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GEOPHYSICAL RADAR METHOD FOR SAFEGUARDS APPLICATION AT OLKILUOTO SPENT FUEL DISPOSAL SITE IN FINLAND

Saksa P, Heikkinen E, Lehtimäki T
JP-Fintact Ltd. Jaakko Pöyry Infra

In STUK this study was supervised by Olli Okko

STUK • **SÄTEILYTURVAKESKUS**
STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY
Osoite/Address • Laippatie 4, 00880 Helsinki
Postiosoite / Postal address • PL / P.O.Box 14, FIN-00881 Helsinki, FINLAND
Puh./Tel. (09) 759 881, +358 9 759 881 • Fax (09) 759 88 500, +358 9 759 88 500 • www.stuk.fi

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Abstract

Finnish Radiation and Nuclear Safety Authority (STUK) as the national authority responsible for the safeguards in Finland in a manner that enables effective implementation of the IAEA system, is assessing methods and practices that will contribute to the development of an effective safeguards approach for the final repository of spent fuel at Olkiluoto. Ground penetrating radar (GPR) and borehole radar has been considered as one possible non-destructive geophysical method to be applied. Radar tomography has been limited outside the scope of this study.

The radar method can be applied with certain precautions to tunnel based imaging of bedrock volume up to distances of 30–40 m from the tunnel surfaces in maximum. However, natural reflectors (faults, shear zones, rock type contacts, gneissic banding and inclusions) together with tunnel construction related obstructions (reinforcement, grouting, excavation damage zone, technical installations, rough tunnel surface, etc) exist in abundance. Numerical modelling indicates that radar method has ability to detect a 2 metre cubic void at 5 metres behind a rock face in typical crystalline rock conditions.

This report describes the Olkiluoto specific bedrock properties which are relevant for applicability of the radar method. The experiences achieved during comprehensive site investigations in Olkiluoto, the geological knowledge, and current plans of underground rock characterization premises were considered in order to describe the potential, limitations, applicability and specific issues.

Most useful are longer survey lines along tunnel walls, roof and in boreholes in close proximity. Low 30–60 MHz frequencies shall be used for maximum penetration and enhancement of large engineered object visibility from natural background reflections. Surveys divide themselves to primary (baseline) and inspection (monitoring) types. The application of radar requires qualified expert for designing the survey, operating the instruments and carrying out processing. Data management requires a system where processing, knowledge, geometries and long-term data archiving are done. The available tools can be tested at a suitable site to study instrumental effects, repeatability, sensitivity, and lay-out issues.

Radar method for safeguards seems to be limited to building confidence on reported as-built information and on geological features around underground rock rooms. This would be possible from limited volumes owing to technical access and rock mass conditions. Partial verification of the absence or disclosure of non-reported features is possible. The origins of all of anomalies can not be verified in a conclusive manner without supplementary measurements. The nature of observed reflectors can act as indicators of geologic media behind covered surfaces.

Preface

This report has been compiled in JP-Fintact Ltd. at request of Finnish Radiation and Nuclear Safety Authority (STUK), to assess the geophysical radar method applicability to the National or International (IAEA) Safeguards System with respect to the possible verification of the design information on Olkiluoto repository. Report forms a part of the Regulatory Research and Development Programme in Nuclear Waste Management commissioned by STUK. The work included localization of radar method for Olkiluoto host rock properties and evaluation of previous radar surveys. Also assessment of the possible design for monitoring work in the planned repository using radar methods was done.

The contact persons on STUK side were Dr. Olli Okko and Mr. Juha Rautjärvi. Work was conducted by Dr. Pauli Saksa (theoretical aspects and safeguards application), Mr. Eero Heikkinen (site investigations and technical aspects) and Mr. Tomas Lehtimäki (numerical modelling) from JP-Fintact. The authors have a dozens of years experience of geophysical and geological investigations for spent nuclear fuel disposal, and engineering geophysics in hard rock environment, and on the radar method.

The authors wish to thank the contact persons, and also Dr. Esko Eloranta of STUK and Mr. Turo Ahokas of Posiva, of their valuable suggestions, constructive review and comments during the work.

Contents

1 Introduction

The objective of this report is to present an assessment of applicability of geophysical radar method in safeguarding underground repositories. Both ground penetrating radar (GPR) and borehole radar types of measurements are considered. This report localizes the concept to Olkiluoto bedrock properties and to the current spent fuel disposal concept. The high level spent nuclear fuel disposal into the bedrock has been studied in detail in Finnish, Canadian, Swiss and Swedish projects over several decades. The investigations 1985–2000 demonstrated the Olkiluoto investigation site and its geological conditions suitable and feasible with respect to long-term nuclear safety (Safety Case) and constructability. The decisions upon the disposal have been based on extensive site characterization programme carried out on six candidate sites (Anttila et al. 1999, McEwen & Äikäs 2000), selected over a hundred of potential land areas in Finland.

The geological disposal of spent nuclear fuel is a task accepted by Finnish legislation. The State Council of Finland (Government) issued and Parliament of Finland ratified a Decision in Principle in 2000 on the disposal deep in the bedrock in Olkiluoto. Posiva Ltd. is the company carrying out the nuclear fuel waste management, R&D tasks and construction related to the safe disposal. Current activities aim at construction of the access tunnel and rock characterisation premises, named as ONKALO, reaching depth of –420 m during 2004–2007. Drill and blast excavation of access tunnel has commenced in August 2004. Before the construction of ONKALO underground tunnels the bedrock in Olkiluoto repository area contained no man-made structures or access routes, other than 33 deep boreholes 56–76 mm in diameter (Posiva 2003a). Underground spaces for low- and intermediate waste (VLJ) storage cavern is located a few kilometres apart and situated in the westernmost part of the island.

Underground facilities for final disposal create a new challenge to the safeguards society. The main concern is that in connection to safe disposal of nuclear materials in the subsurface, there is a need to have a credible assurance about the absence of safeguards-relevant activities; i.e. undeclared rock rooms or access routes (tunnels and large diameter boreholes), reprocessing or diversions of nuclear material in the geological medium, although the nuclear materials are not accessible or re-verifiable using the traditional safeguards technologies. Therefore, new technologies and approaches have been proposed by the Expert Group SAGOR (Safeguards for the Final Disposal of Spent Fuel in Geological Repositories) supporting the IAEA (1998). Satellite imagery and geophysical (mainly seismic and electromagnetic) methods are suggested to have a significant role in safeguarding the repositories during construction and operational phase. These methods were evaluated by Okko and Rautjärvi (2004) and are applied accordingly by the National Safeguards System already in the pre-operational phase of the Finnish repository. The radar method has been considered for verification of as-built information from the underground repository volumes.

Geophysical methods are widely applied in the site characterisation programmes to determine rock mass properties and delineate suitable rock volumes to dispose of highly radioactive spent nuclear fuel materials at the proposed repository sites. It is proposed by the IAEA that “safeguards are not expected to introduce any additional monitoring requirements” to the overall safety monitoring in the pre-closure phases of the repository (IAEA 2001). In order to fit this framework, several methods applied in safety monitoring are understood as proven technologies in the Experts’ meeting on the use of geophysical techniques for safeguarding geological repositories. The main constraints on the use of geophysical monitoring techniques for safeguards applications are defined as follows by the IAEA (2000):

- Does not impact the repository safety envelope.
- Can discriminate declared activities and baseline conditions from abnormal activities.
- Has a low false alarm rate.
- Maximizes efficiency of use of inspector resources through remote monitoring, automated analyses, and random inspections.
- Can be implemented by a well-trained safeguards inspector with back-up support from a specialist in geophysics, as appropriate.
- Fast and easy positioning of equipment with short measurement times (to permit monitoring of large areas), if the equipment is permanently installed.
- High reliability, rugged, and long mean-time–between–failures.

It is desirable, that the new safeguards instruments with minimal operator-dependent parameters could be used by non-professional personnel. In contrast to this, it is typical to geophysics that there are many parameters to be optimised and tested at the survey location for the site-specific circumstances. In a geophysical survey expert judgement is required at several stages of a survey; e.g. at selection of method, its field parameters; selection of processing and interpretation techniques; and finally the selection of the desired print-out parameters with target-oriented illuminations. These parameters have to be selected to support the method's ability to detect the target and its characteristics. The practical safeguards applicability of several geophysical methods is recently described by Won et al. (2004). As the geophysical methods record the earth's local and complicated physical response to the source field applied, the inverse solution is generally non-unique. This implies that multiple earth models can produce almost identical physical response.

Several geoelectrical methods were evaluated regarding their applicability for international safeguards purposes, in particular for an application in underground repositories for final disposal of spent fuel (Seidel et al. 2004). Only the detection capability of the GPR was considered to be studied in detail. The model calculations indicated that the GPR can be applied with sufficient resolution to obtain reflections originating from openings within a detection range of up to 20–30 meters. The final site-specific assessment requires test measurements in the site-specific conditions, including technical efforts and possible disturbances of the respective repository.

Potential on application of radar method for safeguards is based on the fact, that tunnels, large diameter boreholes and man-made structures exhibit themselves as anomalous features to distance of several tens of meters and even up to hundred meters in hard rock environment. The key to apply radar is to recognize any possible tunnel or gallery responses from abundant natural reflectors ("the baseline") as well as with possible repeated measurements, to distinguish the already existing and reported rock facilities of pertinent as-built information from any possible non-reported activities.

The radar method has been applied intensively in Finland for large variety of purposes over three decades (Saksa 1985, Peltoniemi 1988, SGY 1992). In this report, surveys carried out to characterise rock volumes at Olkiluoto are analysed for the site-specific safeguards application and realistic site-specific values as recommended by the Expert's Group meeting at Rauma and Olkiluoto (Okko 2003). The rock characterisation programme at Olkiluoto (e.g. Posiva 2003b) has generated petrophysical data of the local rock types which facilitates the assessment. The effects on the resolution of the GPR method due to estimated technical efforts and disturbing signals are also evaluated by the use of the reported experience in the application of the GPR in circumstances of the Olkiluoto site. Use of radar tomography is outside the scope of the defined task.

The questions set with respect to the compilation of this report were:

1) Can the GPR method be applied in safeguarding Olkiluoto repository site to routinely and systematically disclose any suspect of deviation from reported activities,
2) Can the GPR method be applied for cases, where specific properties are re-evaluated on demand,
3) Assess and report the site properties having effect on radar method,
4) Analyse the method applicability against Olkiluoto bedrock properties and construction lay-outs,
5) Estimate available best practices for radar surveys in safeguards applications.

2 Radar method

2.1 Theory and principles

Radar method belongs to the group of geophysical electromagnetic techniques which utilizes the electromagnetic field generated in an active manner. Both ground-penetrating radar (abbreviated as GPR) and borehole radar are implementations of radar method. In general terms the propagation of electric and magnetic vector fields E and H in an isotropic homogeneous medium are governed by the Helmholz equations:

$$\nabla^2 E + k^2 E = 0 \quad (1)$$

$$\nabla^2 H + k^2 H = 0 \quad (2)$$

and in the equation above the time dependency of the electromagnetic field is of the form $e^{-i\omega t}$. In equations (1) and (2) the term k is the wave number (called also as propagation factor) and is expressed as follows:

$$k^2 = \omega^2 \varepsilon \mu + i\sigma\mu\omega \quad (3)$$

Propagation factor determines important factors of electromagnetic field-like form of wave propagation, attenuation and reflection. Equation (2) contains several terms: angular frequency $\omega = 2\pi f$, where f is frequency (Hz), electrical conductivity of the media σ (reciprocal of resistivity ρ, unit Ωm or ohm-m), dielectric permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$ and $i = \sqrt{-1}$. The influence of magnetic susceptibility is contained into magnetic permeability $\mu = \mu_0 \mu_r$. In definitions above εr and μr are relative dielectric permittivity and relative magnetic permeability of the media, respectively. Factors ε_0 and μ_0 are respective values for the vacuum.

It is important to note from the very beginning that the electrical properties σ and ε of the rock are dispersive which means they depend on and are varying with the applied frequency (for example, Olsson et al. 1987). Typically the magnetic permeability μ is regarded to coincide that of vacuum (μ_0).

The behaviour of the electromagnetic field is described by ratio of the real and imaginary parts of the wave number, defined by parameter $Q = \omega\varepsilon/\sigma$. In the low frequency range when $Q << 1$ the electromagnetic field is diffusive in its character and main response given rise is induction. When the frequency gets higher and parameter $Q >> 1$ the electromagnetic field behaves differently and propagates in wave form. In practice this requires the use of Megahertz (MHz) (radio) frequency range – up to several Gigahertz (GHz) – when earth media is concerned.

The electromagnetic field behaves also differently at varying distances from the source (normally electric dipole antenna). The behaviour is described by term $|kr|$. In the near-field range of the antenna (source), when $|kr| <= 1$, the wave radiation pattern varies strongly and the emitted propagating wave is not of plane wave type. The far-field range of is reached when $|kr| >> 1$. The analysis of the radar wave reflection, propagation and other events taking place at boundaries of electrical properties is based on assumption of validity of the far-field condition. In this situation model calculations can use simplified formulation for plane waves. Thus, in the near-field range the principles of interpretation are not valid without consideration of the wave field and consequences possibly created.

In the range of radio wave frequencies the dominating processes and events are transmission, attenuation, refraction and reflection. Radar in ground investigations gets benefit of the processes involved and recorded waves are processed and interpreted to deduce knowledge about subsurface properties and objects. In the processing and interpretation of radar results it is assumed that the propagation of electromagnetic energy as radio waves is valid.

Radar wave propagates in a medium with a velocity v given as

$$v = c / \sqrt{\varepsilon_r} \quad (4)$$

and the wavelength λ of the propagating radar wave is given by formula

$$\lambda = c / (f \cdot \sqrt{\varepsilon_r}), \quad (5)$$

where c is the velocity of the light $2.998 \cdot 10^8$ m/s in a vacuum. When the crystalline rock mass is considered, typically ε_r is 5–10 and consequently radar wave velocity is about one third of the velocity in air and wavelength some decimetres or meters. In rock mass with $\varepsilon_r = 6$, wavelength is 2.4 m, 0.6 m or 0.24 m when frequency is 50 MHz, 200 MHz or 500 MHz, respectively. Wave velocity is in this case 122.4 m/µs (microsecond) or 0.122 m/ns (nanosecond) as typically expressed in practical units.

Magnetic susceptibility κ has been measured in deep boreholes of Olkiluoto. Relative magnetic permeability is defined in terms of susceptibility as follows:

$$\mu_r = 1 + \kappa \quad (6)$$

For narrow sulphide-bearing sections in Olkiluoto the magnetic susceptibility can exceed 10000 µSI, which will affect (reduce) the velocity more than 1%. Remanent magnetization is also present in the rock mass of the area.

2.2 Measurement techniques

Radar method is a sounding type of geophysical surveying technique. It is used in two basic ways: as ground-penetrating radar (GPR) in surveys conducted along surfaces and as borehole radar.

Surfaces include ground surface, buildings, tunnels and generally any open space accessible. Borehole radar is configured to subsurface borehole and well geometries and conditions. Main characteristics of the implementations are:

GPR:

- Mono-static (one antenna acting as transmitter and receiver) and bi-static (separate antennas with various offset distances) configurations are used
- Antenna design has more freedom because open space can be utilized in surveying and instrumentation
- Portability is important and has influence on transmission power, power source, size and weight and field suitability/handling.
- Shielded and unshielded antennas are used depending on particular survey.
- Reflection measurements are mainly carried out along lines

Borehole radar:

- Bi-static antennas are used, tools are required to be water-proof
- Antenna design is restricted by space and conditions of boreholes and wells
- Long cables and winches needed, portability is not a major issue
- Space available in borehole is a limiting factor
- Unshielded antennas
- High data transmission rate and system control over long distances is needed
- Single-hole line reflection measurements are mainly carried out, but surface–to–borehole and borehole–to–borehole can be utilized.
- Tomography measurement apply transmission of radar waves and is possible between near-by holes or underground facilities (20–300 m apart, depending on attenuation and frequency)
- Good coupling to bedrock has to be arranged
- Primary signal is easily ringing in borehole fluid, requiring processing

Two main measuring modes exist: reflection measurement and transmission measurement. Reflection measurement is the main type of utilization of the radar method. Reflection measurement is useful because it provides an easy to understand and visual result reflecting directly subsurface object boundaries. Example is given in Figure 1 where measurement line is horizontal and radar pulses are plotted against time in vertical section and amplitudes are displayed as a grey scale colour tone. Some wave reflections are emphasised with a red marker line. It is also valid in a majority of situations that subsurface objects do encompass differences between their physical properties and thus give raise to wave reflections.

Radar method uses mainly pulse type of transmitted signal which is continuously transmitted and resulting response signal within the specified time window is recorded. Pulse is repeated continuously for stacking and to achieve desired coverage along the measurement profile. Stacking depresses non-coherent noise and improves the signal–to–noise ratio. The form of pulse radar signal is shown in right part of Figure 1.

The reflection measurement can be performed as point reflection mode (repeated continuously on a profile), or as a Common Mid-Point (CMP) sounding, which is typically used for velocity determination. The latter can be also applied for geometrical stacking, when CMP soundings are repeated over a length of profile, e.g. with a multi-channel tool.

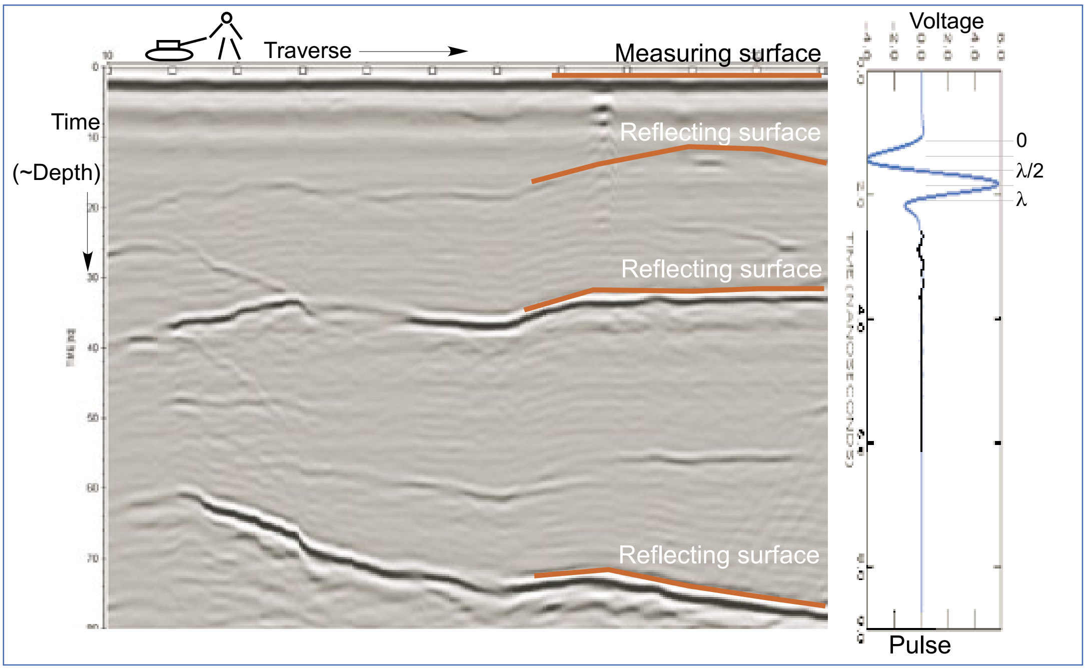
Transmission measurement is used mainly in form of tomography which means that radar wave scans of rays are measured to deduce properties over the plane scanned. In reflection measurements wave transmission between transmitter and receiver along the borehole can be measured. Both time delay and attenuation of the radar pulse carry information of physical variations of the medium.

Radar equipment consists of control unit, power source and antennas. Control unit is connected to computer to allow permanent data storage and further processing. Control unit can also self-contain data storage, display and processing capability. Typical frequencies used in GPR equipment are between 50 MHz–1 GHz. Borehole radar equipment has utilized frequencies between 22–250 MHz. Power used in radar antennas are reported to be in the range of 30–7500 W, borehole radar about ~500 W (SGY, 1992).

Normal type of transmitting antenna is a resistively loaded electric dipole. Dipole radiates most intensively to directions perpendicular to dipole axis or close to it. The length of the dipole can not be shorter than a few parts of the wavelength to be functional. For high and versatile frequencies, a TEM (transient electromagnetic) horn antenna types have been developed (e.g., Millard et al. 2003).

The transmitting antenna is excited by a Gaussian pulse whose width determines the centre frequency of the signal, stated as antenna frequency. Antennas are broadband and coupling to the surrounding media is optimized in design phase. Optical cables are used to avoid the interference caused by coupling between conductor cables and radio waves transmitted. Antennas can be shielded to direct the radiation or non-shielded. Shielded antennas are used in GPR measurements when it is favourable to focus radiated wave energy to ground (45 degrees cone, for example) and to avoid response from surrounding man-made and other objects. For example, metal objects can reflect radar waves from long distance through air. Tunnel walls and roof reflect waves back, too.

Non-shielded antenna is used in borehole meas-



file: radar example fig.CNV

Figure 1. Basic radar surveying, reflection image and example of radar pulse.

urements where electrical dipole placed along borehole axis radiates to all directions. However, the radiation along the borehole direction (along dipole axis) is very limited.

Example Figure 2 illustrates GPR measurement along a measurement line or along a borehole. Radar traces are collected to a sequence. Resulting radar image (reflection map) is an image where traverse forms one axis, time/distance another and radar wave amplitudes are plotted. Transmitter and receiver can be at the same point or have constant separation. Part of the figure on the left depicts basic processes involved in wave propagation and typical related targets. Right part includes a radar image in a grey scale representation. In radar image shapes of anomalies resulting from a reflecting point or small volume, parallel surface and intersecting surface are pinpointed as coloured lines.

Propagation time is converted to distance. Terms depth, distance or radial distance as used called. However, terms are only exactly valid in certain geometric situations. Normally – as Figure 2 also displays – waves can traverse various routes and real depths from the surface or distances from a borehole vary. Wave velocity may differ in volumes of rock because dielectric permittivity varies but conversion of time to distance applies one constant value. In addition, responses from various incoming directions in space are summarised in radar image presentation presented on a plane.

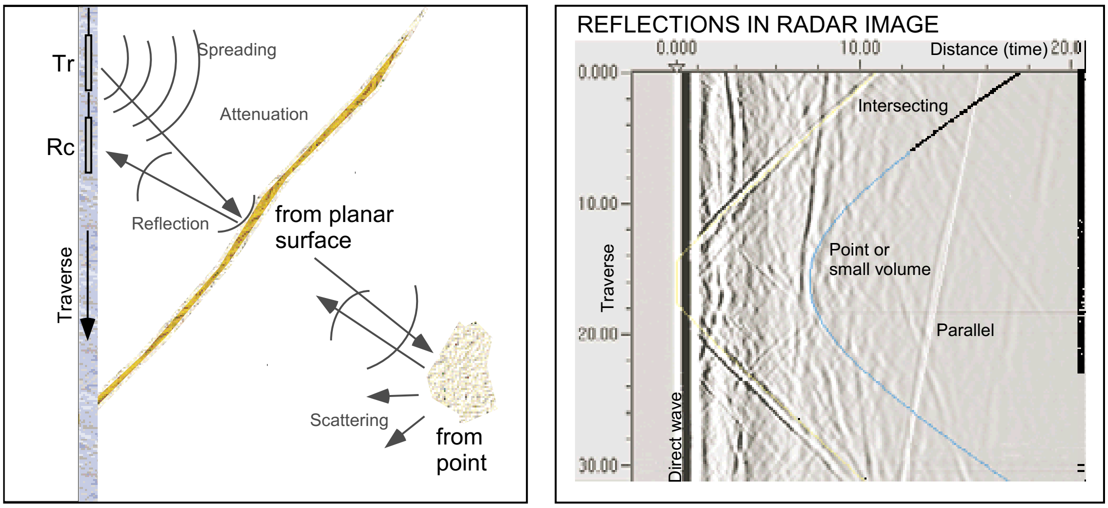
Radar wave frequency and consequently antenna are selected according to the surveying range (depth), subsurface conditions and the level of detail to be covered. Further on, accuracy, detectability and resolution needed are considered. Frequency selected determines the antenna to be used because antennas are tuned to earth conditions.

Either a single antenna for transmitter and receiver can be used (zero offset), or two separate antennas with a defined offset. The offset should be adjusted optimally for the intended target depth. Offset s can be defined as (7) at air–to–rock boundary:

$$s = \frac{2 \cdot \text{Depth}}{\sqrt{(\varepsilon_r - 1)}} [\text{m}] \tag{7}$$

Antenna offset needs to be large enough to avoid direct wave saturation. Optimal offset to detect an object perpendicular to survey line is 20% of the depth, and the offset should not exceed 50% of the depth not to distort the images of the specific target. Increasing the offset will reduce the depth accuracy of objects, but not significantly before the offset is more than half of the target depth (Sensors & Software 1999). Reflections and detection sensitivity of small objects are decreasing with larger offsets, which might be advantageous for tunnel and cavity detection.

Directional radar has been developed from omni directional borehole radar (Falk 1992). Directional radar uses electric dipole as a source and receiver part is formed by two magnetic induction loops. Arriving electromagnetic radar wave induces currents (electric field) to loops which depend on the direction of wave propagation. Responses induced to two perpendicular loops are analysed to solve the direction of wave front. Comparison with electric field dipole antenna signal is used finally to choose



Transmitter = Tr, Receiver = Rc

Figure 2. Radar reflection measurement lay-out and radar image.

between two directions, angle of 180° between them. Directional radar is currently a special tool and available in limited extent.

2.3 Radar waves in host rock

2.3.1 Propagation and attenuation

Radar wave propagates as a plane wave in far-field range from the source. Plane wave means that 2-D wave front has equal amplitude and phase on a plane surface perpendicular to the direction of wave propagation. Accordingly solutions for secondary events caused by wave excitement are easier to calculate.

The attenuation of the plane wave can be defined by using skin-depth as practical parameter to express it. Attenuation is important parameter in consideration of the radar method because it controls the surveying range which can be reached. Skin-depth δ is the distance along with the wave amplitude attenuates down to 37% (1/e) of its initial amplitude. Skin-depth is related to resistivity and dielectric permittivity of the medium as given below:

$$\delta = 2\rho\sqrt{\varepsilon_r} / Z_0, \qquad (8)$$

Where Z_0 is the characteristic impedance of the vacuum $120\pi\ \Omega$. Skin-depth decreases when the rock mass resistivity ρ decreases. This takes place when bedrock fracturing increases, rock porosity increases, the salinity of the groundwater gets higher values and electrically conducting minerals occur in the rock matrix. The increase of the value of relative dielectric permittivity ε_r increases the skin-depth.

Geometric attenuation takes place as radiated energy spreads to larger distances and volumes. Wave amplitude decreases both exponentially (geometric attenuation) and by media attenuation in the near-field of transmitter and as 1/r in the far-field (media attenuation).

However, there is additionally one important phenomena having influence, that is the dispersivity of electrical conductivity (resistivity) and permittivity. It means that both parameters are frequency dependent so that $\sigma(f)$ and $\varepsilon_r(f)$. According to the petrographic sample measurements and literature electrical conductivity is increasing with resistivity, roughly as $\sigma(f) \sim \sqrt{f}$ (Saksa 1985). Dielectric permittivity can slightly decrease with increasing frequency but as reported by Parasnis (1983) has varied less than 10% when frequency increased from 1 MHz to 100 MHz, for example. More detailed discussion of earth properties is in Chapter 3.2 with particular focus to Olkiluoto site in Finland.

Wave attenuation is important parameter that can be utilized both in reflection and in tomographic measurements. Attenuation contains information on permittivity and resistivity variations in rock.

Attenuation ΔV can in certain situations be measured and is expressed as decibels per meter (dB/m) according to (9)

$$\Delta V = -20 \cdot \lg_{10}(A_0 / A_1) / d \qquad (9)$$

The magnitudes of amplitudes are A_0 at transmitting point and A_1 at receiving point (usually measured as voltage), having distance d (m) between them. Value in decibels per meter is useful as it is easy to compare with signal strength and dynamics of the measuring instrument. Attenuation of –20 dB means that wave amplitude is 1/10 of the initial value. Attenuation can be measured also over fixed distance, unit dB/m. The amplitude A_0 at transmitting source point is generally not known.

Attenuation and wave propagation depend on the applied frequency. There are related factors which should be recognised: Frequency fixed is a nominal frequency. In practice a radar pulse wave envelopes a frequency band and it has a central frequency lower than nominal frequency in rock. Figure 3 from

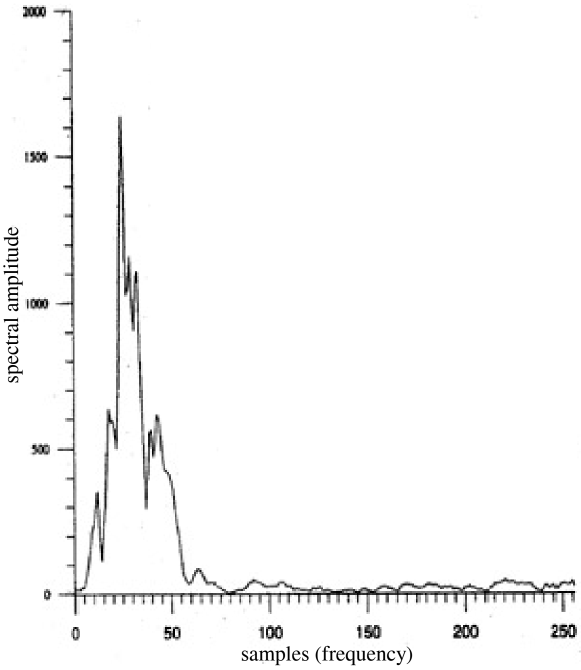


Figure 3. Signal spectrum from dipole component of directional 60 MHz antenna measurement on OL-KR10 borehole at 230 m depth. Frequency in samples in horizontal scale, amplitude in vertical scale (Carlsten 1996).

Olkiluoto results displays a real central frequency about 30 MHz when nominal frequency is about 60 MHz (Carlsten 1996). The radar pulse covers also a certain frequency band.

The radar waves are attenuated as they propagate through the rock. The amplitude of each frequency decreases, greatest loss in high frequency energy. In time domain this shows up as broadening of the pulses. Example from Olsson et al. (1987, p. 83) is given in Figure 4 from Stripa site granite rock. Significance is in the fact that the source signal must be considered as it is in geological media, not at transmitting location. Further on this is linked to reflection and detectability factors of interest.

Small point like perfectly reflecting area as a target is a minimum size of an object that can be considered to be detectable in reflection measurements with radar. Model of point reflector can be used to estimate the depth range which is possible to reach with radar reflection measurements. The attenuation caused to the reflected power from the point reflector depends on media properties (skin-depth δ), wavelength λ used and distance between source and reflector (R). This can be expressed as given below (Olsson et al. 1987):

$$a\,[\mathrm{dB/m}] = -20 \cdot \lg((1.6\lambda)^2 \cdot e^{-4R/\delta} / (4\pi)^3 R^4) / 2. \quad (10)$$

Geometrical attenuation depends strongly upon the distance R, raised to the power of four. Attenuation caused by the media is exponential. Wavelength can be increased (decreasing frequency) to reach larger distances but at the same time the size of a small reflector detectable increases and practical limits of radar systems are intrinsic.

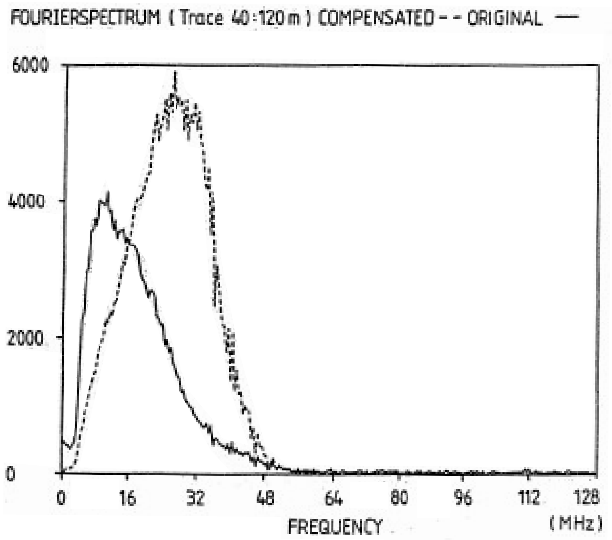


Figure 4. The Fourier spectrum of a borehole radar pulse that has propagated 120 m through rock (solid line), crosshole mode. Nominal centre frequency of transmitted wave was at 22 MHz (Olsson et al. 1987). Dashed line represents AGC corrected spectrum.

Similar limitations apply to the increase of system antenna power. Two times increase in power increases range 20% and five times increase in power, makes the radar range 50% larger. However, reflections from noise causing objects increase and new ones can be enclosed by added range.

2.3.2 Reflection and related events

A basic model for a reflection is an electrical contact between two media 1 and 2 having wave numbers k_1 and k_2. Radar wave propagates from media one to media two and arrives as a plane wave in perpendicular angle to the contact. In this case the ratio of reflected E_{r1} and incident E_{i1} electrical field components (amplitudes) take the form

$$E_{r1} / E_{i1} = (k_1 - k_2) / (k_1 + k_2) \quad (11)$$

In typical crystalline bedrock case variables k_1 and k_2 are complex. Both electrical conductivity and relative permittivity changes do affect. Complexity of k_1 and k_2 means that phase shift takes place at reflection boundary also. In certain situations only variations of relative permittivity may govern the reflection.

Calculation of reflection amplitude and phase shift with formula (11) is fairly applicable for scoping and safeguards purposes. The contrasts between host rock and air/water filled underground room space is large. Reflecting surface resembles a contact as it radiates back much of the arriving wave energy.

Reflection and its detectability from a layer or from a boundary in general case is more complicated to calculate. Distance and media properties are having importance in this. Also the reflection coefficient, layer thickness, reflection angle and prevailing modes of the electromagnetic field (TE- or TM-modes) have their effect on wave reflected.

In geologic media large range of electrical conductivity and permittivity values are possible to be accounted. In surveys related to safeguards surveys targets as man-made structures can be set to known values. Host rock has typically high or medium resistivity; low resistivity does not support propagation of radar waves. In rock rooms resistivity is very high for air filled and low or very low for water filled space. Dielectric permittivity is known and fairly stable for host rock. In rock room permittivity is 1 for air filled and 81 for water filled conditions.

Large contrasts assure that large portion of wave energy is reflected back from the target. Emphasis can be put to geometric considerations of the targets and to study how the hosting media influences the use of radar and how field conditions are best utilised.

The phase shift on boundary reflections may be indicative on the material properties, e.g. air and water behind a rock mass may reflect the wave back at different polarity. This case would need further examination and model calculations.

There are also other events that happen in geological media and influence radar results. Refraction of propagating wave occurs at the surface for the particular part of the wave which is transmitted further in media and not reflected. Refracted wave can in turn be reflected back or refracted consecutively at electrical boundary. Diffraction is one phenomenon which takes place at edges and scatters energy as reflections. Diffractions are indistinguishable from reflections on the basis of character. The amplitude of diffraction is a maximum at some point along profile and decreases rapidly as distance from this point increases. Diffractions can be a basis to detect and distinguish man-made objects from natural reflections. On the other hand, amount of diffracted energy can be reduced with increasing transmitter and receiver antenna offset distance, with geometrical stacking of signal, and with reducing the frequency.

2.3.3 Detectability and resolution of objects

Detectability and resolution are two essential terms which have to be considered in connection to radar method. They are especially important when the potential application to safeguards surveying is considered.

Detectability of objects in the subsurface depends upon their size, shape, and orientation relative to the antenna, contrast with the hosting medium, as well as noise and interferences inherent.

Detectability can be considered geometrically as the smallest size which can be observed with the specified radar unit. Typically the target needs do have a size of about one wavelength at least along one dimension which should align with the arriving electrical field vector. Other dimensions can be much smaller than the wavelength. Thus a borehole filled with electrically conducting fluid or long metal rod can be detectable with borehole radar up to certain distance. Small cavity ($^1/_{10}$ to $^1/_5$ of wavelength) is probably not detectable.

Thickness of observable unit has typically a limit about $^1/_{10}$ of a wavelength ($\lambda/10$). When thickness is less than that reflections from adjacent boundaries are opposite in sign and suppress each other strongly. Decrease of thickness below ¼ of a wavelength which equals the rise of the wave amplitude (see Figure 1 right part) to smaller values causes reflections to get smaller (for example Widess 1973 or Okko 1989). However, strongly reflecting surface (like a metal sheet) has no limit of minimum thickness because the first surface reflects back most or all of the arriving energy.

Second issue related to detectability is that the response originating from the object should exceed the level of noise present. This aspect is discussed more in chapter signal–to–noise ratio below (Chapter 2.3.4).

Resolution is the smallest distance between two near-by objects which can be differentiated from the results. Axial resolution (along the measurement profile) is very likely close to the value of detectability or larger than that. If two objects having size of about one wavelength situate closer than that to each other, the response is summarised and it is not possible to discriminate between two objects or one larger object.

Radial (or along the distance scale) resolution with radar using pulse type of signal is (Peltoniemi 1988)

$$H = \tau c / 2\sqrt{\varepsilon_r} \qquad (12)$$

which can be also expressed as

$$H = (\tau v) / 2$$

where τ is the width of the radar pulse in nanoseconds (ns), when velocity is expressed as meters in nanosecond. H is the smallest distance between two objects that can be separated along the distance scale. Short pulse in time duration and low permittivity host media improves radial resolution between two near-by objects. Formula (12) states that radial resolution is about half of the wavelength used or slightly more.

Typical value for H is 1.2 m when v = $122 \cdot 10^6$ m/s and τ is 20 ns (one wave length peak–to–peak). Pulse length of 20 ns would correspond to one wavelength at 50 MHz in Olkiluoto conditions. In practice the pulse is longer than ideally considered. Radial resolution increases and the value of H decreases (improves) linearly when frequency increases. Thus at 500 MHz radial resolution is about 0.12 m.

Sampling will affect the resolution and detection ability. Typically the radar signal is sampled 10-fold or more for each wavelength (0.3–0.5 ns).

2.3.4 Range and signal–to–noise ratio (S/N)

Instrument and system characteristics determine the absolute minimum signal that can be recorded. Any signal that is detectable from the noise can be useful in principle. Typical current radar tools with 16 bit data resolution and gain functions would allow dynamic range of 110–140 dB, being highest for borehole radar tool, about 135–140 dB. Dynamic range is limited by instrumental properties – like system losses, antenna efficiency and power – and ultimately set by noise obeying physical laws affecting electronics.

For a reflection to be detected above random noise level, the reflected amplitude should exceed the noise level, or lowest detectable signal, by a factor of 2 (–6 dB, so called S/N ratio, signal–to–noise). Summing of pulse signals (stacking) at (close to) a same location is a customary way to enhance the S/N ratio. The random noise would average out, and coherent signal will increase in level to some extent. Typical stacking ranges from 8–64 fold, but can exceed ratios of several thousands. High stacking rates can slow down the measurement.

Large noise components can generate from rock mass heterogeneity or from urban origin. Noise is the part of the signal which can not be interpreted or utilized at the time of consideration. In that sense all anomalies from geological targets not interpreted or explained are noise. Even interpreted geological features can be noise from safeguards point of view if they may obscure targeted objects. Noise and its character in the frequency spectrum should be analyzed at site conditions.

Recognition of radar reflection features relies on continuous and characteristic patterns that events across adjacent traces form. It is difficult to distinguish between noise and useful information if single or a few radar traces are only inspected, example in Figures 15 and 16. When radar images are studied as a composite of traces even very low amplitude reflection events can be distinguished from noise.

One way to increase the signal level is geometrical stacking, which would suppress not only random signal noise, also diffractions and scattered local reflections from small targets. The Common Midpoint (CMP) stacking can be performed and multichannel tools used.

The range can be enhanced to some extent by adding the transmission power. For two-way reflected wave, considering the dynamic range of signal, increasing the initial power two-fold would increase the depth range 20%, and a five-fold increase in power 50%. Increasing the transmission power from fairly standard 30–60 W to 2.5 kW (50–100-fold) may substantially add the range, but increase also the harmful air and wall reflections. At the same time range to receive reflections from noise causing objects increases, for example from objects inside tunnel but further away.

The tunnel reflections, and reflections from ventilation, lighting and electricity installations, are discrete sources of noise, possibly masking certain slice of time window, having certain frequency band or varying in frequency and time. Typical example can be near-by wall or cable, distance to it varying or staying as constant. Electromagnetic noise can also hamper recording on certain frequency band. Swinging of antenna during measurements due to e.g. roughness of the wall will cause distorted traces into the radar images.

2.4 Earth and material properties

The electrical material properties relevant for radar are the dielectric permittivity and resistivity of the rock. They display variability according to rock type and presence of *conductive minerals*, presence of *porosity* and *fracturing*, and finally the *alteration* and mineralogy of *fracture infillings*. The *degree of saturation* with water, the *salinity of water*, and variation in porosity or fracturing intensity will also affect to the net propagation of radar waves in the rock mass. Those are considered as bulk properties of rock mass over intervals of several tens of meters.

The increase of water content in the rock mass

Table I. Physical parameters for GPR and borehole radar investigations.

Medium	Relative dielectric permittivity	Electrical resistivity (galvanic), Ohm-m	Radar velocity
Air (vacuum)	1	>> 1.000.000	299.8 m/µs
Water	81	< 200	33.3 m/µs
Ice	3.2	~ 200	167.7 m/µs
Gneiss	4–8	5.000–200.000	117 m/µs
Granite	4–8	20.000–200.000	
Gabbro	8.5–13	1.000–1.000.000	
Schists	4–8	100–10.000	
Salt formations	~ 5	30–1.000.000	
Limestone	8–12	50–10.000.000	

will increase electrical permittivity (and decrease wave velocity) as well as decrease resistivity (increase wave attenuation). The changes in resistivity and permittivity depend on rock parameters underlined in previous chapter and the net influence needs to be calculated and estimate case by case. The order of magnitude of the differences can be stated, e.g., that when the resistivity decreases to 1/10 of the original value of granitic rock, permittivity will increase from 5 to 10, due to obvious increase in porosity and water content (Saksa 1985).

Some values of dielectric permittivity, electrical resistivity and wave velocity from different media and from site investigation observations are presented in Table I.

Changes in the earth properties may take place after the tunnel excavation. The support structures, like grouting of fractures, would decrease the amount of water in bedrock and thus enhance the propagation of radar signal, and diminish natural reflections. An example of this phenomenon is reported from a Korean Liquid Natural Gas storage, where freezing of fractures near a storage cavern (dielectric permittivity of ice is 3.2) practically prevented any reflections from a fracture to display (Kim et al. 2004).

The draining of tunnels would cause some minor drawdown effects, which probably are compensated by flow of bedrock water towards the tunnels. Nevertheless drying of walls due to hydrological skin effect may enhance the signal propagation. Oppositely, grouting and shotcrete on wall may assist gathering of water into the excavation damage zone, which would weaken the signal propagation. Most influence would be caused by possible up-coning of saline groundwater, due to drain of groundwater in tunnels. This would reduce the radar range at the Olkiluoto case.

Relative permittivity of concrete is strongly dependent on humidity of the material. Tests have been made (Millard et al. 2003) at frequencies 300 MHz–3 GHz with a wide band TEM horn antenna and inverse modelling, where the permittivity has ranged from 8–12 (86–106 m/µs). Under air the surfaces of concrete slabs are drying more and display lower permittivity. In underground conditions, the shotcrete layer or cast concrete on a tunnel wall or floor will saturate with water, and increase the permittivity. Age of the concrete may decrease the permittivity, due to further drying process. Porosity of the concrete mass is nevertheless greater than the surrounding host rock.

The resistivity of the concrete at radar frequencies is lower than that of the surrounding bedrock, and may range from 3–30 ohm-m depending on frequencies applied and water saturation. A concrete layer will attenuate radar signal in a similar manner as a soil layer would.

Concrete grout in the fractures has thus a lower permittivity as the water filling, and may even enhance the radar signal propagation.

Rock stability is enhanced with steel bolting and welded mesh wires. Concrete wall structures include very often either a steel mesh, or steel fibre reinforcement. These increase the conductivity of the structure substantially and may totally prevent the use of radar method. Rebar structures in concrete slab floors or plugged tunnels imply a similar influence.

2.5 Processing and interpretation

2.5.1 Processing

Processing of radar measurements results involves several steps to connect results to geographic coordinates and to compensate effects inherent by instrumentation itself and subsurface physical processes. Modern GPR systems have GPS connectivity and recorded coordinates are attached to radar traces. Also measuring distance along the line can run simultaneously with radar sounding. Measurement can be realized as time based where tie markers with known positions are added into measurement data.

Primary processing steps include:

- Arrangement and adjustment to line and point coordinates
- Topographic variation (surface variation) adding and/or removal
- Determination of average dielectric permittivity (time to depth conversion)
- Compensation for geometric attenuation
- Compensation for attenuation in media
- DC level adjustment
- Band-pass filtering (removal of high and low frequency noise)
- Presentation in various colour scale images or as wiggle-trace plots.

Determination of average radio wave velocity allows conversion from time scale to distance scale. Further on, average dielectric permittivity can be calculated (formula 4). There are several ways to get information on the wave velocity:

- There is target at known distance in reflection measurement
- Object like a horizontal layer is measured with CMP sounding (Common Mid Point where transmitter and receiver is moved in respect to stationary middle point)
- Fitting a hyperbola to point like reflector, where the asymptotes (branches) of the hyperbola will depend on velocity, i.e. permittivity
- Receiving antenna is moved away from transmitter (in borehole measurement, both reflection and tomography surveys)
- Conical TEM horn antenna survey, applying several frequencies
- Petrophysical sample measurement in laboratory
- Literature values as first estimates.

Preceding primary processing steps are executed after most radar surveys. Results are practically ready to be analyzed and evaluated after that. Most of the reflections are visually recognizable and to be analyzed, some additional improvements can be attained in further processing. Commercial radar processing and interpretation software packages contain the processing functionality needed. Multiple lines and large amounts of data can be processed in a batch mode.

Additional processing steps may include:

- Removal of noise (improvement of S/N ratio), band-pass filtering; stacking with CMP or by trace
- Subtracting the average, to remove direct waves and enhance oblique features, if necessary
- Amplitude gain correction
- Moving average filtering
- Median filtering (trace by trace or as 2-D filtering)
- Deconvolution filtering
- Correlation filtering
- More complicated filtering like f-k (in frequency–wave domain)
- Migration to deduce directly 2-D objects and their shapes from radar image.

Direct waves, air waves and tunnel reflections, as well as multiple reflections from several planar features can be removed with specific algorithm. When geology is not of interest but present in all measurement results, it is relevant to select such measurement and processing parameters that the geological features are least affecting the actual images.

There is large dynamics of radar signal up to 130–140 dB achievable but real amplitude range is compressed during compensation of attenuation. Selection of graphic grey-scale or colour scale has a typical range of 20 dB in presentation. So the presentation scale can be varied to display all information embedded.

2.5.2 Interpretation

Interpretation of radar reflection measurements is dependent on how clearly and understandably reflections can be seen in radar image. For geological mapping purposes, realistic interpretation models mimicking geological targets are selected and applied to data. In safeguards application geological targets need to be considered but also varying forms of man-made structures need respective interpretation models.

In geological media basic interpretation models used are plane reflectors, also covering planar or curved surfaces. Also point-like reflectors (voids) and line reflectors (boreholes) are met in hard rock environment.

Plane reflectors in natural objects will represent fractures, fracture zones, dykes, and rock type or mineralogical boundaries. Point reflectors may represent cross sections of fractures, cross sections of fracture zones, inclusions, natural cavities, and pipe like shaped geological bodies.

Boreholes may appear as point-like or line sources. Tunnels act as set of planar and spherical forms, which may cause complicated and multiple reflections. Sharp corners will cause diffractions and interferences in the standard forms of reflections. The direction from where the image is viewed, will affect essentially to the form of reflection. A tunnel aligned parallel with the measurement line (wall, borehole) will be seen as a reflector parallel to line; tunnel aligned perpendicular to the line (being long in the perpendicular direction) will be seen as spherical reflection, and a tunnel approaching to the line, but terminating, will probably be seen as a weaker spherical object. Several overlapping features, specifically those mixed with known and unknown ones, may bring in higher level of complexity.

Point like reflector causes a hyperbola shaped reflection in radargram. Total distance S (two-way travel time) the wave travels from transmitter to reflector and to receiver varies according to formula (Olsson et al. 1987)

$$S = \sqrt{[d^2 + (x + 0.5c)^2]} + \sqrt{[d2 + (x–0.5c)^2]} \qquad (13)$$

where c is the distance between antennas, x is traverse (distance from location of point reflector to recording station) along measurement line and d is closest distance from the measurement line to the point reflector. Station coordinate is the midpoint between transmitter and receiver stations.

Distance can be also converted to two-way travel time easily with formula (13) when dielectric permittivity of the geological media is known. However, as it can be seen from formula 13 that the closest distance can be calculated to point like reflector without knowing the dielectric permittivity of the media, so that (Moffatt & Puskar 1976)

$$d = x_{12} / \sqrt{[(t_{r2} / t_{r1})^2–1]} \qquad (14)$$

where t_{r1} is the shortest two-way travel-time to point reflection (vertex of hyperbola), t_{r2} is two-way travel time picked from another interpretation point (along branches, or asymptotes, of hyperbola) and x_{12} is the distance between selected calculation points (t_{r1} and t_{r2}) along the measurement line.

Point like reflector can be expanded to finite radius spherical reflector (2-D rounded form of tunnel section perpendicular to the measurement line).

The data is measured and presented primarily at a time scale in nanoseconds. The conversion of data scale from time to distance is based to a constant velocity on each presented image. At true case, the velocity can vary along a profile, and in different ground layers in the profile at depth, for which reasons the depth (distance) scale is not uniquely defined and constant, but rather an average depth scale. Applying a dedicated velocity model for each layer, or velocity migration, would allow better depth accuracy in radar imaging.

Plane reflector – applicable to contacts and layers – has its distinct form of anomaly (see Figure 2) and can be expressed with simple formulas for interpretation and nomogram purposes (Olsson et al. 1987, Saksa 1985, for example). Current interpretation software available for radar includes the basic models discussed for interpretation and fitting to the data.

The information obtained from radar images are related to location and form of boundaries. The reflection measurement provides fairly limited amount of information on the properties themselves, namely electrical resistivity and dielectric permittivity. Attenuation of signal along the profile or along the borehole describes rock mass or delimit zones met and can be extracted as useful observation. The thickness of reflectors can be obtained in limited cases. Continuity of reflecting boundaries can be used in reconstruction of object geometries but use needs expertise.

Great care has to be maintained to recognize, that

1) During a first GPR sounding on any bedrock surface, there are only natural reflectors, possible excavation damage zone, and in some cases adjacent borehole visible in the radar images;

2) During the subsequent GPR soundings in same locations, any further and reported man-made activities (floor construction, adjacent tunnels and boreholes, support structures, and disposal boreholes) need to be tracked to distinguish their visible effect from possible non-reported objects;

3) Crucial task is to distinguish between natural objects, normal reported changes in tunnel design, and non-reported objects.

One of major challenges in using the GPR method to safeguards and during the interpretation is differentiation between geological and man-made objects. The false alarm rate should be as low as possible. Proper geological interpretation models based on site evaluation and *a priori* knowledge, as well as the as-built information is required.

3 Field investigation examples

There are available several cases from hard rock investigations, where the pertinent tunnel or borehole radar data can be used to indicate the possibilities of the radar method in safeguards applications. The examples depict relevant site properties, situations met and instrument parameters. Further on the examples lead to conclusions concerning applicability and possible use.

Examples are from Stripa Mine in Sweden used to design the underground investigation techniques including borehole radar (Chapter 3.1 below); the Olkiluoto site itself to provide several examples and site parameters (Chapter 3.2). One example has been included from a mine in Finland, to demonstrate observability of a large diameter borehole (Chapter 3.3). The Olkiluoto specific parameters were used in numerical modelling part studying certain investigation cases (Chapter 3.4).

3.1 Stripa Mine

The example is from International Stripa Project (Olsson et al. 1992), which aimed to methodological development of for site characterisation. The borehole surveys in Stripa Mine included borehole radar investigations, which were applied from a fan of boreholes starting from same drift (Figure 6). Rock type is granite (quartz monzonite). Radar reflection map with the visible features is presented in Figure 5. The single-hole measurement has been performed with 60 MHz borehole antenna using electrical dipole antennae with 7.5 m antenna offset and 0.5 m recording station interval.

The processed radar image in Figure 5 (suppression of direct arrival, median filtering and amplitude gain correction) indicate a number of natural reflectors (plane reflectors displayed with A, C, E, K and X) originating from hydraulically conductive fracture zones, reflections from adjacent boreholes, and strong hyperbola shaped reflection from a nearby drift. The drift is at closest 40 m distance from the borehole. Drift has a diameter of 3 meters. The direction to the drift and orientation of the drift, cannot be deduced without external information. Object resolution is of order of 1 m with 60 MHz antenna (close to the wave length).

The observed features follow geometry presented in Figure 6: The boreholes visible in radargram have been drilled from same niche. Detectability of boreholes is improved by the fact that they are drilled to same direction as surveyed hole (close to parallel) and thus are parallel to the dipolar electric field of the antenna. Directional 60 MHz radar could have resolved also the direction where the drift is located, as would also a GPR applied on tunnel wall or roof.

There are a number of natural reflectors, which are either planar, intersecting the borehole (A, C, K, X) or seen from further away of the borehole or its extension (E), or reflections from point-like or spherical objects. Each reflection has a form of hyperbola, for which the time of vertex indicates for certain wave velocity a distance of reflector, and the asymptotic angles also the radar velocity for point like reflectors, and the intersection angle with borehole for planar reflectors. The width of the base of hyperbola is related to the tool offset, and for spherical reflector the radius of the object. It is good to note that he depth indicated is the distance the wave has travelled back and forth to reflection point.

At Stripa investigations also directional radar was used. A specific directional 60 MHz Ramac tool uses magnetic field vector components to provide the relative azimuth of arriving radar signal.

3.2 Olkiluoto site

The Olkiluoto Island was selected for geological spent nuclear disposal site in 2000. Site characterization using geological and geophysical methods has continued since 1987, and investigations for now operational low- and intermediate level nuclear waste repository were conducted 1982–1994. These both investigations have provided experience and comprehensive information on bedrock properties, which can be applied for assessment of as-built information of the safeguards.

The GPR investigations in Olkiluoto include surface based soundings on outcrops and along investigation trenches, tunnel based investigations in VLJ repository, and borehole radar applied in VLJ repository and in deep boreholes at HLW investigation site. The knowledge on geological and geophysical properties of the site is extensive on the basis of the characterization programme.

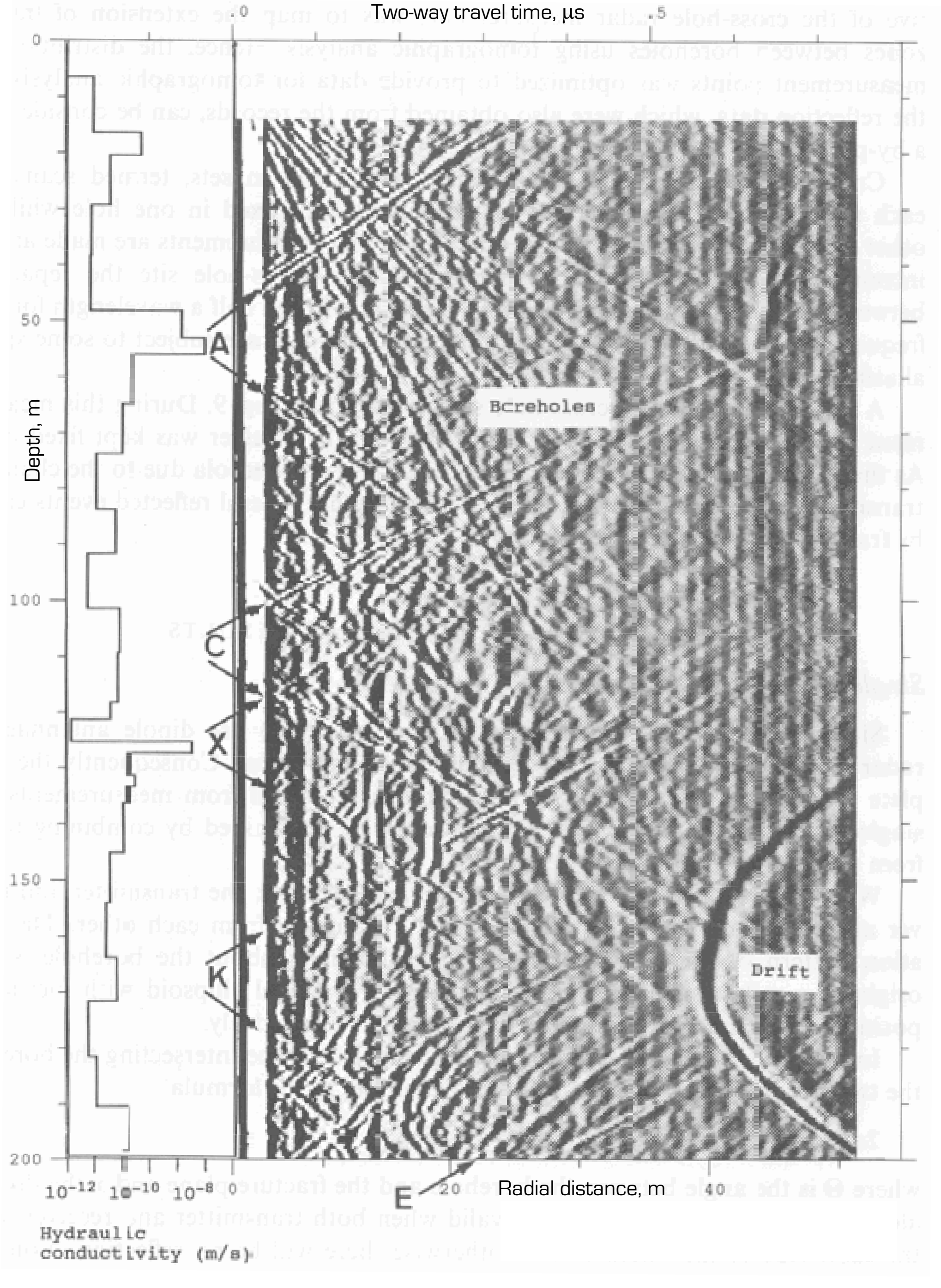


Figure 5. Radar single-hole reflection image from Stripa Mine investigations, 60 MHz borehole radar. The adjacent boreholes and drift can be seen clearly. Radar range exceeds 50 m. Survey was run in borehole F4 (in Figure 6) (Olsson et al. 1992).

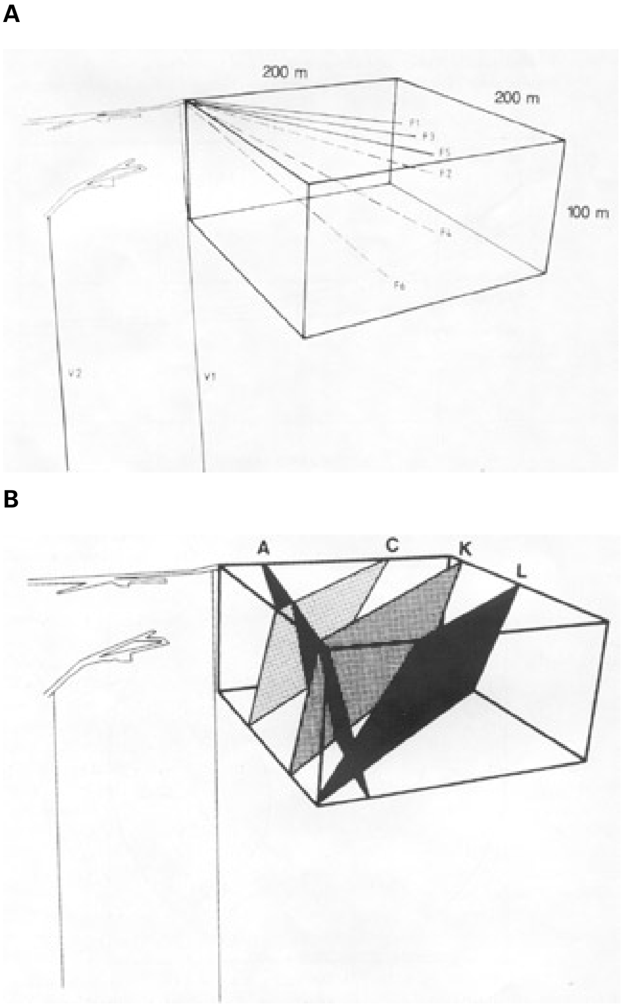


Figure 6. A) The measurement borehole F4, shaft and other boreholes at the Stripa test site. **B)** The deduced reflecting planes (fracture zones) intersecting or near the borehole (Olsson et al. 1992).

3.2.1 Geology of Olkiluoto

The Olkiluoto bedrock consists of highly metamorphosed, partially segregated ancient (+1860 Million years) sand and clay sediments (Gehör et al. 1996, Anttila et al. 1999), where the present major rock type is banded migmatitic gneiss. The gneiss contains variable amount of granite pegmatite neosomes and veined granite intrusions. Migmatite consists of foliated (mica lamellae are oriented) mica gneiss palaeosomes and granite neosomes. Proportion and size of neosome veins are varying so that the rock mass displays in places more granitic composition. Main migmatitic rock types display variants ranging from typical banded migmatitic gneiss and fine grained mica gneiss to massive, fairly weakly oriented grey gneiss, and amphibole-bearing mafic gneisses. These gneisses are cut by coarse grained granites and granitic pegmatites. The site contains also younger, intersecting metadiabase veins.

The rock mass contains in places electrically conductive minerals, either disseminated or veined in host rock, or layered on fracture coatings. These minerals include e.g., pyrite, pyrrhotite, chalcopyrite, sphalerite, and graphite. Though the actual occurrences of conductive minerals are very narrow, few centimetres in thickness and probably discontinuous, these are accumulated into larger layers indicating ancient shearing and hydrothermal activity which are often several tens of meters thick, and display greater continuity. The orientation of such layers is subhorizontal and consequently parallel to gently inclined access tunnel or near-horizontal future disposal tunnels.

The gneiss is typically strongly banded, the intensity of banding and foliation is varying to great deal. The bedrock implies preferred orientation of banding and veins/contacts dipping gently to moderately to southeast-south (90–180°/10–50°, with a maximum orientation to 140/35°). Banding and foliation displays a clear microfolded structure, indicating fold axis dipping gently to the East. The banding is a product of several tectonic deformation phases, ranging from ductile shearing via brittle-ductile transition to brittle faulting.

The fracturing in the rock mass displays one well developed orientation of slickensided fractures concordant to foliation, and two-three intersecting subvertical orientation sets (160°/60–70°; 220/50–80°, 270/80–90°) which are varying in orientation at the site to some extent (Vaittinen et al. 2003). Fracture frequency is in general roughly 1.7 fractures/m in boreholes, implying higher fracturing intensity in first 0–100…150 m depth in the bedrock and in well developed shear or fracture zones of thicknesses ranging 0.5 m to tens of metres. Many of the specifically gently dipping fracture zones are deemed continuous, are hydraulically conducting and imply significance to rock engineering. Fracture zones of various types have been considered with care in ONKALO and future repository design. Depending on their properties, fracture zones call for specific planning and may require avoidance of disposal tunnels and canister deposition holes in the repository design. Fracture zones occupy the average length of 7–8% of borehole core. By definition the disposal facilities are designed to least fractured sections of bedrock.

Table II. The Olkiluoto radar investigations and related bedrock conditions.

Investigation (Reference)	Frequency, instrument	Application	Bedrock conditions	Experiences
GPR (Koskiahde 1989)	80 MHz, SIR-10 GPR	Continuous profiles on road lines and pathways, soil thickness and bedrock fracturing.	Mostly soil	Peat and sand can be measured, silty till prevents any deeper penetration.
GPR (Leino 2002)	100 MHz and 300 MHz, SIR-10 GPR	Continuous profiles on bogland, definition of peat, sand and mud.	Bog	Soft layers well defined, silty till prevents rock surface observation.
GPR (Sutinen 2002, 2003)	100 MHz and 300 MHz, SIR-10 GPR	Continuous profiles on exposed investigation trenches, bedrock fracturing.	Varying rock types, both high and low resistivity.	On surface, the migmatic gneiss, range is 3–8 m in granite.
Tunnel GPR (Koponen 1994a, b)	100 MHz, 300 MHz, 500 MHz SIR-10A GPR.	In low and intermediate waste repository, investigation tunnel. Sounding of tunnel wall, and full scale disposal holes, to detect fractures.	Grey gneiss (amphibole bearing) high resistivity, low fracturing, electrical permittivity = 114.7	Good observability of fractures, range 7–8 m with 500 MHz; 10–14 m with lower 100–300 MHz frequencies. Adjacent borehole can be seen at a distance of 5 m.
Borehole radar, 22 MHz dipole (Carlsten 1990, 1991a, 1996a, b)	RAMAC Borehole antenna, 15 m Tr-Rc offset. Measurements at 1 m interval.	Deep investigation boreholes KR1–KR8 and KR10, VLJ repository boreholes KR1–KR3.	Varying rock types, fracturing, conductive minerals and groundwater salinity.	Frequency of reflecting objects at 15–30 m interval. Range 10–50 m.
Borehole radar, 60 MHz directional (Carlsten 1996a, b)	RAMAC Borehole antenna, 7 m Tr-Rc offset measurements st 0.5 m interval.	Deep investigation boreholes KR1–KR8 and KR10.	Varying rock types, fracturing, conductive minerals and groundwater salinity.	Frequency of reflecting objects at 5–20 m interval. Range 15–30 m.
Borehole radar, 100 MHz dipole (Saksa et al. 2001, Julkunen et al. 2004)	RAMAC Borehole antenna, 2.5 m Tr-Rc offset, measurements at 0.3–0.1 m interval.	Borehole KR10 (feasibility study) at 40–140 m, tunnel pilot hole PH-1.	Varying rock types, fracturing, conductive minerals. Fresh groundwater.	Frequency of reflecting objects at 1–2 m interval. Range 5–20 m.
Borehole radar, 250 MHz dipole (Saksa et al. 2001, Lahti & Heikkinen 2004, 2005)	RAMAC Borehole antenna, 1.7 m Tr-Rc offset, measurements at 0.3–0.1 m interval.	Borehole KR10 (feasibility study) at 40–140 m, repository access tunnel pilot holes PH1 and PH2.	Varying rock types, fracturing, conductive minerals. Fresh groundwater.	Frequency of reflecting objects at 0.5–1 m interval. Range 2–14 m.

3.2.2 Performed investigations

The radar investigations performed in Olkiluoto and information on bedrock properties are presented in Table II. Ground level surveys are not applicable for bedrock investigations and mostly only soil layers can be mapped. This is a coastal region property in general in Nordic glacial terrain. On surface moderate penetration can be reached but the migmatite can be opaque to the radar waves when being intensely foliated or fractured with sulphide infillings.

The VLJ repository research tunnel was used for bedrock characterization and different tests related to full scale disposal well design. Radar method was applied to map fractures from bedrock. The GPR method was implemented in well prepared and clean tunnel floor, and on wall of one full face bored deposition well of 1.5 m diameter.

The spent nuclear fuel site investigations have included borehole radar soundings in nine of the deep boreholes, named KR1–KR8 and KR10. Work has been performed with lower frequencies of 22 MHz and 60 MHz, using at 60 MHz the directional tool, which provides orientation of the

Table III. Olkiluoto rock mass conditions, resistivities (in ohm-m) and radar ranges.

	22 MHz		**60 MHz**		**100 MHz**		**250 MHz**	
Bedrock and groundwater conditions	**Range, m**	**Resistivity**	**Range, m**	**Resistivity**	**Range, m**	**Resistivity**	**Range, m**	**Resistivity**
Grey gneiss, granite, veined migmatite, sparsely fractured, fresh water (DC resistivity >10.000 ohm-m)	20–50	300–1000	15–30	280–700	15–20	300 – 420	9–14	170–300
Migmatite, mica gneiss, moderately 3–10 1/m fractured, fresh water DC resistivity 5.000–10.000 ohm-m	10–20	200–300	10–15	160–280	8–15	170 – 300	5–9	82–170
Grey gneiss, granite, migmatite, sparsely fractured, saline water DC resistivity 5.000–10.000 ohm-m	10–20	200–300	10–15	160–280	8–15	170– 300	5–9	82–170
Migmatite, mica gneiss, moderately 3–10 1/m fractured, saline water DC resistivity 1.000–5.000 ohm-m	5–15	65–240	5–10	75–160	5–8 m	75 – 170	3–6	44–103
Densely >10 1/m fractured zones, intensely foliated migmatite, altered or porous zones, saline water DC resistivity <1.000 ohm-m	<10	<200	<10	<160	3–8	40 – 170	2–5	27–82
Sulphide or graphite bearing zones, fracture zones with saline water. DC resistivity < 200 ohm-m	None		None		None		None	

reflectors in 3-D. The directional measurements are comparably slow, and due to high attenuation and wide variation of possible explanations in presence of pyrite and graphite layers, the method has not been applied in the most recent site characterisation boreholes KR11–KR33 up to date.

The high frequency borehole radar has been applied in denser sampling rate in borehole KR10. Borehole KR10 contains section over 40–140 m with several frequencies, 22 MHz, 60 MHz directional, 100 MHz and 250 MHz. This offers valuable data on range and resolution of the different frequencies. The highest frequencies, 100 MHz and 250 MHz have been applied in ONKALO access tunnel pilot boreholes PH1 and PH2. Obtained physical parameters, and more specific examples are presented below in Chapters 3.2.3 and 3.2.4.

3.2.3 Physical parameters in Olkiluoto host rock

The physical parameters affecting to considered application are the electrical conductivity and the dielectric permittivity of the rock mass. Averagely fractured Olkiluoto bedrock has the relative electrical permittivity ε_r = 6.6–6.8 (velocity 115–122 m/µs). Porosity and water content affect the radar range. Porosity ranges from less than 0.1% of non-broken host rock to 3–7% in broken rock mass. Physical properties and related radar values are shown in Table IV.

The dielectric permittivity and velocity has been defined in places in the Olkiluoto bedrock. The velocity values are determined from direct radar wave or from a distance from a known object (ground surface in PH1, pilot borehole VLJ-KR4 from full scale deposition test hole etc.), or using VRP sounding or CMP sounding.

Permittivity varies to some extent according to mineralogy, alteration and fracturing (water content). The radar wave velocity varies from 114–115 m/µs (in VLJ-repository grey gneiss 114.7 m/µs) of mafic grey gneiss (< 20% amphibole) in PH2 and VLJ-tunnel to 117 m/µs in migmatite and mica gneiss (PH1–PH2 and KR10), and even to 122–125 m/µs in granite (approximately, in PH2). These values are in accordance with those reported in literature and observed at elsewhere. Close to surface, and in fracture zones, the velocity can decrease 10–20% down to values of 90–100 m/µs.

The galvanic (DC) electrical resistivities, available from borehole geophysical logging, are indicative of the range of radar wave. Resistivity varies from very high 10.000–60.000 ohm-m in weakly fractured (< 3 fractures/m), low-porosity gneissic and granitic rocks, to moderate 1.000–10.000 ohm-m in moderately fractured 3–10 fractures /m or foliated rock mass. Values in the range <1–1.000 Ohm-m are met in intensely fractured or foliated, or altered rock mass, often containing banded layers of pyrite and graphite.

Table IV. Bedrock physical properties involved in the radar range and attenuation in Olkiluoto.

Rock type and quality	DC Resistivity	Effective resistivity at 100 MHz (estimated)	Relative permittivity	Radar velocity, µs/m	Water DC resistivity	Porosity
Grey gneiss	10.000–30.000 ohm-m	300–420 ohm-m	6.8 (defined in VLJ-tunnel)	114.7 (in VLJ tunnel)	20–100 ohm-m	0.1–0.5%
Grey gneiss, saline water below Z: 500 m	5.000–10.000 ohm-m	170–300 ohm-m			<1 ohm-m	
Migmatite, strongly foliated migmatite is less resistive and attenuates the signal more	5.000–10.000 ohm-m	170–300 ohm-m	6.7 (defined in PH1) 6.67 (defined in VLJ-tunnel with borehole radar)	117	20–100 ohm-m	0.2–1%
Migmatite, saline water below Z:500 m	1.000–5.000 ohm-m	75–170 ohm-m			<1 ohm-m	
Granite	10.000–20.000 ohm-m	300–360 ohm-m	6–6.5 (estimate for granite met in PH2)	118–122	10–100 ohm-m	0.1–0.5%
Granite, saline water at depth of 500 m	5.000–10.000 ohm-m	170–300 ohm-m			<1 ohm-m	
Fracture zones, fresh water	1.000–10.000 ohm-m	75–300 ohm-m	7.5–11 (estimate)	90–110	10–100 ohm-m	3–7%
Fracture zones, saline water	100–1000 ohm-m	<75 ohm-m			<1 ohm-m	

At Olkiluoto bedrock is groundwater saturated and the groundwater table is typically at 1–5 m depth below ground surface. The rain infiltrated recent groundwater is fresh, and DC resistivities are c. 20–100 ohm-m or TDS < 1 g/l. Infiltrated brackish Baltic sea water can be found from some parts of bedrock at 0–200 m depth range, the salinity being of order 6 g/l (1 ohm-m). Salinity increases with depth and at disposal depth range 400–550 m the salinity gradually increases at 10–40 g/l, resistivities 1–0.2 ohm-m. Deeper down, even salinities of 75 g/l (0.1 ohm-m) have been encountered. The salinity of groundwater reduces severely the radar range also in the low porosity (0.1–1%) host rock.

The resistivity is frequency-dependent and actually the useful parameter is the resistivity at the radar frequencies, which is substantially lower than the DC resistivity. The measured radar ranges can be used to estimate resistivity along the Olkiluoto deep boreholes at different frequencies (Saksa et al. 2001).

Host rock resistivity is for 500 MHz only order of 140–160 ohm-m in fairly resistive grey gneiss in VLJ tunnel, allowing the radar range with $\varepsilon_r = 6.8$ and velocity 114.7 some 7–8 m. Though resistivity with more penetrative 50–100 MHz nominal frequencies would be higher, the figures give an estimate of the achievable ranges in Olkiluoto.

Relative magnetic permeability is usually considered as 1. In typical Olkiluoto bedrock the magnetic susceptibility is low < 2000 (µSI) but in veins rich in sulphides can exceed 10.000, which may affect to the radar velocity and attenuation.

The radar attenuation can be measured over a longer section (crosshole tomography and inversion), from direct wave amplitude variation (borehole radar) and iterative backprojection (Saksa et al. 2001), or estimated from the range achieved. The resistivity and the range are strongly frequency dependent. Table V displays the parameters with respect to frequency. The resistivity affecting to the attenuation of radar signal most, has been exhaustively defined in the deep boreholes using geophysical wire-line logging.

3.2.4 Investigations in deep boreholes

The borehole radar investigations have been performed in deep boreholes KR1–KR8 and KR10 with 22 MHz dipole antenna tool, and with 60 MHz directional receiver tool. The lower frequency can achieve radial ranges of 20–50 m from the borehole. Range of the 60 MHz directional tool has been most typically 15–20 m in averagely fractured bedrock; and in maximum 20–30 m in resistive bedrock.

Table V. Frequency dependency of observed propagation parameters in Olkiluoto.

Frequency	Range (observed)	Resistivity (computed)	Wavelength	Experiences
500 MHz GPR	8 m	160 ohm-m	0.23 m	Optimal for detailed fracture mapping in tunnels. Shielded antenna used.
250 MHz borehole radar	8 m	145 ohm-m	0.5 m	Highest resolution, good connection to rock; mica gneiss values. Offset 1.7 m.
100 MHz borehole radar	12 m	215 ohm-m	1.2 m	High resolution, good connection to rock. Less power than with GPR, mica gneiss values
100 MHz GPR	15 m	290 ohm-m	1.2 m	Longer range, less fractures seen; tunnel side reflections as problems.
60 MHz borehole radar	30 m	650 ohm-m	1.9 m	Good penetration. Less natural features. Feasible frequency area. Antenna separation: 7.5 m. Directional, very slow to measure.
22 MHz borehole radar	50 m	1100 ohm-m	5.2 m	Least resolution and natural fractures, most penetration. Antenna separation 15 m. Slow to measure.

Schistose migmatite, and presence of sulphide layers, has reduced the range in places to 10–15 m. Below 500 m the presence of saline groundwater has reduced the range more.

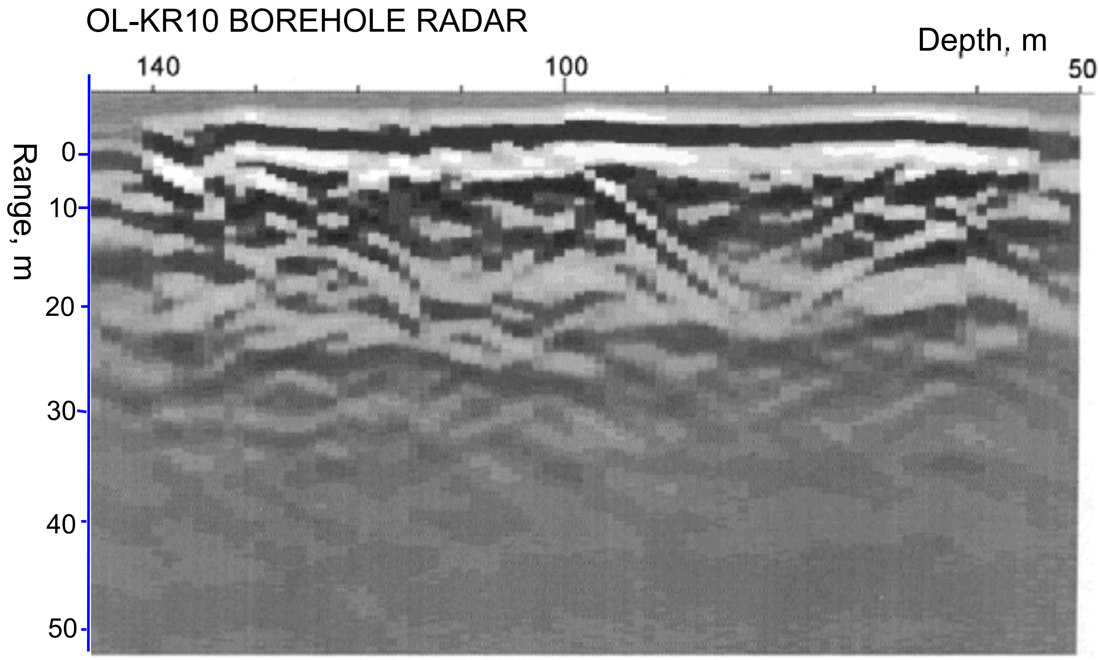
Comparison of images and ranges and observability of natural fractures has been produced for KR10 section 40–140 m, where all frequencies 22 MHz, 60 MHz, 100 MHz and 250 MHz have been measured. Sampling intervals have been 1.0m, 0.5 m and 0.03–0.05 m, respectively. The 22 and 60 MHz data belongs to site characterization work (Carlsten 1996), and the 100 and 250 MHz data to the borehole radar method feasibility study (Saksa et al. 2001). Borehole diameter is 115 mm at 40–100 m and 86 mm below that (until 178 m). The large diameter causes ringing of the direct wave. Borehole fluid has been fairly resistive, which allows rather good penetration of the signal to the bedrock. The comparison of the different frequencies is illustrated in Figure 7. An extract of the image is displayed in Figure 8.

The frequency and the transmitter-receiver offset govern the amount of natural reflections observed with borehole radar. Using KR10 as an example in Olkiluoto, the 22 MHz antenna has produced 0.055 reflectors a meter at 40–614 m borehole interval or one reflector in average at 17 m interval (median 16 m, distributed between 4–46 m). The 60 MHz antenna produced 0.1 reflectors a meter or one each 10 metres in average (median 8 m, distributed between 0–35 m). Reflectors met with 100 MHz at 40–160 m interval produced 0.5 reflectors a meter, or one at each 2.5 m (median 2 m, distributed between 0.25–7 m), and for 250 MHz 0.8 reflectors a meter or one at each 1.44 m (median 1.44 m distributed between 0–3 m).

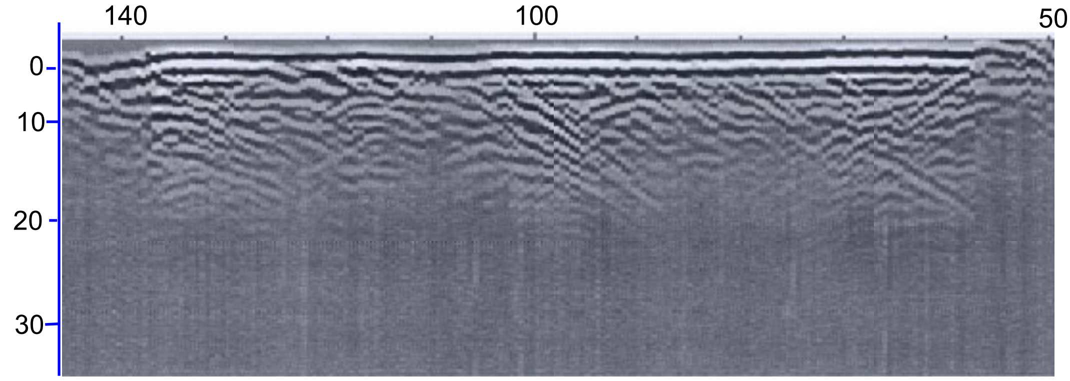
The natural conditions in Olkiluoto bedrock display a large amount of reflectors of different amplitude intensities and continuities. Within section 40–140 m, seven reflectors were recorded at 22 MHz, 13 at 60 MHz, 48 at 100 MHz and 78 at 250 MHz. Considerable ringing caused of antenna is also visible as horizontal striping, see 250 MHz result.

The natural reflections are at low (22–50 MHz) frequencies and large tool offsets (Tx-Rx 2–15 m) most often local or regional fracture zones and continuous layers containing conductive minerals. Approaching to the higher frequencies 100–500 MHz, shorter tool offsets (0.2–1 m) and dense sampling rates, the amount of reflectors is dramatically increasing, representing occurrence of individual fractures (coated and/or clay or water filled), surfaces of intense foliation with preferred orientation, and rock type or vein contacts. Olkiluoto has also high attenuation (1–3.3 dB/m for 60 MHz tool) near ten-fold compared to most other hard rock sites (Romuvaara 60 MHz: 0.3 dB/m), and thus a reduced range of investigation.

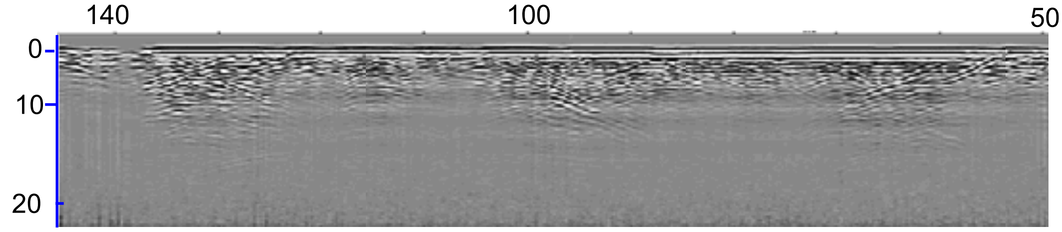
Point like natural reflectors do exist in Olkiluoto bedrock mass also in radar results. Examples have been found e.g. in PH1 and PH2, and in KR10. The origin of point-like objects may be crossings of fracture planes or thin zones or fold crests comprised of changes between mineralogical layers. Also mineralogical inclusions or small cavities may exist.



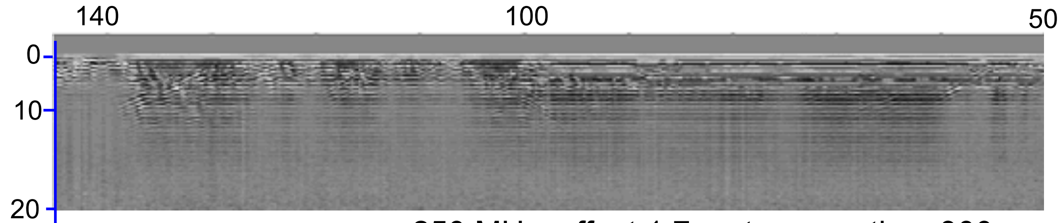
22 MHz, offset 15 m, two-way time 800 ns



60 MHz, offset 7.5 m, two-way time 550 ns

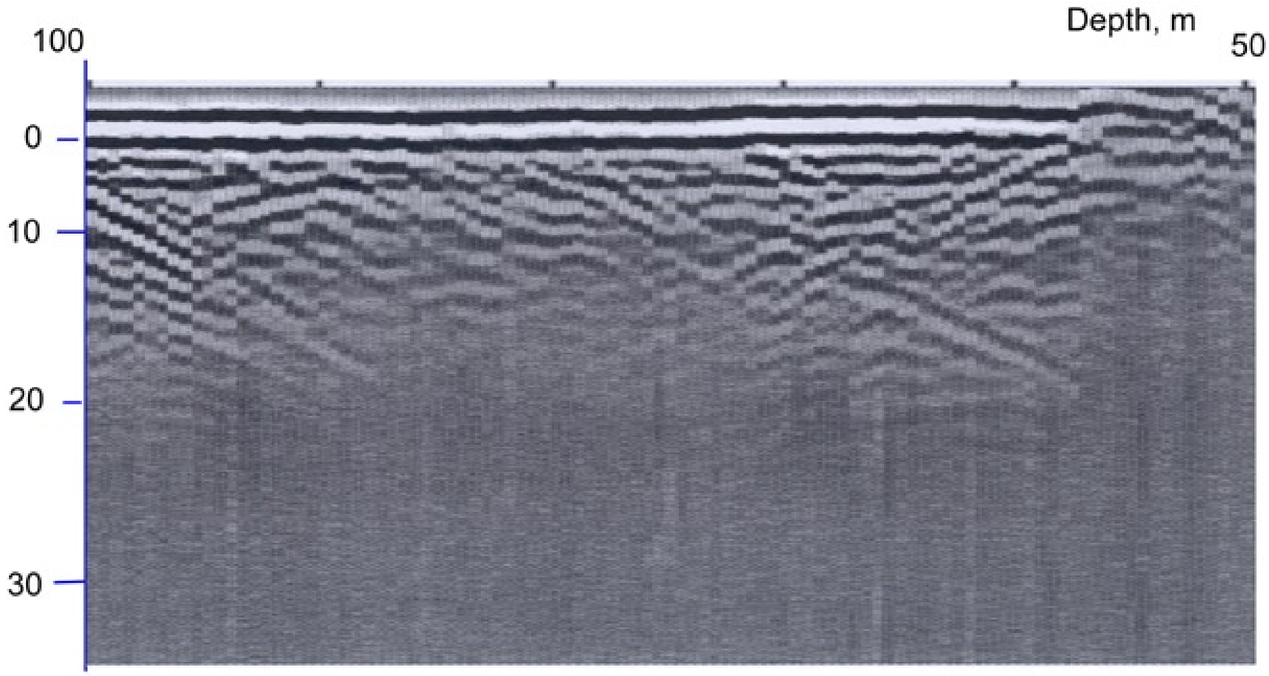


100 MHz, offset 2.2 m, two-way time 350 ns

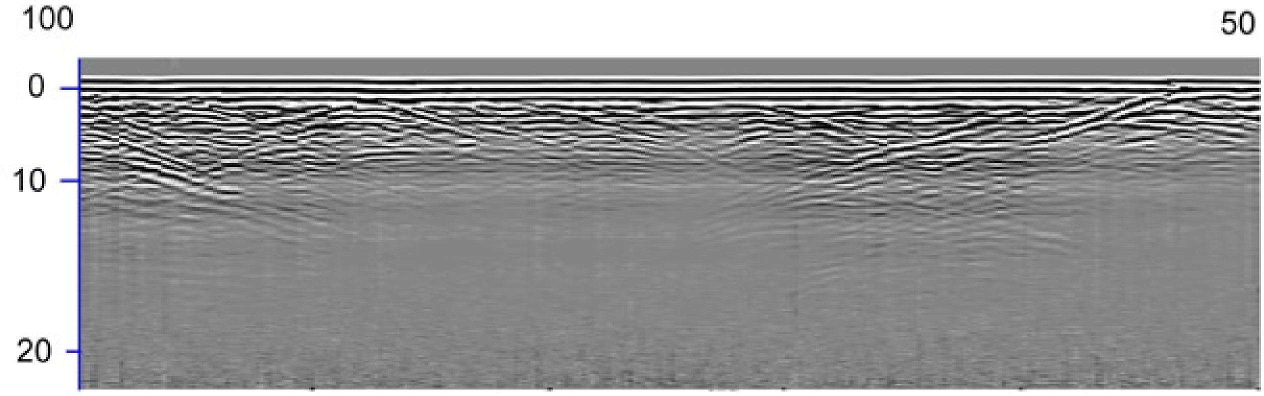


250 MHz, offset 1.7 m, two-way time 300 ns

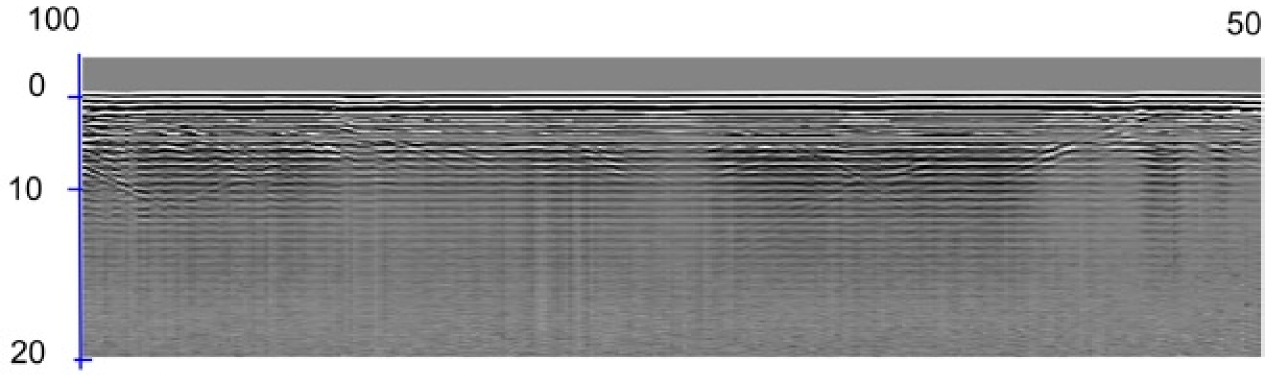
Figure 7. Radar images of frequencies 22 MHz, 60 MHz, 100 MHz and 250 MHz.



60 MHz, offset 7.5 m, two-way time 550 ns



100 MHz, offset 2.2 m, two-way time 350 ns



250 MHz, offset 1.7 m, two-way time 300 ns

Figure 8. Radar images of frequencies 60 MHz, 100 MHz and 250 MHz. Extract of Figure 7, depth interval 50–100 m more in detail.

Examples of point-like reflectors are displayed in Figure 9 (Carlsten 1996, Saksa et al. 2001).

Paulamäki (1996) has reported according to geological mappings that two types of inclusions are encountered at migmatitic mica gneiss. One type is fine grained, grey gneiss without any granite veins in it and other type consists of concretions, ovoidal inclusions. The other type is zonal and calcsilicate in composition, example given in Figure 10 mapped at the investigation trench TK1 (Paulamäki 1995). When the inclusion differs from the surrounding rock mass in mineralogy, internal porosity or fracturing, it may differ also in physical values and give rise to radar wave reflection from a point-like source, accordingly.

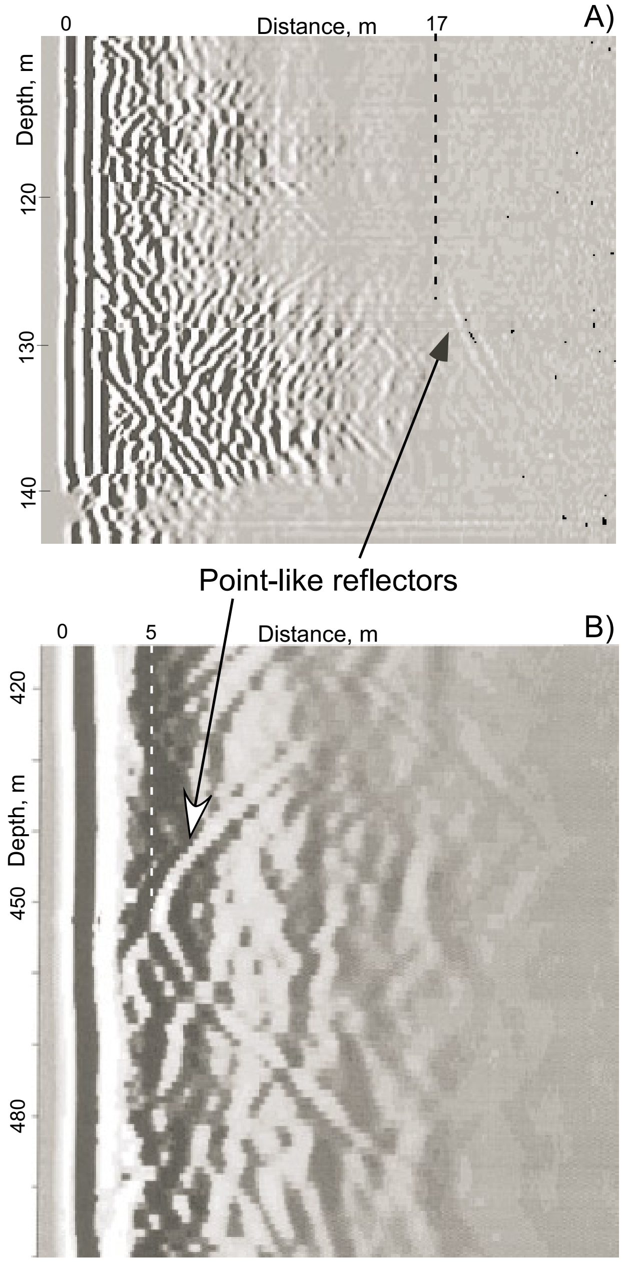


Figure 9. Point-like natural reflectors, **a)** 100 MHz, 128 m depth at 17 m distance (Saksa et al. 2001), and **b)** 22 MHz, 450 m depth at 5 m distance (Carlsten 1996).

The natural reflectors are sometimes very continuous and strong although their geometric character may be irregular. Figure 11 displays a reflection map of 22 MHz radar survey in borehole KR5 in Olkiluoto. A strong linear reflector is related to metadiabase dyke not intersecting the borehole (but interpreted and directly observed from surface) and could be mixed with man-made objects unless a geological explanation was known.

3.2.5 Investigations in a research tunnel

The operational low and intermediate level nuclear waste repository (VLJ) in Olkiluoto was used for methodology development. A GPR measurement was carried out along carefully excavated and cleaned research tunnel floor to map subhorizontal fractures (Koponen 1994b). These fractures were detected to intersect 76 mm pilot boreholes, used to investigate the tunnel base before full face boring of the full scale canister holes for tests. After one of the deposition wells was finalized, KR5, the radar profiling was applied along the vertical walls of the well (Koponen 1994a). Measurement was performed at 8 profiles on compass directions N, NE, E, SE, S, SW, W and NW, and on three levels 2, 3.5 and 4.5 meters in circular path around the well. The well is 1.5 m in diameter and 7.5 m deep. The measurement aimed to detection and orientation of subvertical fractures. Measurement arrangement is depicted in Figure 12.

The tunnel work applied shielded 500 MHz double antenna as a major tool. Tests were run with 100, 300 MHz non-shielded single (zero offset) and 300 MHz Dual antenna. Measurement was run continuous recording 25 traces per second and pulling the tool at constant velocity. Point measurements on profile were run at 50 cm interval, stopping the antenna during each measurement for time stacking.

Transmission power for 100 MHz single antenna was 60 W, and for 300 MHz single and 500 MHz shielded antenna 30 W. For 300 MHz dual antenna a transmission power of 7500 W was applied, but the environmental reflections were too large. For 500 MHz also 2500 W high power transmitter was applied, but the advantage of deeper penetration was lost with higher intensity tunnel reflections.

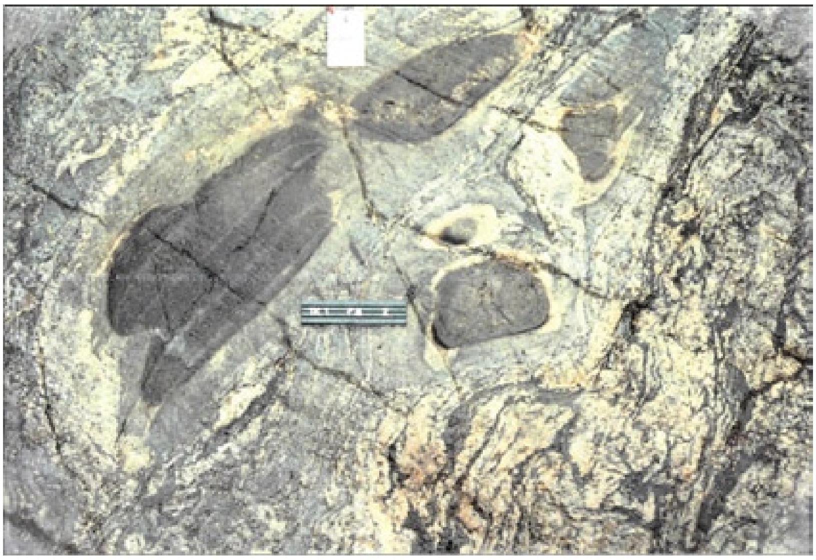


Figure 10. Zonal calcsilicate inclusions in migmatitic gneiss. The length of the plate is 17 cm (Paulamäki 1995).

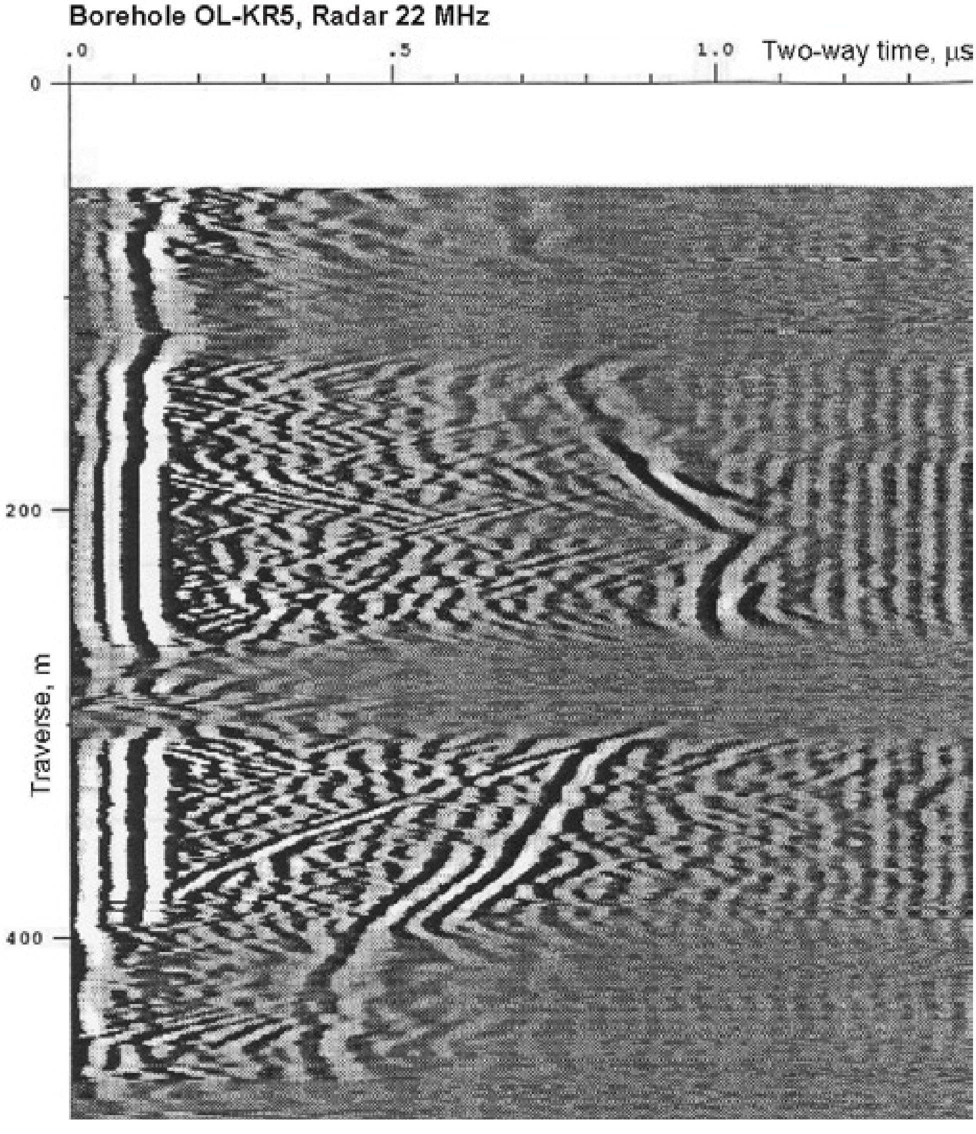


Figure 11. 22 MHz radar reflection image from KR5, Olkiluoto. Strong, undulating and continuous reflection from metadiabase dyke is seen in middle. Horizontal darker grey areas depict zones of wave attenuation (Carlsten 1991b).

Small dimensions of 500 MHz antenna allow smooth contact with rock surface, and there was also a metal case shielding preventing tunnel reflections. For longer penetration distances 50–100 MHz frequencies would have been better and shielding would be necessary. The coupling to bedrock would require care with lower frequency case. The tool is large in dimensions and heavy, so the actual measurement cannot be performed hand held, but would require a transportable stand, vehicle installation or platform for operation at different levels on the wall and roof of tunnel.

The rock type is fresh water saturated, low porosity grey gneiss, where radar velocity is 114.7 m/ µs. The range 6–8 m was achieved with 500 MHz (30 W transmitter), and 12–14 m with 100 MHz (60 W transmitter).

The 100 MHz radar profile along tunnel floor is shown in Figure 13. Range up to 15 m was achieved. Natural reflections are clearly seen. The tunnel roof reflections are observed at apparent depth values of 2 and 4 m (radar velocity in air is 3-fold faster than

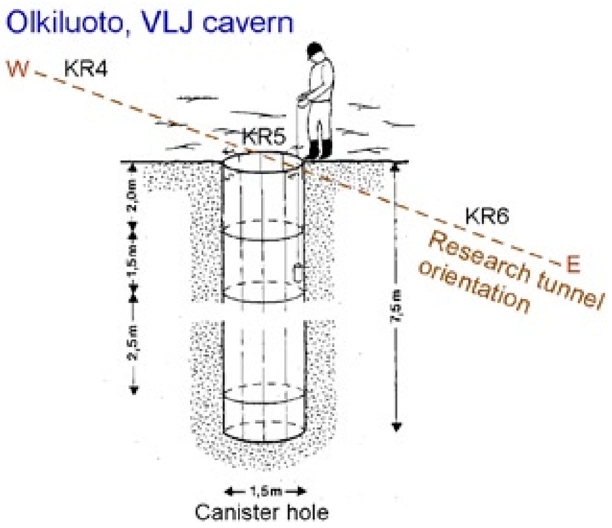


Figure 12. Radar measurements in VLJ tunnel floor and in full scale deposition hole.

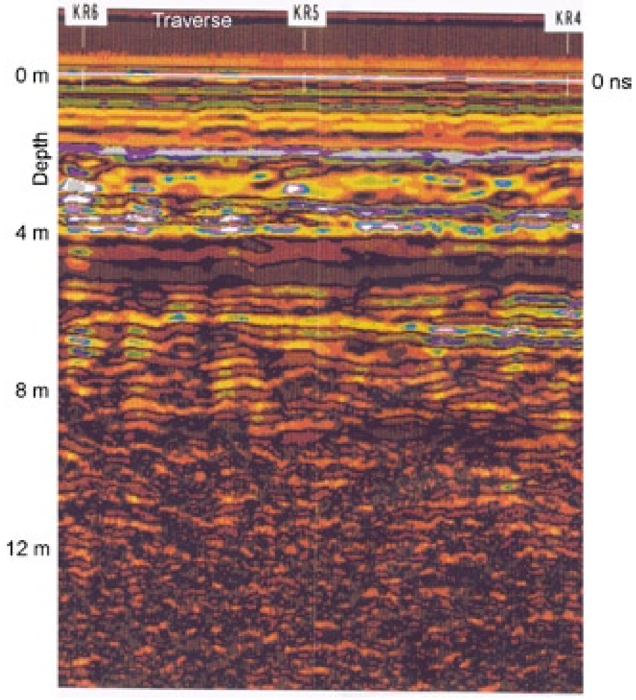


Figure 13. The 100 MHz radar profile along tunnel floor.

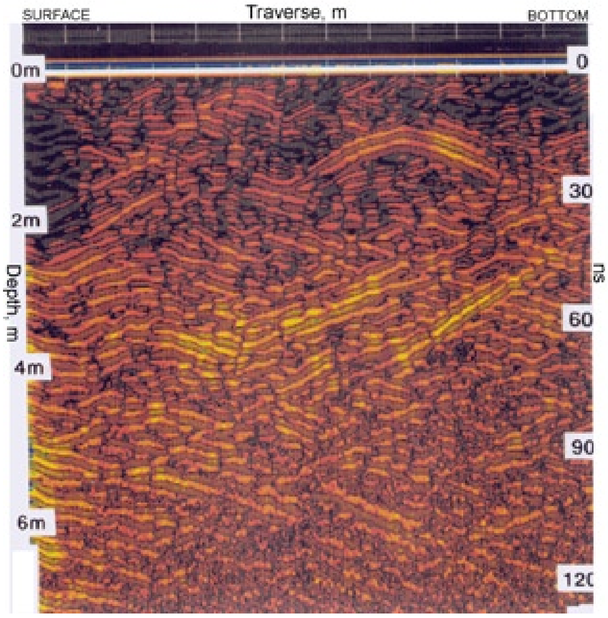


Figure 14. The radar response along full scale deposition hole, line is towards NW.

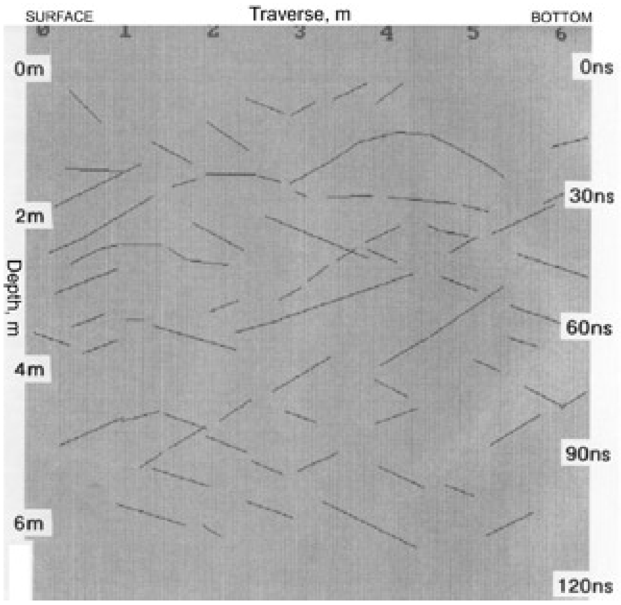


Figure 15. The interpreted reflections from image in Fig. 14.

in bedrock). Locations of pilot boreholes are marked onto the image.

Figure 14 reproduces the filtered radar signal along full scale deposition hole, using 500 MHz antenna, Measurement line is towards NW. Only natural reflections can be seen in the image. Interpreted radar reflections are displayed in Figure 15.

A discrete point measurement at 50 cm interval in full scale deposition hole is given in Figure 16. Result shows that the spatial sampling rate has to be dense to maintain continuity of features. Continuity and form facilitates recognition of the reflections partly.

A circular measurement at 3.5 m depth in full scale canister hole is in Figure 17. Note the point reflector towards W at 5.25 m depth (90 nanoseconds) which indicates a pilot hole (76 mm, water filled) at that location. There are few reflections of similar amplitude towards N and SE, where man-made objects do not exist (fractures).

Figure 18 visualises a vertical profile measured to W. The continuous horizontal reflector at 5.25 m indicates water-filled 76 mm pilot borehole KR4. Additionally a profile measured to WSW is printed in Figure 19. Reflection from pilot borehole KR4 has significantly diminished with 22.5° change of direction, indicating the direction sensitivity of GPR antenna transmitting and receiving in tunnel wall measurements.

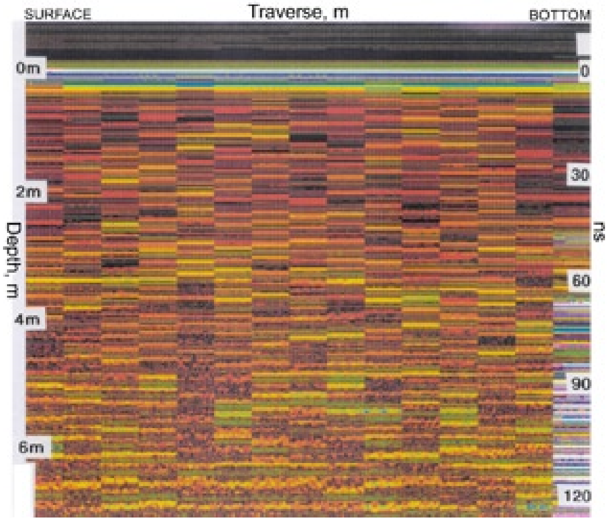


Figure 16. A discrete point measurement at 50 cm interval in full scale deposition hole.

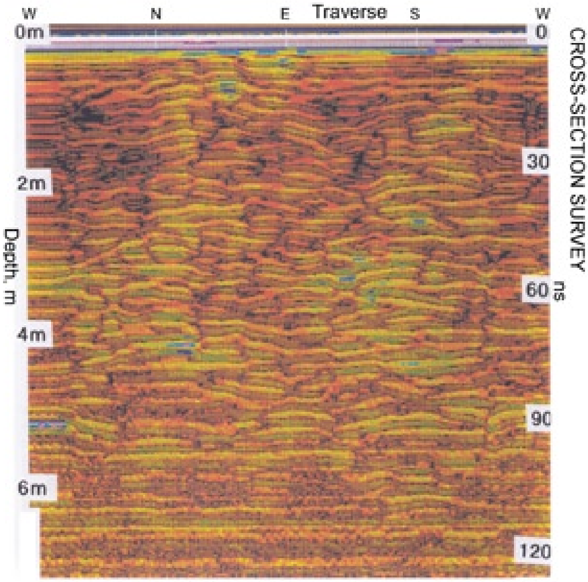


Figure 17. A circular measurement at 3.5 m depth in full scale canister hole.

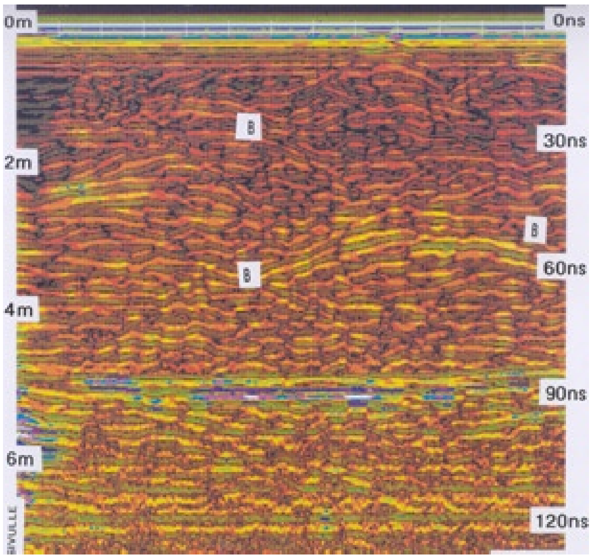


Figure 18. A vertical profile measured to W.

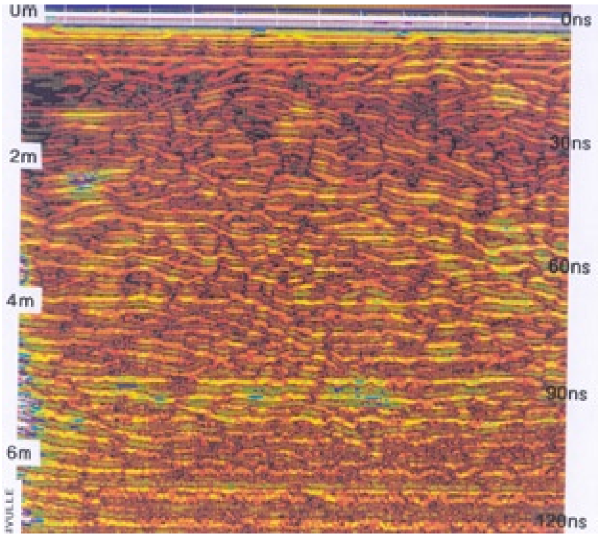


Figure 19. A profile measured to WSW otherwise comparable with Figure 18.

3.3 Detection of a large diameter borehole

An example from a mine in Finland shows a typical response from a normal drill–and–blast tunnel wall. A 310 mm cased borehole was searched at level +1225 m in a mine. The borehole searched was metal cased and filled with groundwater which was added some 100 kg of salt to improve the reflectivity (increasing electrical conductivity) of the hole. The borehole terminated close to the floor level. Approximate distance of the borehole was known to be 3–10 m from the drift.

A 100 MHz SIR-10 tool was used for sounding at 2 m level above tunnel floor in the tunnel. The rock type was hard, mafic vulcanite, which is fairly high in resistivity. The results are presented in Figure 20.

The borehole is located 5–6 m from the wall at 23 m of profile length. Borehole was found from the indicated location (yellow arrows), when excavating the drift.

The attenuation of signal is fairly high. There is ringing present in the data, and probable tunnel surface reflections can be seen. Several locations indicate roughness of the wall, or antenna temporary losing of contact to the wall, since air reflections penetrate longer times at narrow 20–50 cm bands at 14, 15.5, 25 and 27 m profile length. Higher 400 MHz frequency was tested but ringing and spurious disturbances were severe.

The case indicates, that applying normal design and processing, range is limited, noise level can be high and small targets can be difficult to distinguish from the natural and tunnel related reflectors and scattering.

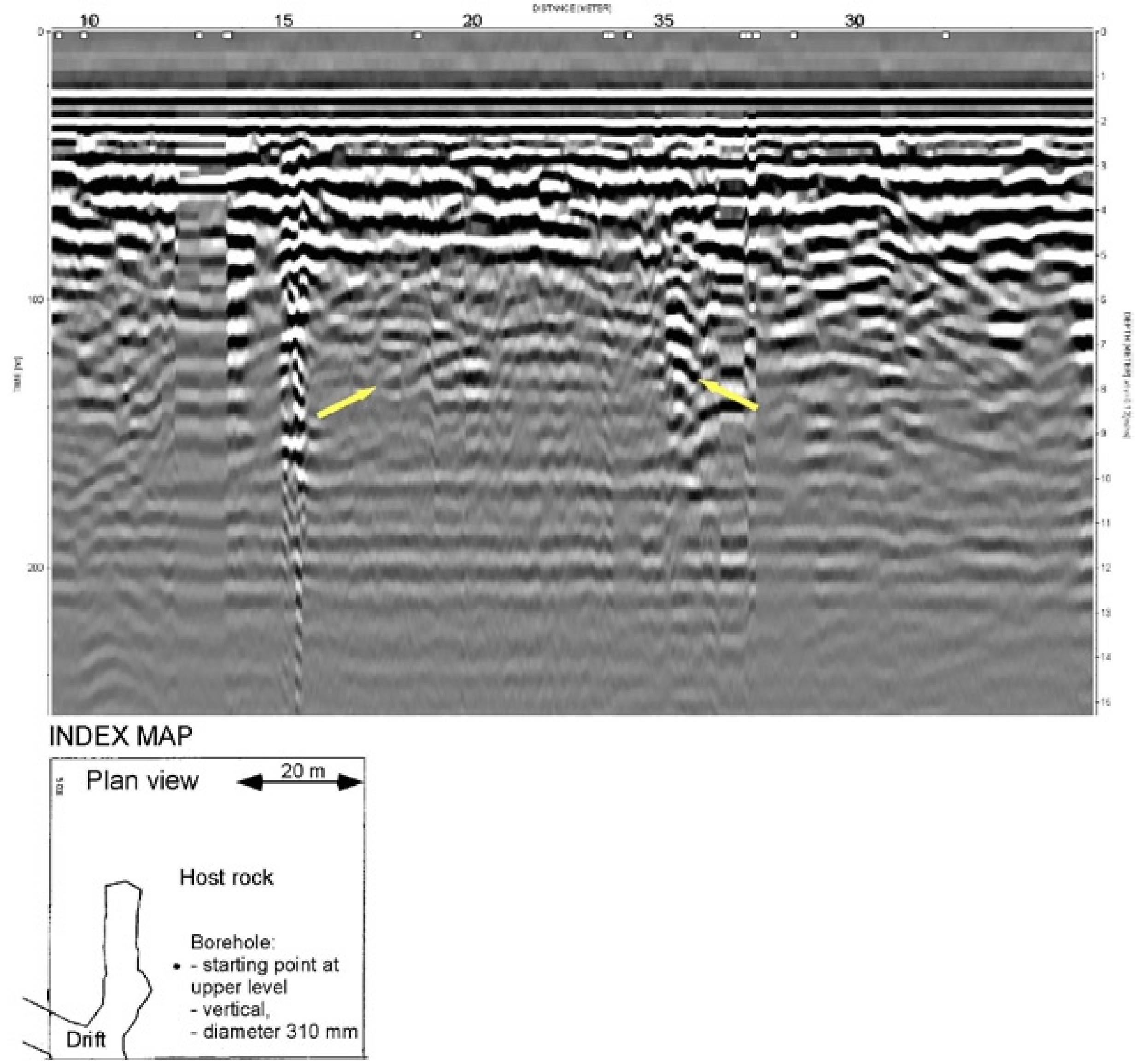


Figure 20. An example of 310 mm borehole detection from tunnel wall.

3.4 Numerical modelling

Extensive numerical modelling exercise had been done previously by Seidel et al. (2004) in relationship with radar method and safeguards use. The reader is kindly referred to the published report. Many geometrical situations with one-tunnel, two near-by tunnels, and large diameter borehole were analysed for their reflectivity and detectability. Variations were run where the basic models were embedded behind reflecting media contact or reflecting layer overlaid the tunnel(s) or hole. It was summarised that in 2-D tunnel detection case range of up to 20–30 meters is available and on the basis of 3-D test models up to 15 meters. Final assessment will only be possible after test measurements in the specific conditions of the respective repository. The application of GPR was concluded to be done by specially qualified personnel.

Supplementary modelling was made with ReflexW software, version 3.0.7 (Sandmeier 2003) in this study. Two additional models were derived to for Finnish repository construction conditions. First example illustrates tunnel shotcrete and grouting effects added. Second example is to study if canister disposal hole could be investigated and monitored from the neighbouring disposal tunnel. Frequency selected was 50 MHz.

Two important factors having influence in practice have been considered. Olkiluoto specific resistivity and dielectric permittivity values were used and this means that EM range of resistivities are considerably lower than DC values. Lower and frequency dependant resistivities mean lower detection range. Geological background as a component always included to output was taken into account. When geology originating part of the signal is considered as noise, detection of man-made or changed structures is more limited and demanding.

Model 1 is a tunnel detection example. The basic model (Figure 21) is built up of a thin, 0.5 meter thick, layer at the tunnel surface that represents the excavation damage zone (EDZ) including the

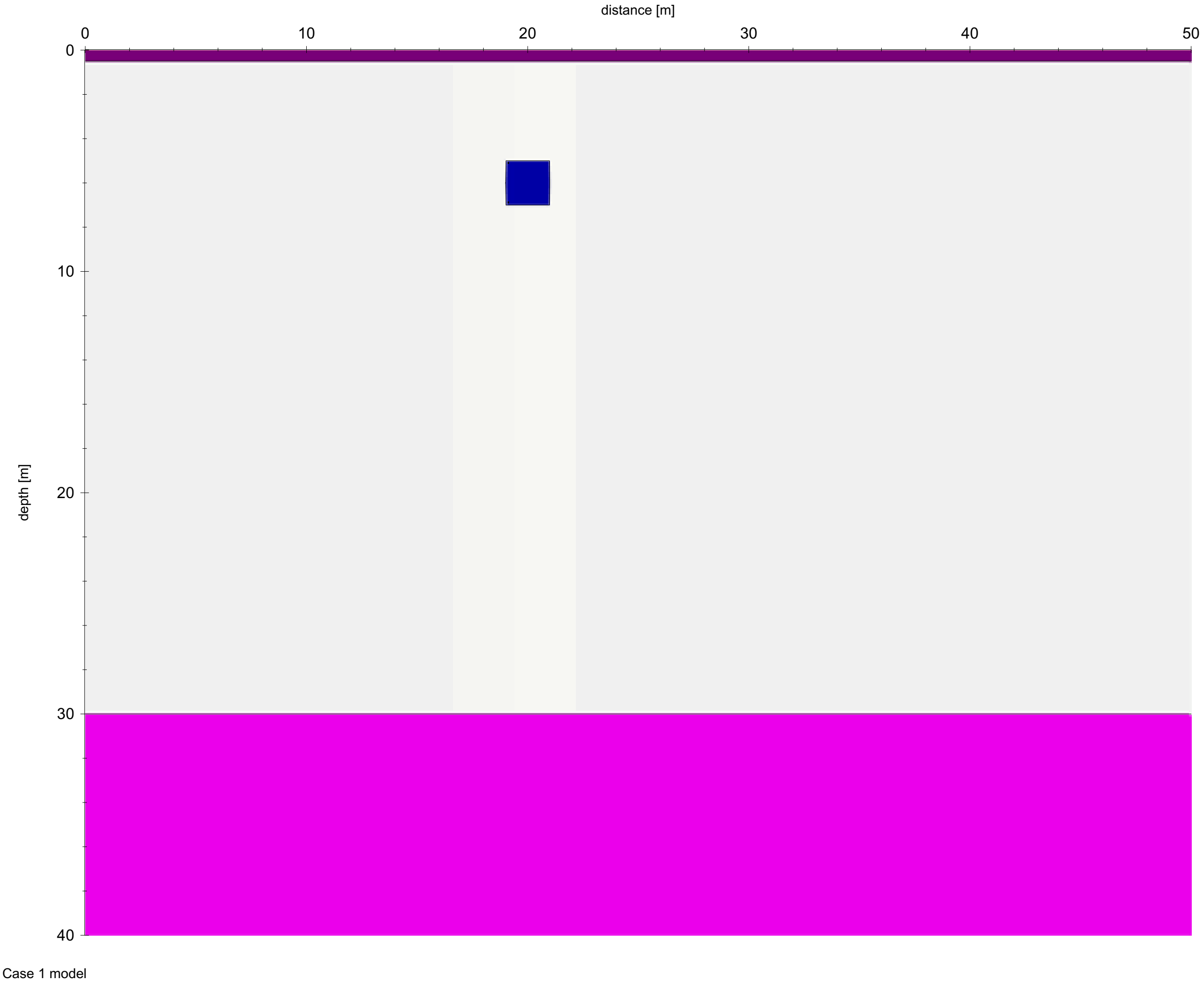


Figure 21. Model 1. The 2 × 2 m opening is located at the distance of 5 meter. The thickness of the conductive EDZ and grout-layer is 0.5 meter.

Table VI. Parameters used in model 1, cases 1–4.

Case nr.	EDZ		Host rock		2 × 2 opening		Reference layer	
	ε	σ (S/m)	ε	σ S/m)	ε	σ S/m)	ε	σ S/m)
Case 1	12	0.01	6.8	0.002	1	0	10	1
Case 2	12	0.01	6.8	0.0067	1	0	10	1
Case 3	12	0.1	6.8	0.002	1	0	10	1
Case 4	12	0.01	6.8	0.002	81	0.1	10	1

grout layer. A 2 × 2 meter opening at the distance of 5 meter is the target object as in the modelling by Seidel et al. (2004). Furthermore a horizontal interface at a longer distance of 30 m is added which will act as a reference reflection. This horizontal layer has high conductivity and permittivity values just to make it visible. The parameters for all the objects in four different model cases are listed in Table VI. The magnetic properties of the rocks is neglected, i.e. the magnetic permeability is set to $\mu = 1$.

Figure 22 displays reflection radargram resulting from the modelled basic model in Case 1. The 2 × 2 meter opening is filled with air. In case 2 the conductivity of the host rock is increased to 0.0067 S/m (Fig. 23). In case 3 the conductivity of the thin EDZ layer and grouted layer is increased to 0.1 S/m (Fig. 24). In case 4 the 2 × 2 meter opening is filled with water (Fig. 25).

Results show that both host rock as well as EDZ and grouting layer decrease in resistivity diminish strongly surveying range and reflection amplitudes. In all cases EDZ and grouting layer reflections are very strong. It is likely that in practise these will cause secondary reflections and ringing even more than seen in the numeric results. Response from the opening is strong in both air and water filled cases because the physical contrast is very high anyway.

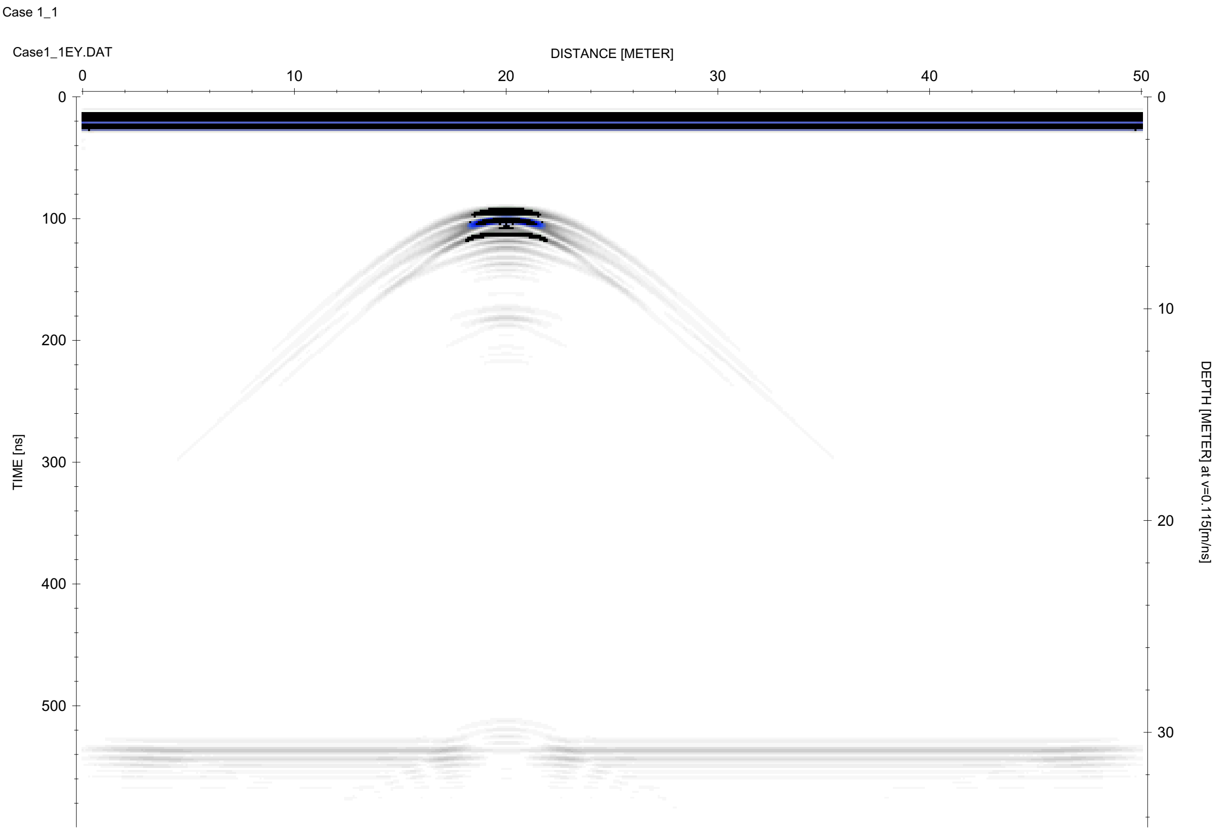


Figure 22. Model 1, case 1. The 2 × 2 m opening is filled with air.

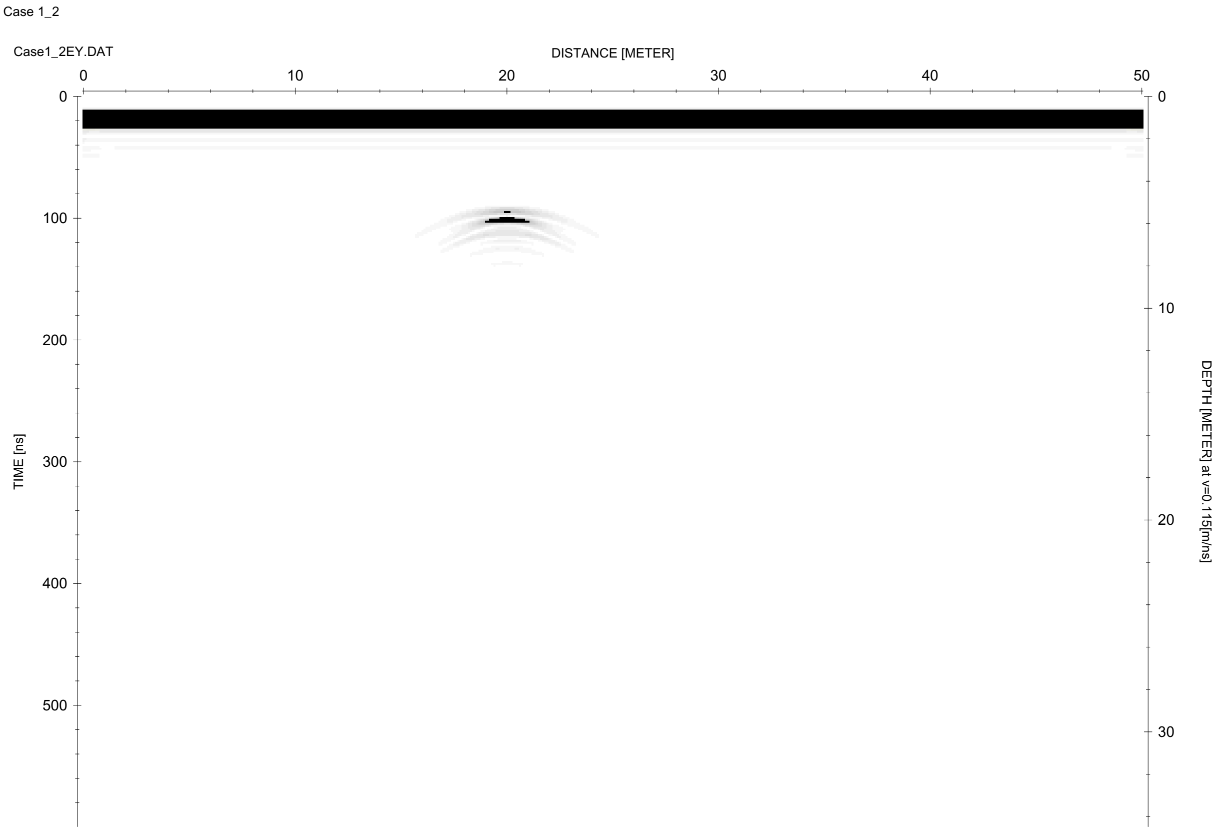


Figure 23. Model 1, case 2. The conductivity of the host rock is 0.0067 S/m and opening filled with air.

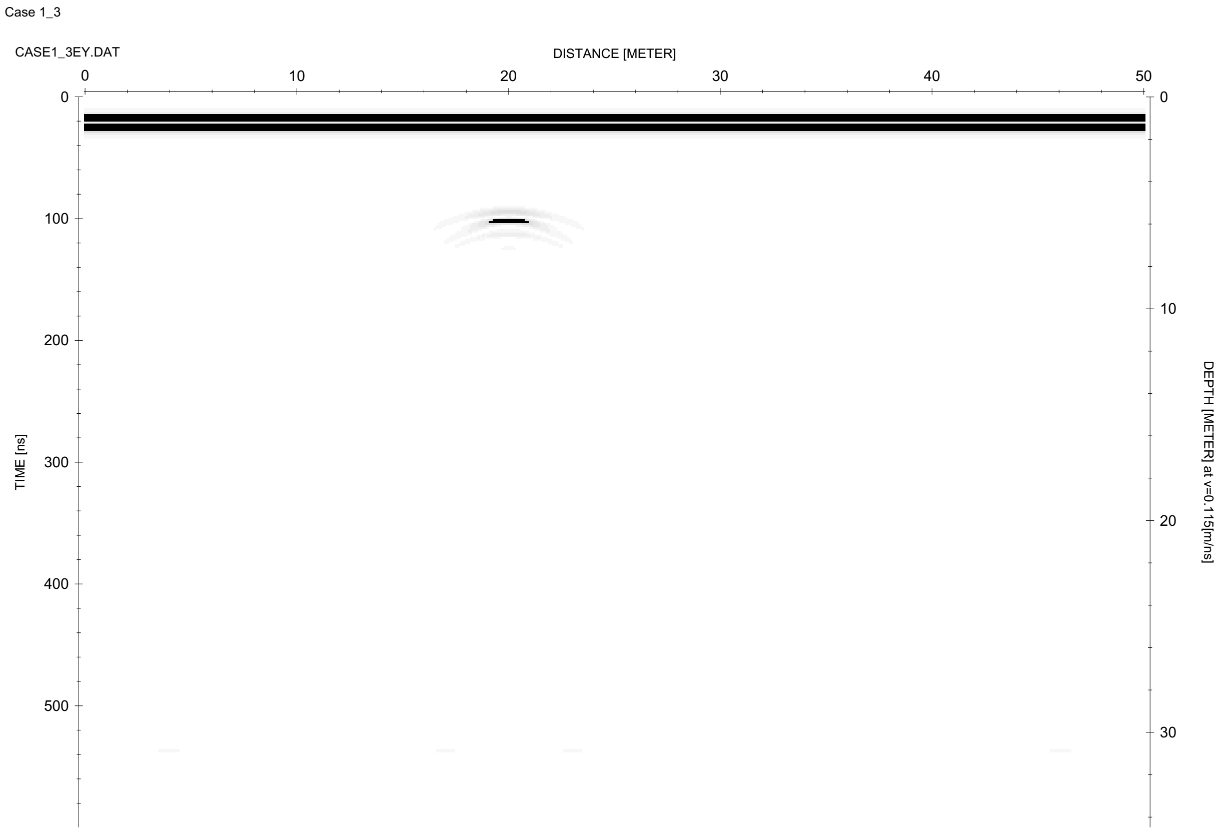


Figure 24. Model 1, case 3. The conductivity of the EDZ and grout-layer is 0.1 S/m.

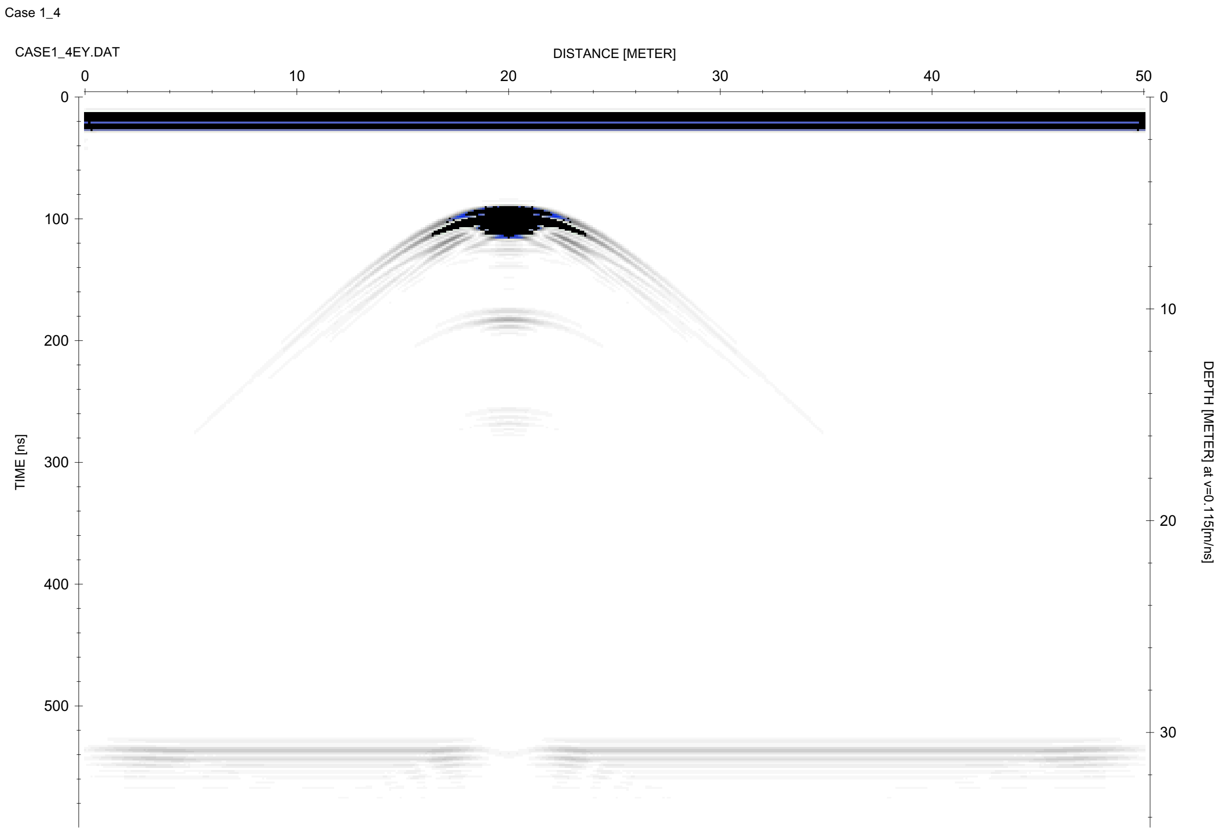


Figure 25. Model 1, case 4. The 2 × 2 m opening is filled with water.

Model 2 describes a theoretical situation where detection of a capsel and deposition hole is studied from a near-by tunnel. Geometric lay-out is shown in Figure 26. GPR line is run along tunnel wall characterised and excavated. Disposal activities run parallel to this at distance of about 25 meters. Disposal operations consist of installing the canisters, backfilling and construction of plug structures. Red coloured canister holes mark bored but empty canister holes. Grey shaded tunnels and vertical holes indicate tunnels and deposition holes backfilled, respectively.

The geometry is naturally a full 3-D situation but some insight can be gained with the help of 2-D models. Host rock resistivity is set in model to 600 Ohm-m. The basic model is built up of three layers. The first is thin, 0.5 meter thick, layer at the surface that represent the excavation damage zone (EDZ) and the grout layer together. The second layer is the host rock and the third layer is added at a distance of 28.5 m that acts only as a reference reflection surface in the modelling exercise.

In case 1 three different cylinders of diameter 1.5 meter are added at a distance of 23.5 meters (Fig. 27). The first cylinder represent the copper canister (ε = 10, σ = 10) within a layer of bentonite (ε = 4, σ = 0.01) the second cylinder is filled with air (ε = 1, σ = 0) and the third one is filled completely with bentonite (ε = 4, σ = 0.01).

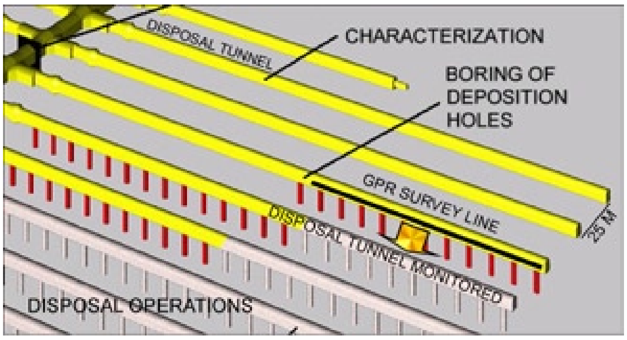


Figure 26. GPR inspection survey lay-out along tunnel in disposal area (image modified from Saanio et al. 2003).

Table VII. Parameters for the basic model 2.

EDZ		Host rock		Reference layer	
ε	σ (S/m)	ε	σ (S/m)	ε	σ (S/m)
12	0.01	6.8	0.002	10	1

In case 2 a layer (ε = 4, σ = 0.01) at a distance of 21.5 meter is added to the basic model to represent the filled tunnel. The centre lines of disposal tunnels are located at distance of 25 meters, tunnel width is about 3.5 meters, thus the separation between adjacent walls is 21.5 m. Canister hole has a distance about 23 meters from the measurement line along the wall. The result of model 2 cases 1 and 2 were added together to represent the situation where the filled tunnel situate above the cylinders (Fig. 28). It is good to note that summing is approximate because the targets are 3-D objects in reality having very finite extents. However, the result can be representative as both objects (tunnel, canister hole) have enough size to give raise to a reflection and situate side by side so that the responses from them are separate and not mutually coupled.

Case 3 includes five cylinders of diameter 1.5 meter which are added to the basic model. One cylinder contains only bentonite (ε = 4, σ = 0.01) and four copper canisters (ε = 10, σ = 10) inside a layers of bentonite (ε = 4, σ = 0.01). The results of cases 2 and 3 are summed together in Figure 29. Reflection from bentonite only filled canister hole is weaker than from the copper cylinder filled ones.

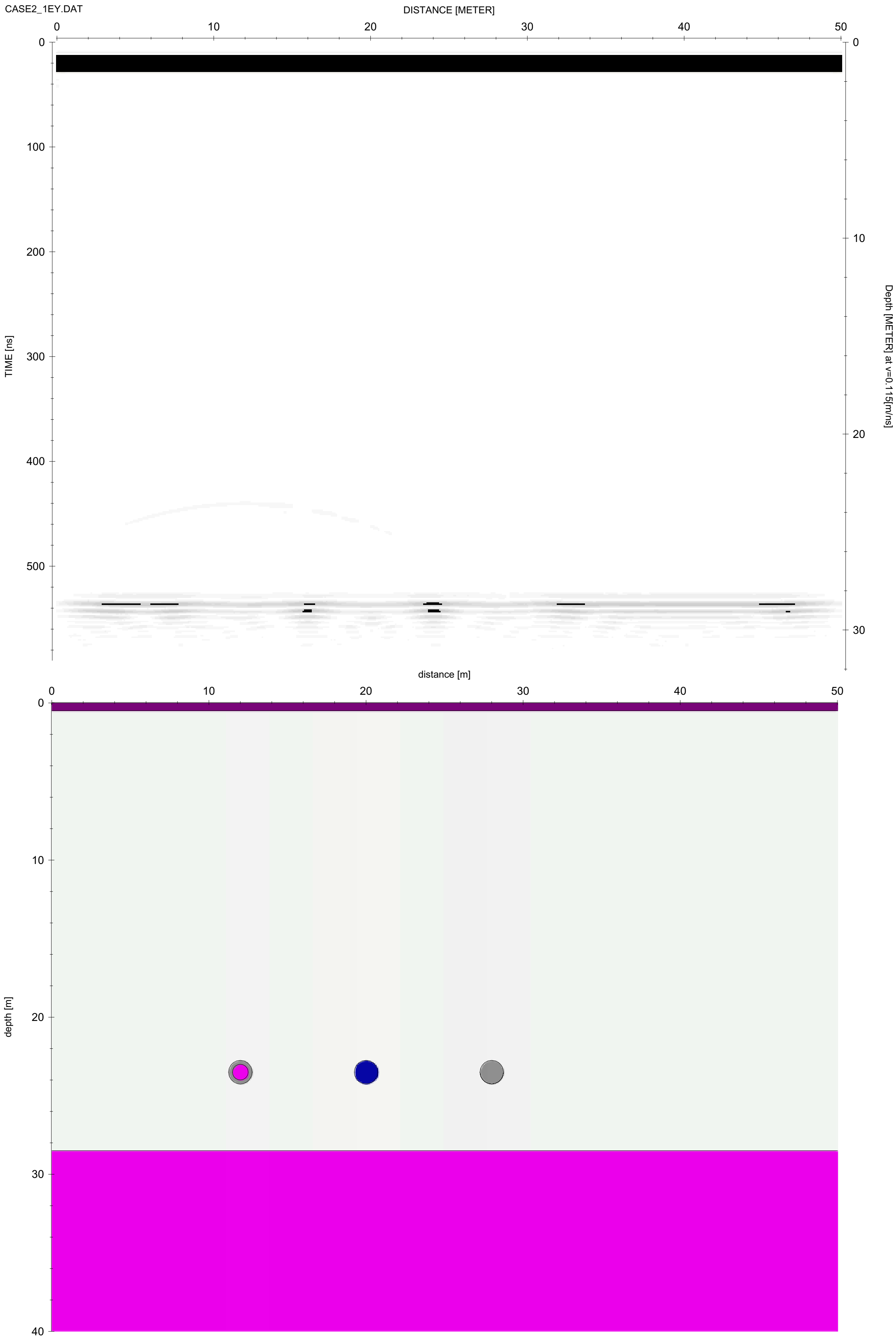


Figure 27. Model 2, case 1. Three different cylinders with 8 meters interval at the distance of 23.5 meters.

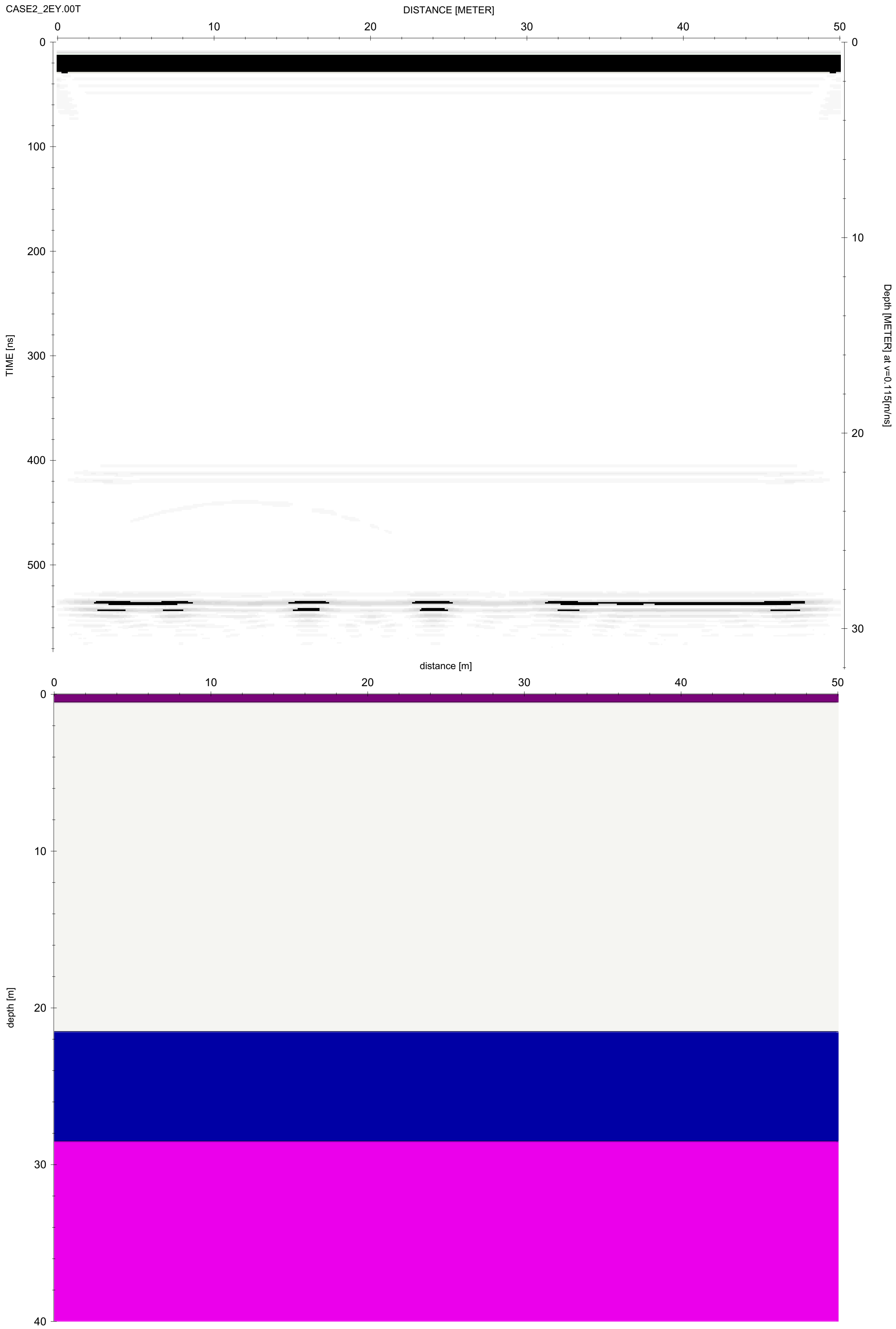


Figure 28. Model 2, case 2. Upper figure is the added result of cases 1 and 2. The lower figure is the model used in case 2. A layer is added at the distance of 23 meters that represent the filled tunnel located above the cylinders.

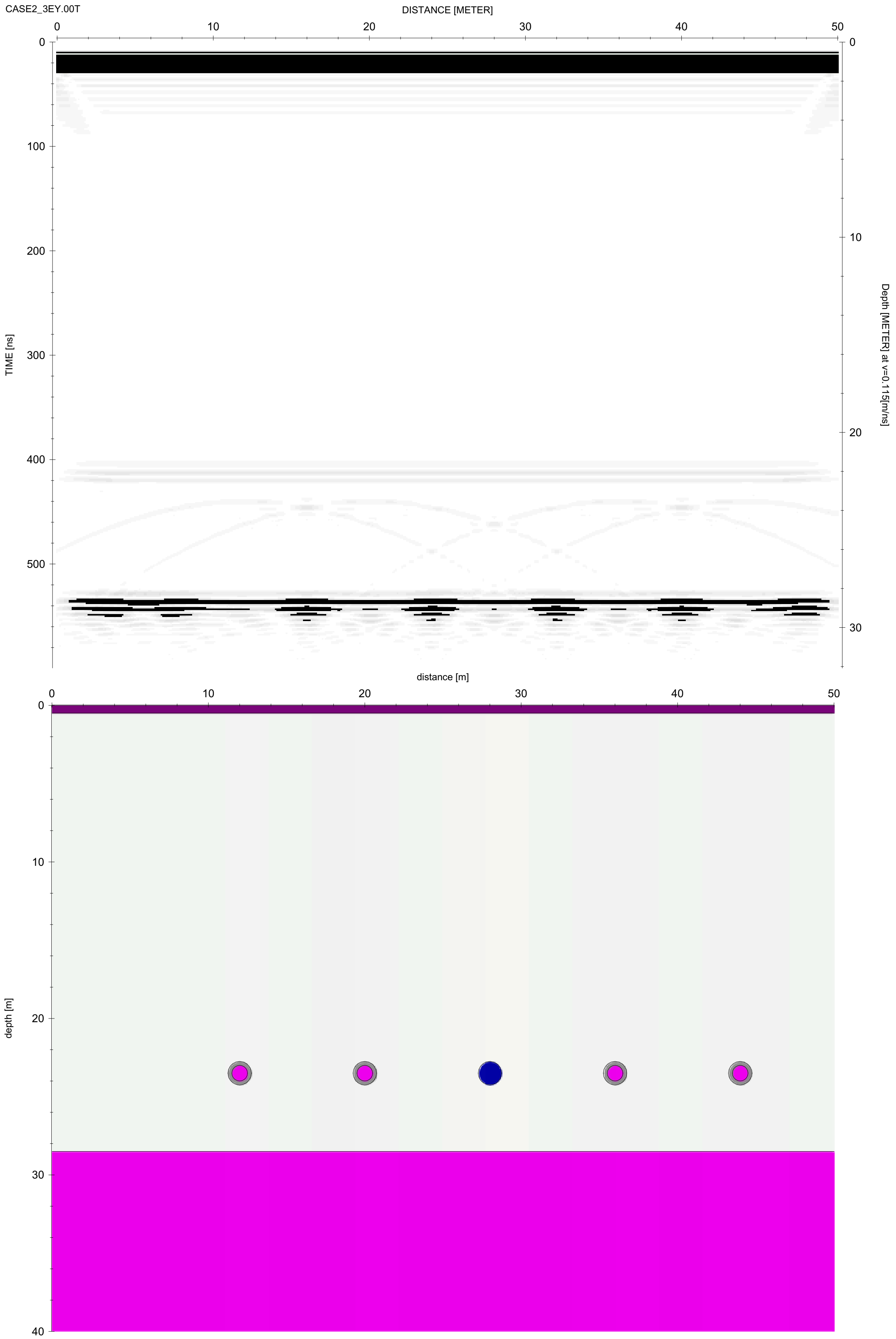


Figure 29. Model 2, case 3. Upper figure is the summed result of cases 2 and 3. The lower figure is the model used in case 3. Five cylinders of diameter 1.5 meter is added to the basic model.

One test where the modelled data was summed into to a real measured data set were done. The real data is from borehole KR10 in Olkiluoto measured with borehole radar using a nominal frequency of 60 MHz. Result of combination is illustrated in Figure 30 as a colour scale plot and in Figure 31 as grey scale image. The two variations are shown to illustrate effect of graphical scale chosen. The sampling frequency and trace distance in the real data set is very sparse (sampling interval 1.4 ns and the trace distance 0.5 meter). The modelled data is from model 1 case 1 and model 2 case 3 thus including both the 2 × 2 m opening filled with air and tunnel configuration with five deposition holes, the central

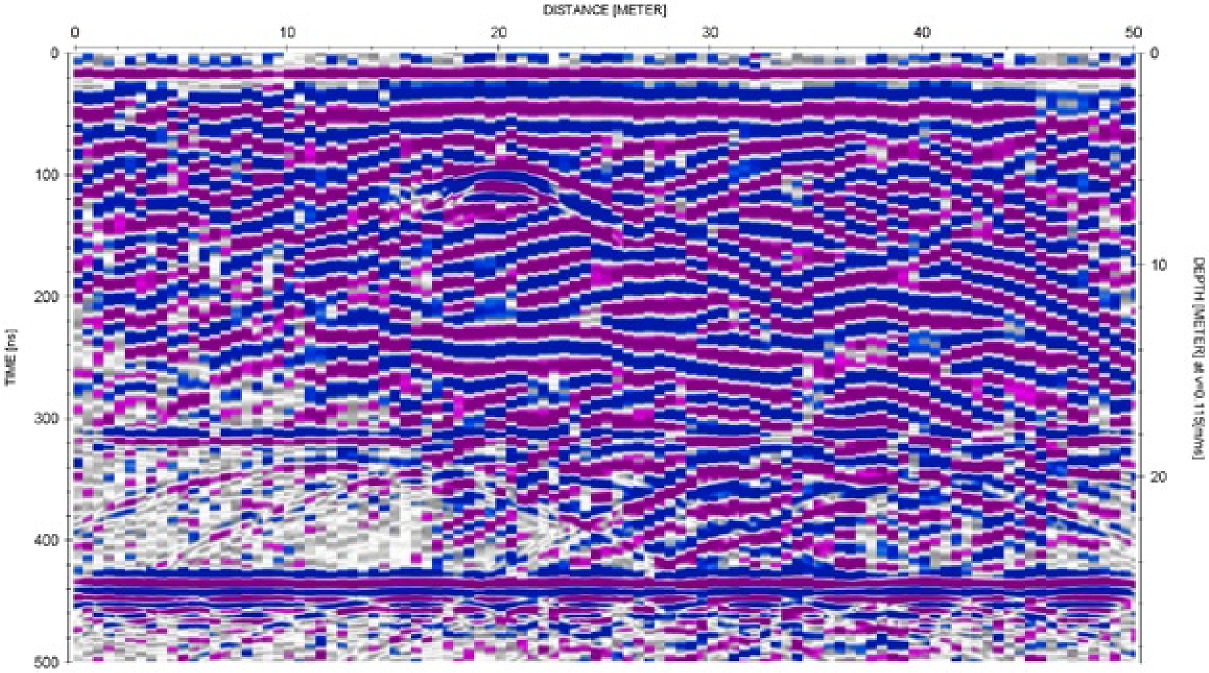


Figure 30. A real measured 60 MHz data is added to the results of model 1 case 1 and model 2 case 3.

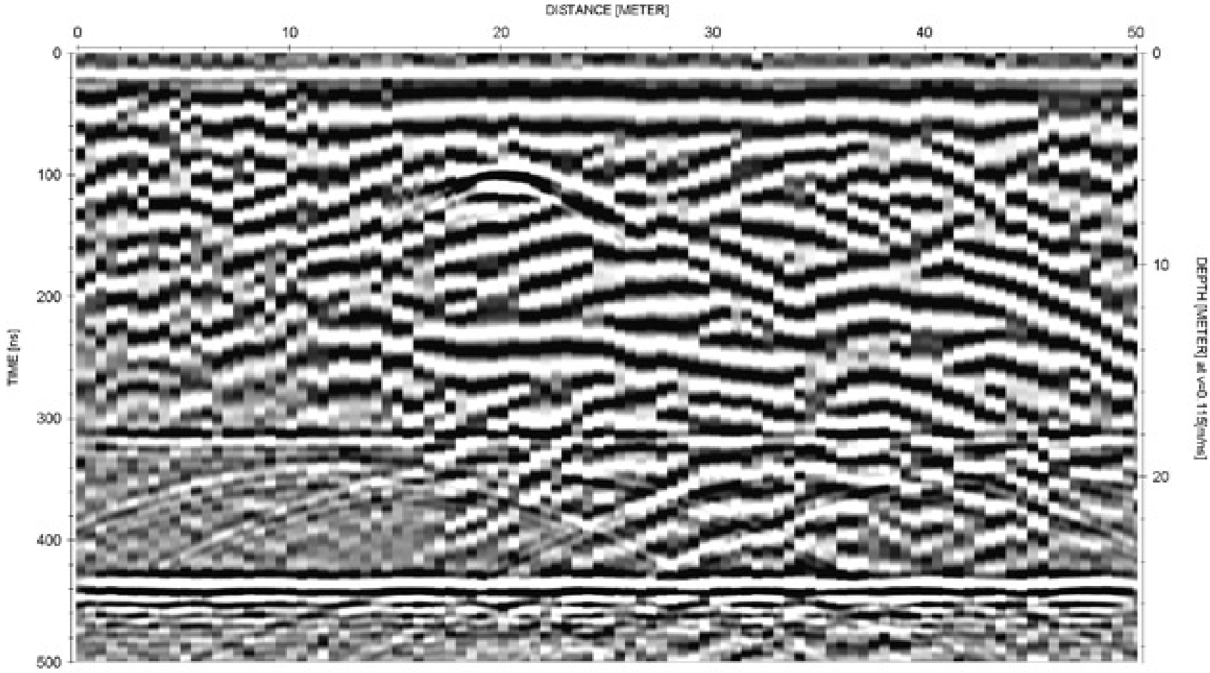


Figure 31. Combination of real measured data and results of model 1 case 1 and model 2 case 3 in a grey scale plot.

one bentonite filled. The distances in model 2 case 3 were decreased with 3.5 meters. The reason for this was that original measurement time range was shorter than really required. Further on, the time window in both models was limited to 500 ns.

The model 1 case 1 and model 2 case 3 reflections superposed with KR10 60 MHz borehole radar reflection image (traces corrected for geometric decay) will display as modelled “the mirror” reflection from highly conductive plane (decay from original strength –36 dB); then the 340 ns hyperbola reflection from canisters (–46 dB; reflection strength smaller than from a perfect plane), and a tunnel front at 320 ns. There is also a reflection of 2 × 2 m wide tunnel from 5 m of the tunnel wall. Decay of signal, –12 dB, would allow observing the reflection well with Olkiluoto parameters, but the natural reflections are masking severely the signal from the tunnel object. Thus it would be essential to plan the survey parameters as well as possible, to distinguish the man-made objects from natural. In a monitoring type of survey it is favourable that accurate geometries are known as a basis. Man-made objects are visually very straight and coherent.

Differences with reality in Figures 30–31 presenting modelling as incorporated to the natural measurement case are:

- The frequency content in numerical model is the theoretic, as the measured one displays the dispersion of the signal to lower frequencies (from 60 MHz to 30 MHz).
- The borehole radar has been measured with radially symmetric dipole field, with 7.5 m offset between transmitter and receiver, whereas the model has been calculated for normal incidence, zero-offset geometry from tunnel wall.
- Superposed results do not encompass the natural delays or speed-up of signal due to air or water, so one essential mean to recognize tunnels – modification of natural reflections – does not become visible.
- Borehole radar data taken is omni directional covering radially full 360°. GPR along tunnel covers only a limited less than 90° sector and correspondingly the amount of natural reflections occurring will be less.

4 Applicability in repository safeguards

4.1 Surveying alternatives

4.1.1 General

Surveying with radar has several geometry and accessibility related possibilities. Naturally suitable ground conditions, tunnel surfaces or boreholes are required. Various configurations available for radar utilization are depicted by Figure 32. Boreholes, ground surface or tunnel surfaces are usable for underground measurements. In tunnel conditions walls (W) are easiest to measure along and roof (R) requires vehicle installation of equipment and antenna as well as cross section (C) line. Measurement along the floor (F) is easy to carry out but filling layer and possible rock damage zone underneath may severely hinder radar penetration and cause disturbances. Penetration with ground measurements (G) is limited to some tens of meters at the highest from the outcrops. Boreholes are drilled from ground surface (S) or from underground rock space (T) for characterisation purposes in the Finnish case at Olkiluoto. Availability of boreholes for radar measurements may vary considerably through time and depends also on the rock quality and amount of groundwater outflow.

Positioning is important part in radar measurements. Positioning can be made by attaching coordinates directly from GPS unit, tachymeter or from other similar instruments. Coordinate values are collected to radar traces forming a radar image. Measurements of line coordinates or time based recording can be made and with tie points the

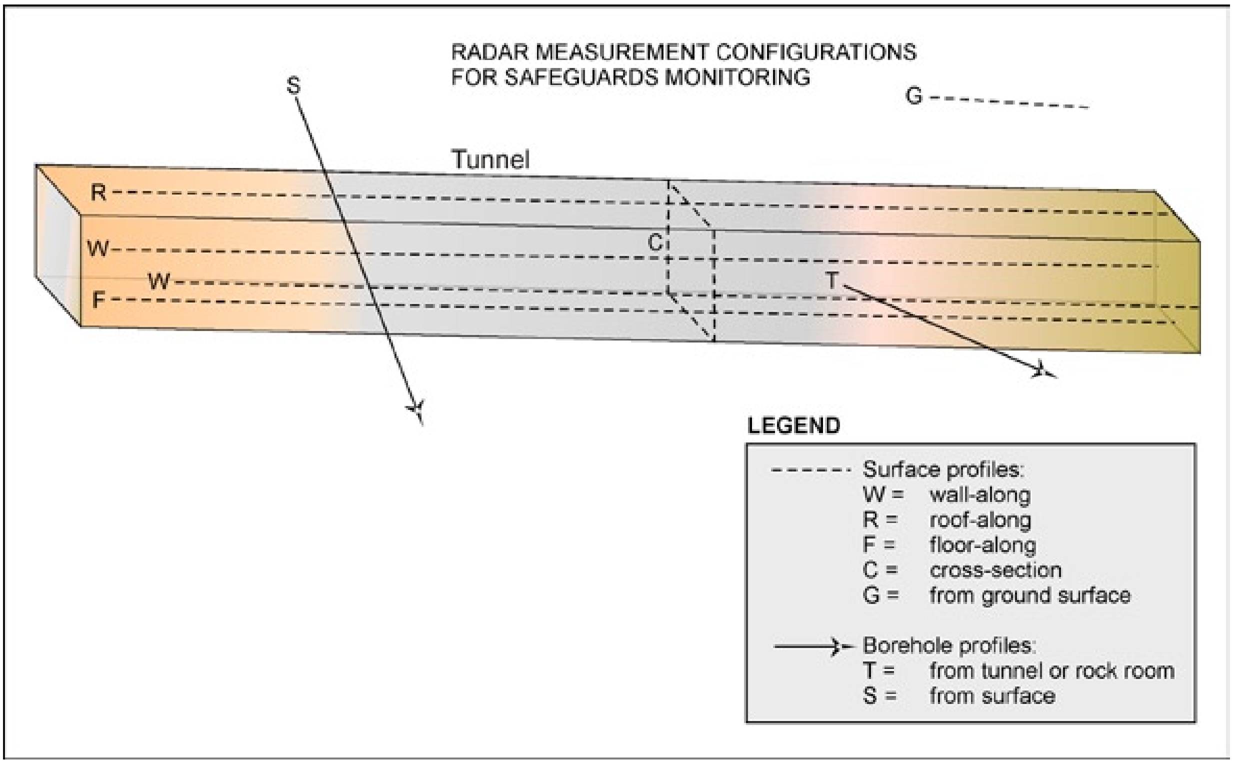


Figure 32. Radar measurement configurations for safeguards surveying.

coordinates are estimated. Markers can be added to radar records when any point having significance in location or showing up in radar results is met. Different timing options and schedules of the surveys are presented in Figure 33 below, and in Chapters 4.1.2–4.1.3.

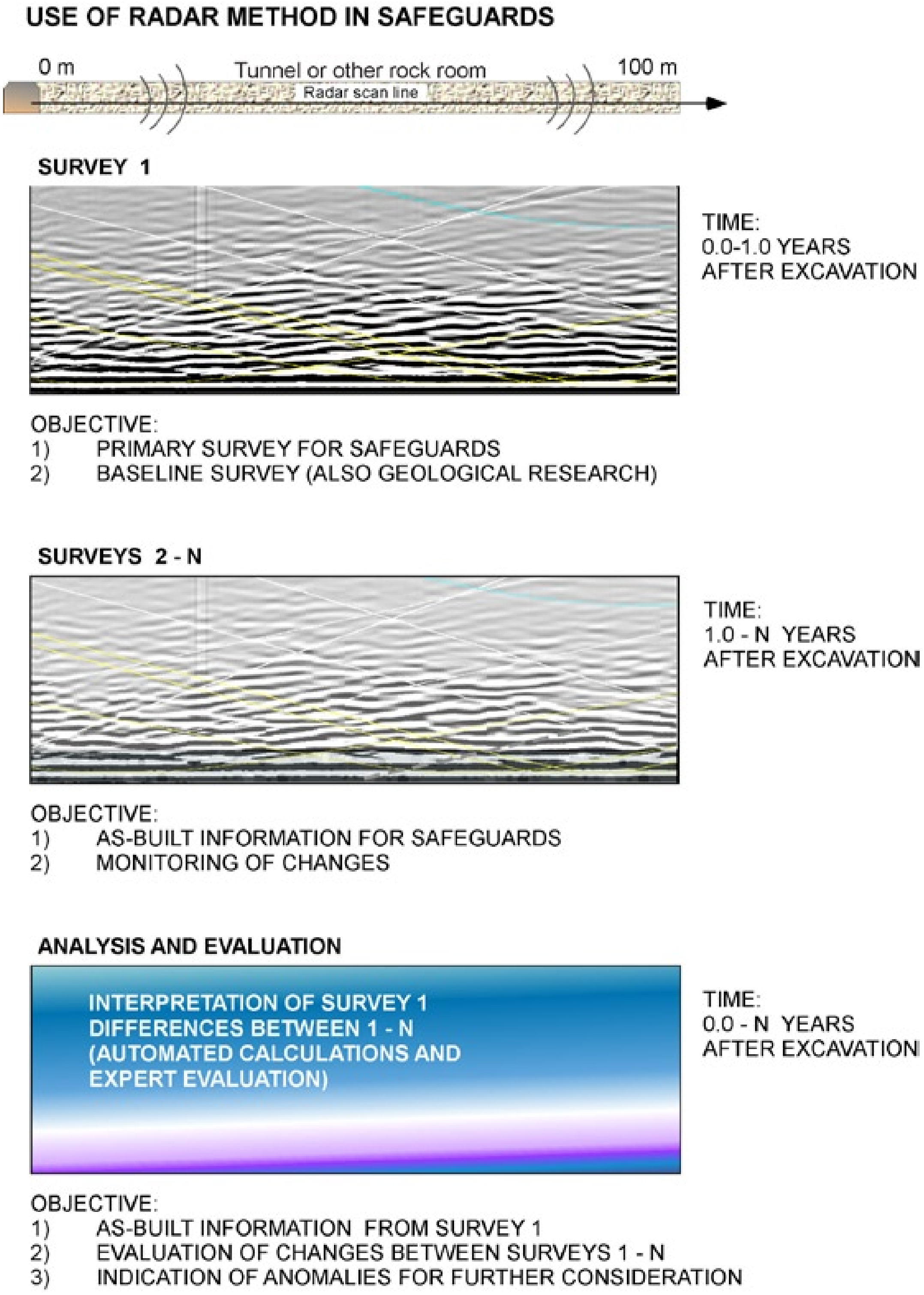


Figure 33. Schematic of the radar measurement timing and purpose during repository construction.

4.1.2 Baseline type of survey

First radar survey forms a baseline which is comparable against the later conducted ones. The survey can also be run only once which means that it is the primary safeguards measurement of its kind. Survey may have been carried out already before any underground construction has been commenced as typically is done in boreholes drilled from ground surface or along surface GPR lines. Baseline survey can be realised also along selected tunnel surfaces when they are accessible or in boreholes drilled from underground space. The purpose of a baseline survey is two-fold: to investigate if there would be indications from undeclared man-made activities and secondly to establish characteristics from the surrounding undisturbed rock mass. It is important to document all survey parameters – layout, positioning, time, instrumentation, settings, calibration, processing steps including also software and its version as well as in-house algorithms and functions applied if any.

The results previously presented from Olkiluoto area indicate that geological objects causing radar anomalies do occur frequently and in a continuous manner in crystalline rock mass. By using higher frequencies smaller features in closer proximity do show up and with lower radar frequencies larger objects can be seen within larger range, respectively.

Natural reflectors are mixed with man-made objects and materials which do show up in measurement results. So the basic task is to separate between geological objects, known man-made objects and non-identifiable ones. Non-identifiable objects can be nature originating or man-made.

In tunnel conditions especially near-by walls, floor, roof, drilling niches, cables, construction materials, communication systems and other EM noise, probe holes (filled) outside tunnel etc. may be visible in the results. All these factors should be documented when the measurement is executed or checked immediate after survey when noticed from results. Identified man-made objects are to be marked in processed data records and described in a log. On the other hand, a priori known sources of disturbances (like vehicles) should be removed temporarily from the measurement site to improve overall performance. Non-covered tunnel surface improves data quality compared to shotcrete covered one. Irregularity of tunnel surface with concave and convex edges, steel rods, accumulated water and any swing caused to antenna package does cause additional noise and quality variations into radar records. The loss and masking of information in radar images caused by these factors is irrecoverable.

Baseline survey may have usage also because there might be changes in the rock mass itself – like drying in rock (both fractures and pore space), chemical precipitation, changes in water chemistry, up-coning of saline water, stress state changes etc. – which may later on manifest themselves in follow-up measurements.

Characteristics of the anomaly can discriminate its source. The shape of anomaly – especially in form of hyperbola originating from tunnel and small rock room – is characteristic for man-made objects. Magnitude of anomaly from a man-made object is typically large because of the high contrast in physical properties. Bearing this in mind a large number of near-lying objects associated with weak anomalies can be classified as of geological origin. In distant and margin areas reached by radar also response from open rock space is a small one but normally larger than from a geological object residing at a similar distance.

Identified man-made objects should be labeled in processed data results. Observations which

- Can not be explained with available geological background data
- Conform with characteristic target shapes searched
- Can not be explained with identified man-made objects

need further evaluation. Careful evaluation is required as it has been made known in previous chapters that in Olkiluoto crystalline rock mass responses from various types of geological objects are met.

Further actions derived from analysis of baseline or primary survey can be

- Repeated survey in a particular place paying special attention to reduction of noise sources or solving them
- Surveys designed to determine the position of the non-identified reflectors (radar or other geophysical method)

It is essential for the safeguards performance of the method, that the procedures are thoroughly designed and quality assured, then tested and validated, and while applying, properly documented and verified. Application of construction design data and expert group in survey design, processing, evaluation and documentation of the results achieved is a necessity in successful application. Expert group work can also diminish subjectivity in evaluation and develop the use of radar further.

4.1.3 Monitoring or inspection type of survey

Second type of radar survey is of monitoring or inspection type. Its purpose is to explore differences between two or several surveys conducted at various times. First or previous survey forms the result against which it is compared.

The technical effort can be repeated in such a manner that the effects due to installations and reinforcements remain invariable and the radar method may be applied to monitor changes in the rock volumes near the tunnel. During a repeated survey it is important to follow the positions, geometry, instrumentation, settings and conditions implemented in a previous survey as accurately as possible. All deviations need to be recorded. Also similarly as during the baseline survey one must document survey parameters – lay-out, positioning, time, instrumentation, settings, calibration, processing – so that differences caused by these are traceable and can be treated accordingly.

Results from a monitoring survey contain in most cases add-ons. Noise signal from constructions and changes in natural conditions may be integrated to results at any phase. Changes in rock mass can take place through drying of rock, stress state, new microfractures, mineralogical–chemical changes and change in groundwater composition. In order to limit groundwater ingress the tunnels will be pre-grouted and post-grouted according to the results of rock mechanical investigations. The methods and the amount of reinforcement and grouting will depend on local conditions, and may thus vary even within short distances along the tunnel wall. Tunnels and rock rooms contain also cables, permanent instruments, electromagnetic noise sources like communication systems, illumination, dielectric and conducting other installations. Also new boreholes for characterisation or grouting may have been established as well as near-by rock rooms may be in a position visible in results. Electrically non-conductive reinforcement is almost transparent to radar waves. Again all these factors should be documented when the measurement is executed or checked immediate after the survey when noticed from results.

It is possible to use also characterisation boreholes drilled from surface or from underground space. Availability of boreholes for surveying may vary. The conditions in the surrounding rock mass outside the boreholes can stay stable and favour in that sense safeguards survey. However, boreholes may not be located in areas of primary interest.

Processing is done in a similar way than for a baseline survey. New reflection events caused by man-made structures are first to be identified and labelled. Design and as-build information is of help to label observed radar features. After that the interpretation and assessment of differences between two consequent surveys can take place. Other geophysical methods like microgravity, electrical or acoustic measurements would supplement the above mentioned design data, and allow cross-checking with non-destructive methods when required.

Natural geological conditions and its inherent presence in radar images is important part in the comparison of the results from the surveys. Two main uses can be:

- Comparison between two radar images and finding differences in them which are not explained by geological features, known man-made structures or changes in the environment.
- Using radar response from hosting rock mass as evidence of natural, geological conditions. Parts of radar profiles indicating disturbances may point out areas where unknown rock rooms or open spaces situate. This is the way how GPR is routinely used to locate subsurface areas where digging or burial has happened–nature originating characteristics has been disturbed (spectral content changes, time deviation, spatial move or end of reflection). Similar type of indication has also been reported by Seidel et al. (2004) where open space between tunnel and reflecting natural surface causes a time shift to the part of the reflection image behind the open space.

The crystalline bedrock at Olkiluoto is of intact quality, homogeneous in larger scale and mainly sparsely fractured. However, rock mass contains fractures in various orientations and properties, there is schistosity and foliation as well as gneissic and granitic variations and veins do occur. Also fracture zones and faults of varying types situate in large volumes of rock. As previously discussed in chapter 3.2.3–3.2.4 rock mass will create almost continuous series of wave reflection events into radar records.

4.2 Operations and instrumentation

Excavation of ONKALO underground premises with tunnels, drifts, shafts, additional rock rooms together with characterisation boreholes will form spatially complex combination of space and related structures. Example of planned underground rock rooms at depth about 420 m is shown in Figure 34 which visualises the concentration of the spaces. It is impossible yet to compile a plan which would be applicable in all different situations to be met. In the future also repository areas will be developed design of which is currently at preliminary stage. Also varying geological conditions have been encountered at Olkiluoto.

The access tunnel to the Olkiluoto deep repository begins at one of the local rocky hills at the level of 9–10 meters above the present sea level. The excavation itself is done by using the classical drilling and blasting method. The ventilation shafts will be first made by the raise boring technique and later slashed up to larger diameter. According to the present plans, the access tunnel to the deep underground repository will advance 20–25 m in a week, and 1 km in a year. The duration of the excavation of the ONKALO will thus be 6–7 years. Continuing the disposal activities after commissioning of the repository around 2020, the disposal would tentatively proceed in panels of 10–20 disposal tunnels 100–150 m long and separated with 25 m of each another, of which 2–4 would be used for disposal and backfilling in each year. All these tunnels are targets of any safeguards activities during the process. Only a part of the tunnels are exposed for such investigations at a time.

The safeguards activity using GPR can take place in boreholes or in tunnel walls (see preceding Chapter 4.1). Boreholes can be used to view the volumes surrounding them to radial distances of 30–40 m. Of suitable boreholes, some may be available drilled from surface investigations and some will be drilled for characterisation from tunnels. Long term availability of boreholes for comparative studies is unknown. Boreholes providing a hydraulic conduit between levels of the underground facilities need to be sealed. Water pressure and collapse of boreholes imply a personnel and tool safety risk for borehole based work, respectively.

Borehole does not suffer from poor conditions due to engineered, supported and excavation damaged surface. For boreholes, a specific low frequency and high power transmission is necessary to obtain

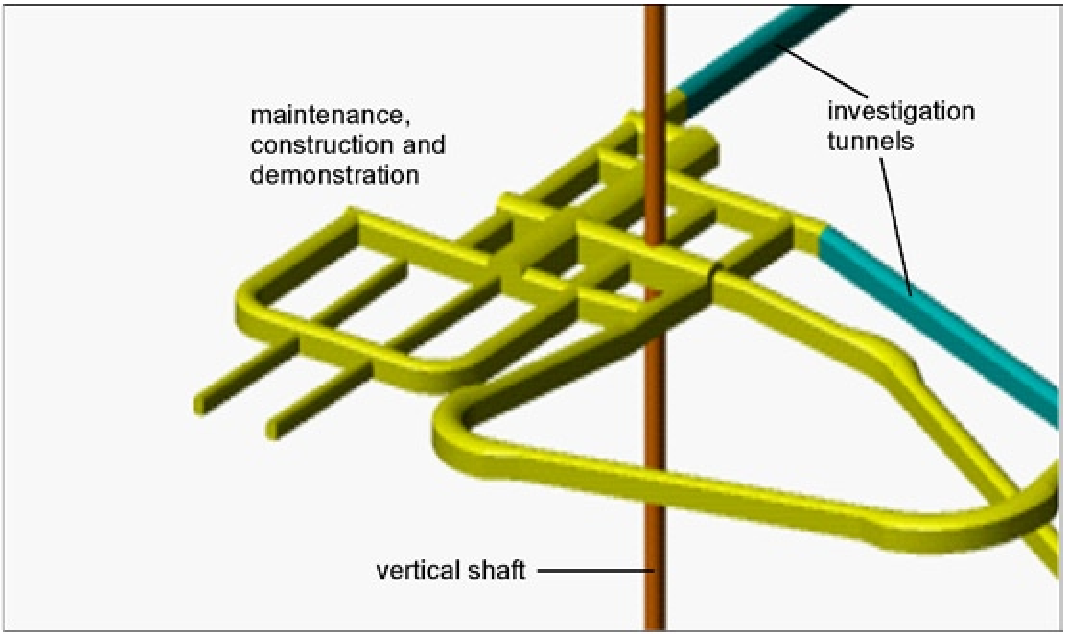


Figure 34. ONKALO underground design at +420 m level. Multiple rock rooms will set high demand for as-built information and its validation. Shaft diameter is about 6 meters.

highest performance. The measurements need to be done in max. trace interval of 0.05 m and time sampling of 0.2–0.3 ns to obtain best accuracy. The antenna offset should be small enough to avoid distortion of images near boreholes. A multi-offset approach aiming to CMP stacking would enhance the image, suppress the noise and enhance the range (Lane et al. 1998). Application of such radar investigation would take approximately a day for map a 300 m long borehole. Processing to a stage allowing exclusion of deviations from as-built information and reported geological site models would take some days to finalise.

Apparently the best antenna solution for tunnel based approach is low frequency 20–50 MHz and high power, properly shielded multi-channel (multi-offset) tool. The antenna design (shielding) and power transmission (up to kilowatt level) would need to be tailored for Olkiluoto specific conditions. The radar tool can be arranged direction sensitive, which on the other hand will set requirement of survey to several directions. The tool offsets need to be designed.

The coupling to the rough tunnel wall has to be organised well. Best applicability of the method will be achieved along tunnel and rock room walls. Long lines are better than short ones. The floors are difficult to see through, and the roof needs special vehicle mounted installation. Smooth tunnel and in general the rock surface improves quality of radar signal.

The tools of low frequency are heavy and large in size. Practical tunnel based work of 6–8 profiles along tunnel, and probable circular measurement around the tunnel rim (2–5 m interval), would proceed in a few days over a 100–150 m tunnel length, as well as processing, too.

Processing practises for both borehole and tunnel based works must be specified during test measurement and documented. This requires involvement of qualified personnel recognising the site conditions, radar method principles and the electromagnetic wave propagation issues. The interpretation and processing procedures shall be followed carefully and the success in this documented.

No complete information coverage around tunnels is possible. In other words no 100% checking of non-reported activities is possible with radar. Tunnel floors and constructed rooms provide obstruct for investigations. Natural reflection objects will generate risk of false alarms and would also mask relevant reflections from man-made structures. Existing and known structures need to be tracked carefully to avoid misunderstanding of the responses.

Geological response is in hard rock always present. Hyperbola shaped natural reflectors and strong planar reflectors exist randomly is rock mass. So, straightforward use of radar for inspection purposes is not possible. Geological response can be used to yield reference data and to separate between natural and underground construction related reflections. Geological response and its character may also indicate disturbed conditions.

Considering constructed underground rooms hidden behind a cast concrete wall, the existence of such may be inspected either from side with Vertical Radar Profiling array or using acoustic tools, or by inspecting directly the concrete structure. Combination of high frequency radar antenna and EM inductive antenna has recently been made available to map steel and iron support structures within concrete. The instruments are targeted for very low (some tens of centimetres) penetration (Malå Geoscience 2005, Sensors & Software 2004, Millard et al. 2003).

4.3 Data management system

In connection with measurements and subsequent interpretation, it is important to consider the overall data management and knowledge components required. Radar instrument itself produces measurement data with positioning data attached or recorded separately. Processing, interpretation as well as 2-D and 3-D presentation needs a software to be applied (“Processing System”). Processing system will also yield the reflections and other anomalies interpreted in a suitable format.

Area information is also a vital part needed to design the survey lay-outs, instrumentation, settings and to estimate influencing factors and achievable results. Environmental description, geological characteristics, geological model in a regional and detail scale if available and petrophysics belong to this category. This is the “Knowledge System” of the area. Test or previous measurement results from the area–if conducted–form part of the knowledge.

“Geometrical System” is currently most efficiently collected to a CAD-system. Underground design data, as-built information and radar survey lines (line codes, line arrangement and line points) need to be stored there. CAD system can also visualise inferred reflections and anomalies and also the geological model(s) available as a reference data. Radar results can be posted as images to actual locations and to section planes. Accordingly results proceed to assessment and evaluations phase both from processing and geometrical systems.

Finally, after evaluation phase all instrumental, measurement, positioning, processing, interpretation and evaluation related data as well as documents (reports) needs to be stored and stay retrievable. This can be arranged in a database. Other possibility is a meta-database within which all data is stored as individual files. Metadata describes at a higher level the content and attributes of the files stored. This part forms the “Archiving System”.

Figure 35 describes the overall data management environment which is needed for efficient and reliable safeguards related geophysical survey, including radar method. Repetitive surveys add-on new measurement data and background data may expand but same procedure applies.

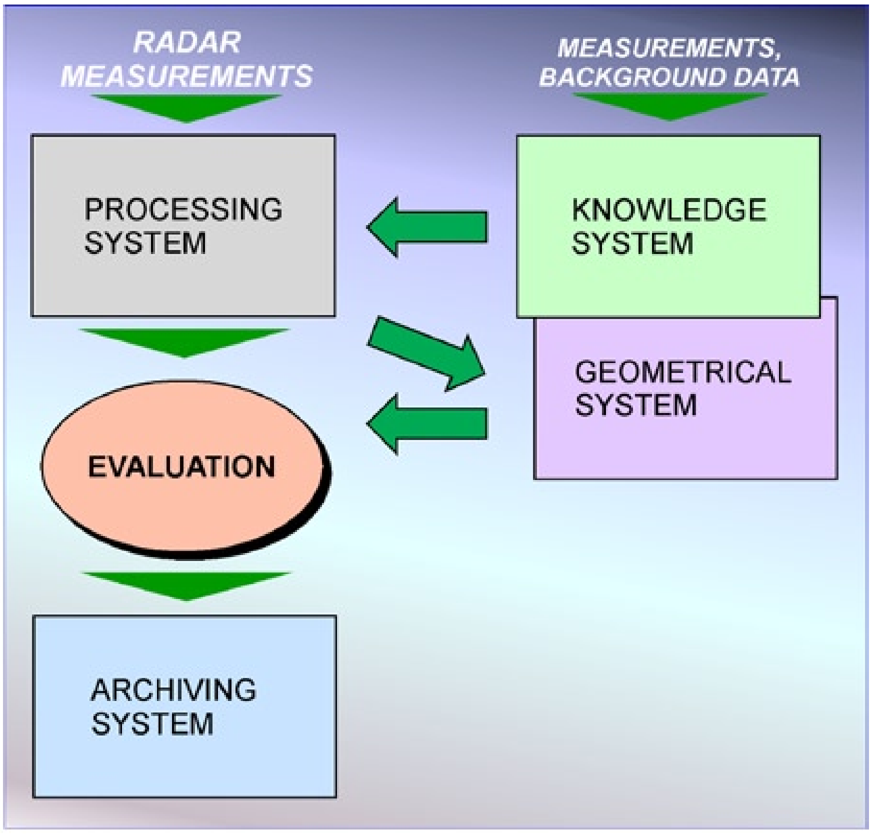


Figure 35. Data management environment which is suitable for reliable and long-term geophysical measurements for safeguards purposes. Arrows indicate the main data flows.

5 Conclusions

Under favourable conditions Ground Penetrating Radar (GPR) will record reflections within a short distance from a rock face. Borehole radar instruments can be used in boreholes to analyse rock volume around the boreholes. These radar methods can be applied to partial verification of as-built information and collecting of characterization data from tunnel walls and from boreholes. The potential role for GPR is in design information verification (DIV), in particular finding undeclared cavities or tunnels. Radar method has ability to detect a 2 metre cubic void at 5 metres behind a rock face in typical crystalline rock conditions.

Based on results presented from Olkiluoto, it is typical that a number of radar reflections will originate from bedrock itself. The origins of all of anomalies can not be verified in a conclusive manner without supplementary measurements and direct observations (drilling and sampling).

The use of GPR in safeguards will be essentially based on possibility of combining the geological data and underground facility design data to information obtained from the radar data interpretation during evaluation. Baseline type of survey establishes results against which possible inspection type of surveys are compared. Radar survey may provide also useful data for characterisation purposes in local and detail scale. Radar response from geologic media can be used as an indication of underlying natural and undisturbed conditions if the rock surface has a permanent cover.

There are several temporal moments when the radar method can be applied. Baseline type of survey can be run soon after primary construction phase. Inspection types of surveys are applicable through long time span. As the modelling example of this study indicates, radar method may have potential in monitoring of future disposal operations and their completion from adjacent tunnels. After backfilling, no adequately detailed inspection method is currently available. There would be plenty of time to carry out the 1–2 week measurement and interpretation period required for the task each time.

The survey design can be assisted with geological site description, geological model(s), limited tests on site and modelling of the physical environment based on estimated or known site properties.

The application of the method requires qualified expert for designing the survey, operate and do processing. After the initial geophysical survey is carried out, processed and documented, a follow-up or monitoring programme may be re-run by less experienced personnel, under supervision of the above mentioned expert. A designated and trained operator can provide the survey on request following given specification.

Radar surveying requires a system with data processing and management capability. A combination of radar processing software and CAD-system is appropriate. Information consists of measurement and positioning data, line arrangements, design and as-built data, processing, interpretation and evaluation records, site data and visualisations. Each surveying round produces own data set and may have individual as built data accomplished.

Indicating and tracking the origin of the recorded data and processing steps involved is of crucial importance in the process. The repeatability and comparability between different measurement times need to be specifically concerned. All tool and processing related information has to be documented thoroughly. Making deductions from the obtained radar data and interpretations will require maintaining the geological characterization data along with the design information. Still the decisions upon the “alarm status” would require tracking of all relevant information, and involvement of qualified personnel. Modelling of expected radar responses from the existing constructions can be of help in evaluation.

A GPR baseline for the whole of the repository may not be needed, since the reference is the declared repository design. Applicability of radar method is limited to the partial coverage of immediate volumes at proximity of the tunnels and building confidence to established as-build information as given. Only a partial verification of absence or disclosure of non-reported features is possible. There are limiting factors like engineered structures, radar range, and dead angles present, and the accessibility time span is limited due to backfilling of the disposal tunnels.

The verification of the progress in tunnelling should be carried out in such a manner that the excavated volume can be documented in concordance with the geological investigations before the rock walls are reinforced. After the reinforcement, the existence of any undeclared voids is very difficult to prove without disturbing the operational safety of the facility.

Supplementary safeguards measurements are possible to solve reflection anomalies. Density variations can be mapped with microgravity (fast to perform, general in nature), and seismic high-resolution reflection (for example, tunnel VSP array) or transmission investigations are applicable. Electrical mapping-soundings can achieve similar or larger range of investigation than radar, but using longer investigation time and lower in resolution. Electrical soundings can be applied through reinforcement steel mesh or shotcrete. Integration of interpretation results from several methods explains anomalies and positions them more accurately.

For re-verification of as-built information, a standard procedure shall be designed and tested, which would include the necessary descriptions and precautions concerning the radar method, tools (central units and antennae), application methods, imaging and processing/settings, interpretations, required and adequate competences, and documentation. This would aim to assure the proven reliability of the repeated measurements and their relevant interpretations. The available tools can be tested at a suitable site to study instrumental effects, repeatability, and sensitivity to optimise surveying geometries.

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