general, the speed of electromagnetic wave propagation in the sounded medium is unknown, as it depends on both the composition of the medium itself and its moisture. The latter value is unknown *apriori*. Besides, the soil moisture itself can vary considerably with depth and distance along pass, or even be subjected to jumps when crossing the water table in low soils, e.g. in sands. In this case, the very idea of synthetic aperture can become invalid because of the violation of the basic space-time relations used in the calculations. In particular, the assumption of the proportionality of the round-trip propagation time of electromagnetic wave to the propagation distance will not be satisfied. This assumption is as usually meant by default and is not mentioned specially.

Another important fact, hindering the processing of subsurface radar signals using this algorithm, is dispersion and strong attenuation of microwaves in sounded mediums. It manifests in the dependence of received impulse form on the location depth of the sounded object [5]. Due to the listed difficulties, many papers related to the use of the migration algorithm in subsurface location illustrate the efficiency of the proposed technique by mathematical models, and not by the results of a real subsurface radar operation.

However, in some cases, related to the sounding of sands or uniform building materials, the migration algorithm can be helpful for the detection of small-size objects. In particular, in case of ferroconcrete pavements of airfields, the properties of the sounded medium can be considered as uniform.

Let us consider basic geometrical relations, which arise while forming a subsurface image by impulse time-domain radar. Let's believe, that the subsurface radar antenna system consisting of a transmitting A_t and receiving A_r antennae and separated by a constant distance x_a moves along the X-axis, which is directed along the surface to be examined, Fig. 3.

Suppose the sounded object be at the point corresponding to the coordinate x_o at the depth h_o from the surface, and the width of the antenna beam be equal to 2θ. Then the distance from the transmitting L_t and receiving L_r antennas to the object are equal to

$$L_t = \sqrt{h_0^2 + \left(x + {x_a}/{2}\right)^2} \qquad (1)$$

and

$$L_r = \sqrt{h_0^2 + \left(x - {x_a}/{2}\right)^2} \qquad (2)$$

The signal round-trip time delay $\Delta t(x)$ between the transmitting and receiving antennae relative to the direct signal travel time from one antenna to another is equal to

$$\Delta t(x) = \frac{1}{c_m} \cdot \left[\sqrt{h_0^2 + \left(x + {x_a}/{2}\right)^2} + \sqrt{h_0^2 + \left(x - {x_a}/{2}\right)^2} \right] - \frac{x_a}{c_s} \qquad (3)$$

where c_s = the speed of electromagnetic wave propagation along the sounded surface
c_m = the speed of electromagnetic wave propagation in the sounded medium.

The following equation is valid for the speed of electromagnetic wave propagation in the lossy medium:

$$c_m = \frac{c}{\mathrm{Re}\sqrt{\varepsilon'}}$$

where c = the speed of electromagnetic wave in vacuum
ε' = the complex permittivity of the sounded medium.

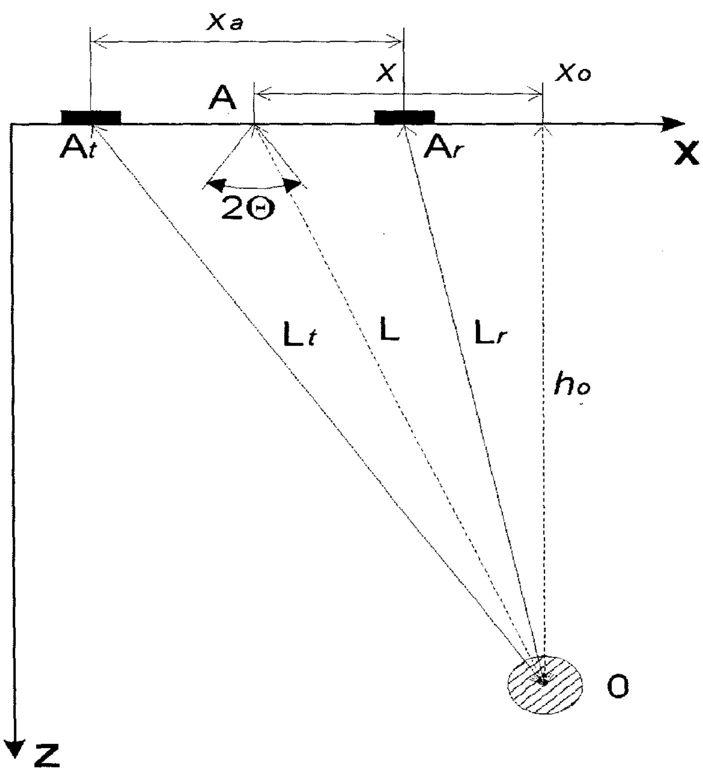

Fig. 3. The subsurface radar antenna system arrangement relative to the sounded object.
In this picture x is the coordinate along the sounded surface; z is the coordinate into the depths of sounded medium; O is the position of the object; h_o is the depth of location of the sounded object; x_o is the object coordinate relative to the sounded surface; A is the current position of the antenna system center; A_t is the position of the transmitting antenna; A_r is the position of the receiving antenna; L is the distance from the antenna system center to the object; L_t is the distance from the transmitting antenna to the object; L_r is the distance from the receiving antenna to the object; 2θ is the width of the antenna-beam pattern.

Let's see eqn. 3 in linear approximation and assumption $x_a \ll h_o$. In this case we obtain the following approximate relationship for the signal time delay $\Delta t(x)$

$$\Delta t(x) \approx \frac{1}{c_m}\cdot\sqrt{h_0^2+x^2}\cdot\left(2+\frac{x\cdot x_a}{h_0^2}\right)-\frac{x_a}{c_s} \qquad (4)$$

In our subsequent reasoning we will assume that $c_m = const$ throughout entire sounded medium. For simplicity, we will even assume that $x_a = 0$. The latter condition is sufficiently well satisfied at $x_a \ll h$. Then eqn. 4 is reduced to:

$$t(x) = \frac{2}{c_m}\cdot\sqrt{h_0^2+x^2} \qquad (5)$$

where $t(x)$ is the target signal time delay relative to its emission time.

Eqn. (5) is the equation of a hyperbola with the vertex at the point $(x_o, 2h_o/c_m)$ and with the vertical axis passing through the sounded object, see Fig. 4. Relatively robust evidence of the advisability of using the migration algorithm could be the presence in the obtained image of hyperbola segments arising due to reflection of the impulse from concentrated objects in the soil or another sounded medium. A question arises in this case: What is considered a focused image? Eqn. 5 contains two unknown parameters: c_m and h_o. The uncertainty of h_o value is associated with the fact that direct signal from the transmitting antenna to the receiving one, whose front at the image can be conditionally assumed to be a surface line, can be absent. The uncertainty degree of c_m value may be quite high. In many cases it has been proposed to use as focusing criterion the form similarity of the object reflected signal and antenna-transmitted signal.

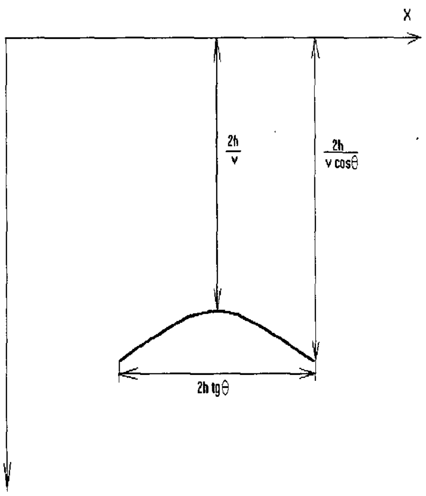

Fig. 4. The outline of a dot form target on a subsurface radar image.

However, as was shown [5], the propagation of subsurface radar signal is substantially affected by the frequency dependence of the medium dielectric parameters. In particular, the form of a received signal can considerably differ from that of a transmitted signal, and, moreover, it depends on the depth of object location. The present paper proposes a realization of a focusing synthetic aperture based on the geometric relations of the initial image of the subsurface radar. As for initial image in Fig. 2, we assume that separate signal realizations are obtained as a result of rectilinear radar movement along the ground surface, and the sounding being carried out equidistantly.

As another unavoidable assumption, mentioned earlier, we consider that c_m=*const* throughout the sounded medium. As for hyperbolic formation at the processed image we assume that they are obtained as a result of radar signals reflections from subsurface objects of dot form, i.e. the objects whose linear dimensions in sounding plane are much less than the central wavelength of a transmitted impulse.

4. RESULTS

The proposed image processing technique does not require any preliminary information about the subsurface radar operation modes, transmitted signal form, medium properties, and nature of detected objects, etc. In fact, all the required information is contained in the initial radar image. Let us use the described above algorithm for processing of the radar image shown in Fig. 2.

This image explicitly shows several hyperbolic form fragments that are the evidence of satisfying the above mention conditions. The operation of the proposed algorithm consists of the following steps:

1. Indication at the image of a line of the sounded surface
2. Choice of a point corresponding to the supposed hyperbola vertex
3. Choice of a second point corresponding to the end of a hyperbola segment
4. Reading of numerical values of the points coordinates of an assumed hyperbola and calculation by the equation (5) of c_m, h_o and θ corresponding to the image.

Let the brightness of the image point with the coordinates (x, t) will be the parameter $\sigma(x, t)$. Then the brightness of each point of the transformed image $\sigma^*(x, t)$ is calculated in accordance with

$$\sigma^*(x,t)=\frac{1}{\sigma_0}\cdot\int_{-\theta}^{\theta}\sigma(x_l,t_l)\cdot dl \qquad (6)$$

where the integral is taken along the arc of hyperbola, eqn. 4, the vertex of which is at the point (x, t), σ_o is a normalized factor which is constant for the entire image. If the integration area in eqn. 6 exceed the limits of the processed image it is assumed that $\sigma(x_l,t_l)$=*const* and equal to the average brightness of the initial image.

The result of the application of the described algorithm to the image shown in Fig. 2 is given in Fig. 5. It is seen that arc-like elements of the initial image are reduced to a more compact form and can be considered as lumped. The quality of the image focusing depends on the operator's skill and the focusing itself can be an iteration process adjusting the sounding surface location and points, defining the hyperbola segment position.

It is seen that multiple reflections disappeared from the calculated image in Fig. 5. It is associated with the fact that phantom images do not satisfy the initial geometrical relations used in the calculations.

Additional improvement of the image quality is possible by using a filter emphasizing local symmetrical objects. The idea of such a transformation consists in the following. An inversion of the image with respect to the vertical and horizontal axes, passing through the central element, is performed in a filter window. The initial and inverted images are multiplied element by element and summed, and the resultant sum is assigned to a pixel of a new image. Fig. 6 is shown the result of application of the proposed filter to the image in Fig. 5. The location of the rebars relative to the sounded airstrip surface is seen more clearly in this image.

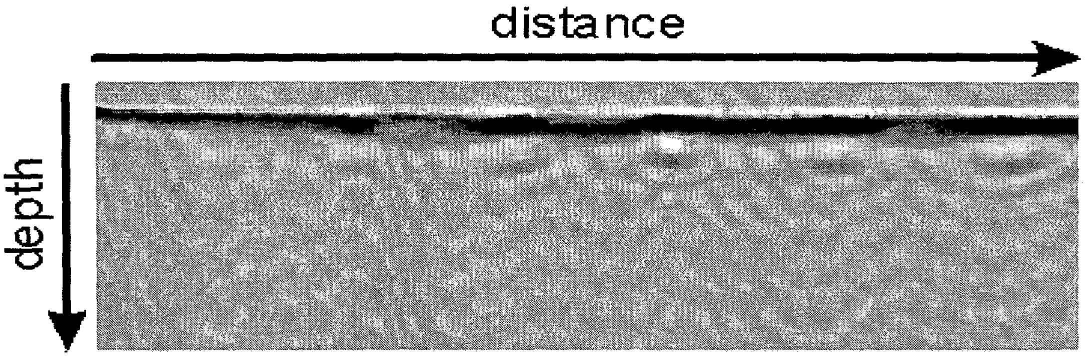

Fig. 5. Result of migration algorithm application to the initial image in Fig. 2.

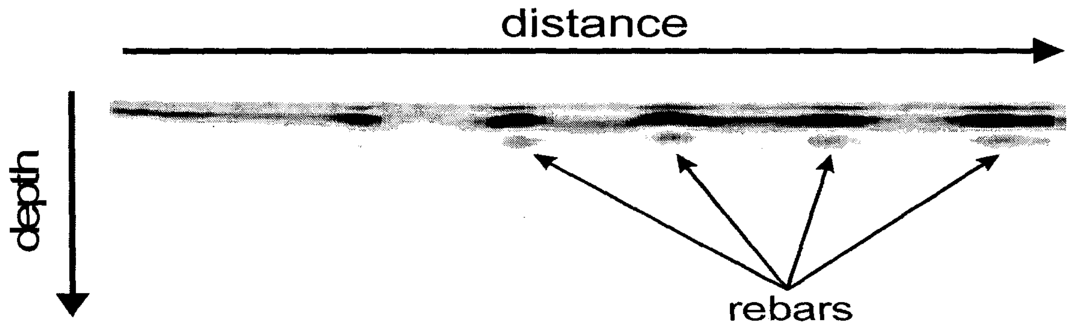

Fig. 6. Result of symmetric filter processing of the image in Fig. 5.

5. CONCLUSION

The improvement of subsurface radar equipment and signal processing algorithms will allow lowering of airfield pavements repair and maintenance cost in future. Subsurface radars can be subsequently used together with other existing techniques, including conventional ones [6], for solving these tasks. The flight safety ensuring is a complex task, and subsurface radars have to find its place in this process.

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