SKB

TECHNICAL REPORT

91-43

SKB - PNC Development of tunnel radar antennas

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July 1991

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SKB - PNC
DEVELOPMENT OF TUNNEL RADAR ANTENNAS

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Swedish Nuclear Fuel and Waste Management Co, (SKB) and Power Reactor and Nuclear Fuel Development Co, (PNC), Japan have carried out a development project concerning tunnel radar antenna. The project has been managed by SKB. The development and construction have been made by ABEM AB. Field tests are performed by ABEM AB at suitable underground tunnels in Sweden and Japan.

This report concerns the development work which has been carried out in the project. The conclusions and viewpoints presented in the report are those of the author(s) and do not necessarily coincide with those of the client.

Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32), 1989 (TR 89-40) and 1990 (TR 90-46) is available through SKB.

DEVELOPMENT OF TUNNEL RADAR ANTENNAS

FINAL REPORT

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July 1991

ABSTRACT

Tunnel antennas for the RAMAC borehole radar system have been developed and tested in the field. The antennas are of the loaded dipole type and the receiver and transmitter electronics have been rebuilt to screen them from the antennas. A series of measurements has demonstrated that the radar pulse is short and well shaped and relatively free from ringing, even compared with the existing borehole antennas. Two antenna sets were tested: one centered at 60 MHz and another above-100 MHz. Both produced excellent radar pictures when tested in tunnels in Stripa mine. The antennas have been designed to be easy to carry, since the signal quality often depends on the way the antenna is held relative to electric conductors in the tunnels.

CONTENTS

1. INTRODUCTION

1.1 Background

The RAMAC borehole radar system was originally developed during phase 2 of the Stripa project (Olsson et al., 1987) and has by now become a commercially available product. A number of systems have been constructed and applications in different areas have dictated several improvements. In particular the computer software has been considerably developed to simplify mesurements and analysis of the collected data. A directional antenna has also been constructed which allows the operator to determine the azimuth of a target from measurements in a single borehole.

In many applications it is necessary to place the radar antennas on the ground or in tunnels near a borehole. The velocity calibration of the radar pulse is for example often performed by placing an antenna at some distance from a borehole and then moving the other antenna down the borehole while measuring the position of the pulse. In many cases the fixed antenna is placed on the ground but it is preferable to locate it in a tunnel or borehole to avoid the influence of the overburden, where the properties of the rock are often modified.

Tunnel antennas increase the possibilities of measuring in other configurations than in single boreholes or between two boreholes. It is sometimes necessary to measure from a tunnel to a borehole, between a tunnel and the ground, etc. Such configurations have been tested in the borehole radar project, e g during tomographic experiments in Grimsel in Switzerland, where the number of rays was extended by moving one of the borehole antennas along the tunnel from which the boreholes had been drilled. The quality of the signals was quite good and the measurements contributed significantly to the success of the salt injection experiment. This was in fact the first experiment which tested the principle of difference measurements with a borehole radar. The analysis requires good signal quality, since the two measurements were performed several months apart (Niva et al., 1988).

In this and other experiments the quality of the signal did not deteriorate significantly although the antennas were placed in a tunnel rather than a borehole. The borehole probes are awkward to carry because of their length and weight; in addition to the antennas they contain both the electronics and the batteries. Minor differences were noticed between signals transmitted from the tunnel and from the boreholes, when signals were compared near the intersection of a boreholes and the tunnel, but the effect was not large enough to prevent tomographic analysis of the data.

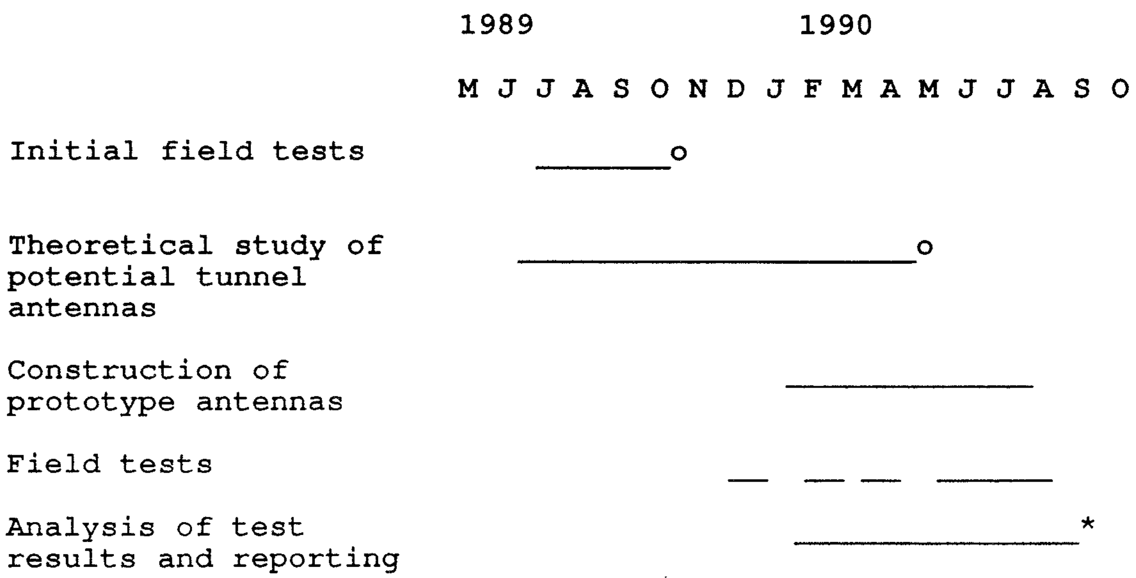
Borehole antennas have occasionally been used from the ground in ground-to-borehole measurements, but they are too heavy to be employed regularly. The freedom offered by a tunnel compared with a borehole makes it very attractive to construct special antennas for tunnel use which would be easy to handle. The first antennas of this type were tested in 1988, but experiments performed on the ground and in Stripa mine were only moderately successful; in particular there was an unexpected amount of ringing in the signal. A year later the tunnel antenna project was initiated with the support of Svensk Kärnbränslehantering (SKB) and Power Reactor and Nuclear Fuel Development Corporation (PNC) to develop radar antennas directly designed for tunnel use.

1.2 Project organization

The tunnel radar project has been funded by PNC and SKB and managed by SKB with Karl-Erik Almén as project manager. The development and construction of antennas has been conducted by ABEM with Dr Olle Olsson as development manager until July 1990 when Dr Lars Falk assumed responsibility for the project. A joint project coordination and reviewing group was formed to supervise the technical work. This group consists of four persons:

Dr Olle Olsson, ABEM
Dr Koiji Tsubota, PNC
Mr Hideki Sakuma, PNC
Mr Karl-Erik Almén, SKB

The project plan involved theoretical and numerical studies of broadband antennas and the construction of a field equipment for experiments in tunnels. Initial field tests with existing antennas were performed in Kamaishi in 1989. After an initial delay the project timeplan was fixed as follows:



o Interim reports
* Final report

The tests in Kamaishi were performed by Olle Olsson and Lars Lundmark (Olsson, November 1989). The theoretical analysis was reported in an interim report surveying the literature and the theory of broadband antennas (Falk, September 1990). The numerical and experimental work performed with different antennas in order to select antenna types was described in a second interim report (Falk et al., November 1990).

The following construction and field tests were delayed because of difficulties with antenna ringing, which would have made measurements meaningless. This problem required extensive testing in the laboratory until it was clarified that the ringing was caused by coupling between the antennas and the electronics. The control unit was rebuilt to improve the screening and the field tests were then performed in Stripa with excellent results. The radar measurements were briefly decribed in a report on Technical Results in December 1990 and the final report was issued in draft form in April 1991. The present report describes the principles, the design and construction of the antenna and the final tests performed with the equipment.

1.3 Project description

At the beginning of the project previously constructed tunnel antennas were tested during measurements in the Kamaishi mine. The original borehole antenna unit had been rebuilt by placing the electronics and batteries in a housing over the antenna. The antennas were loaded dipoles of a type successfully used in the borehole probes. The pulses were fairly good but ringing often occurred. Ringing produces clutter which makes it very difficult to observe weak reflections, but reflections from fracture zones could still be discerned. The reflections were, however, rather diffuse compared to typical borehole measurements. The amount of ringing varied with polarization and measurements on the smooth floor produced for example better results than antennas pressed against the walls (Olsson, 1989). The reasons for these difficulties were obscure at the time. It was assumed that the antennas were sensitive to the distance from the wall but other parameters might also be involved.

From this early test the work continued in two directions:

1) a theoretical study was performed of different broadband antennas near an interface between two media;

2) antennas were tested in the laboratory to investigate how sensitive different antennas are to variable external conditions.

The theoretical study is recorded in a review of the literature on broadband antennas (Falk, September 1990). There are hardly any published studies on the antennas used in ground penetrating radars, though successful systems have been developed, e g by GSSI in USA and Software Systems in Canada. For commercial reasons very little has been published about the performance of radar antennas, though the basic principles are well known. Some details can be found in a study of the GSSI radar antenna performed by Duke in his Master of Science thesis, where he measured the radiation pattern of a GSSI antenna (Duke 1990).

The most detailed calculations concerning antennas near an interface between two media are presently available in papers on printed circuit antennas, a field which has developed rapidly during the eighties; from this work some conclusions can be drawn about possible designs. The theory of broadband antennas is reviewed in section 2.

The experiments performed in the laboratory at first produced confusing results. It is an old dream of many radar groups to construct a ground penetrating radar, where only the antennas are moved by hand by the operator while the electronics and the batteries are carried separately. Experiments demonstrate, however, that a coaxial line connecting the antennas with the signal unit will couple to the radiated field in an unpredictable manner which may produce errors in the measurements. The experiments designed to overcome these difficulties will be described in section 3 together with the final construction.

Many experiments were performed with a HP network analyzer. This instrument displays antenna properties as a function of frequency but the analyzer can also Fourier synthesize the results and display the antenna response directly as a function of time. The instrument would in fact be an excellent radar, if it were more robust and attempts to use it this way have been undertaken by at least two groups, at BRGM and NGI, though not yet quite successfully. The network analyzer permits a direct study of broadband antennas. The early experimental results were discussed in the second interim report (Falk et al., November 1990) and are described in section 3, since they in effect decided which antenna should be used in the field equipment.

The two candidates selected for tunnel antenna tests were wellknown broadband antennas: the resistively loaded dipole and the bowtie antenna. Tests with more exotic types such as magnetic dipoles and transmission line antennas were not promising enough to merit further experiments. The candidate antennas were tested both in the laboratory and in Stripa, where it soon became obvious that ease of handling the antennas is just as important as the quality of the signal.

Many questions concerning the antennas were only resolved after real tunnel measurements; in particular some of the results obtained in the laboratory apparently contradicted the numerical calculations. The most important problems were as follows:

1) How sensitive are antennas to the distance from the tunnel wall?

2) Which electric parameters will determine antenna performance?

3) Is it necessary to screen the antennas to reduce interference

with waves propagating along the tunnnel?

4) Which is the optimum antenna design?

All these questions were considered already during the theoretical stage of the work, but they involve so many parameters that definite answers could only be obtained during experiments. The external interference from the electronics forced us to rebuild the measurement equipment completely at one stage, which delayed the field tests. Thus the work described in this report does not only concern the construction of efficient antennas but also the antenna electronics units. The equipment was redesigned by Olof Forslund and built by him and Bernth Johansson. Most parts of the RAMAC equipment were, however, used in their existing form (signal unit, computer software, etc). The presentation owes much to the talents of Bo Hesselström, who has produced most of the software presently used with the system.

2. THEORY

Ground penetrating radar has mainly been discussed in the form of articles and conference papers; a comprehensive source covering the whole subject is still not available. A review of some problems can be found in a recent issue of IEE devoted to ground penetrating radar (Daniels et al. 1988). Some conclusions can also be drawn from two recent conferences devoted to ground penetrating radar: the SEG meeting in Dallas 1989 and the conference on ground penetrating radar in Denver 1990. The conference papers are mainly devoted to measurements and their interpretation and very little information is presented about the construction of radar systems. The workshop at the SEG meeting in Dallas 1989 was, however, entirely devoted to antenna design for ground penetrating radar, but few details of importance were revealed during the discussion. The conference indicated that many problems are related to the manner in which the equipment is used and the results interpreted by the operators.

The lack of published information is particularly noticeable concerning antennas for radar measurements from tunnels or the ground. Most of the work in this field is proprietary and there do not exist any complete descriptions of functioning system.

2.1 General principles

The frequency window suitable for radar work is limited: below 1 MHz there is hardly any wave propagation in rock and above 1 GHz the penetration is restricted to distances less than a meter. Ground penetrating radar is used at frequencies 100-1000 MHz in order to detect objects close to the surface. The range is typically a few meters, but it can vary significantly depending on external conditions. The RAMAC borehole radar is on the other hand designed for frequencies below 100 MHz in order to map large volumes of rock. The range is on the order of 100 m in crystalline rock as demonstrated during the Stripa project (Olsson et al., 1985; 1987). Borehole radar has also been tested in other types of rocks with reduced but still acceptable range. The most popular antennas are the 60 MHz units which produce good resolution though they have only half the range of the 20 MHz antennas.

The radar pulse must be very short to produce acceptable resolution of a reflecting object. A pulse radar is thus by necessity a broadband system and the pulse is in general not much longer than the average wavelength. The bandwidth is on the order of the central frequency of the pulse and this condition introduces severe restrictions on the radar components. All parts of the equipment must be designed to handle short pulses with minimum distortion: this problem is particularly difficult to solve for radar antennas because their function is restricted by other factors determining their size and shape, in particular the total weight of the system and borehole diameters.

Antennas are often designed to have welldefined properties in a stable environment. A radar antenna for tunnels must instead be insensitive to changes in the environment. Such variations are caused by inhomogeneities in the dielectric properties which occur as the antennas are moved over the ground or in a tunnel. The presence of a layer of soil is particularly annoying. The main fluctuations are caused by variations in the height of the antenna over the surface. Even small variations in height can change the antenna pattern and input impedance. Theoretical investigations of these effects in tunnels have not been published in the literature, except in work devoted to communication in tunnels where some information can be obtained about antenna properties (Delogne, 1982, 1991; Wait and Hill, 1974, 1975, 1977).

In radar applications it is not necessary to solve a boundary value problem for a specific antenna, but rather to design an antenna which is unaffected by the boundary values. This means that the pulse emitted by the transmitter electronics must see a nearly constant antenna impedance, since otherwise it will be reflected and distorted at the antenna feed. The radiated energy should be transmitted into the rock in undistorted form. On the other hand as little energy as possible should be radiated upwards or into the tunnel in order to reduce reflections. Screening of the antennas is a possible remedy but screens are difficult to design at the low frequencies used by a radar in rock. The wavelength is about two meter and the pulse will consequently leak past most screens of practical sizes.

2.2 Properties of the ground

From the radar point of view the ground is characterized by two parameters: the dielectric constant, which determines the velocity of the radar pulse, and the electric conductivity, which is related to attenuation of the radar pulse. These parameters vary with frequency and depend on composition and water content. Radar measurements are only possible if the wave can propagate many wavelengths without significant attenuation and distortion. This condition restricts ground penetrating radar to frequencies above 1 MHz, because below this limit the electric field propagates by diffusion.

Typical values for the dielectric constant in rocks are 5-10 but occasionally higher values are observed, while soils can vary in the range 5-20. The wavelength will as a result be 2-4 times smaller than in air at the same frequency. Typical values for different rocks can be found in the literature (Cook, 1975; Sandberg at al, 1991). The parameters have been measured at radar frequency, which is essential since the dielectric permittivity and conductivity vary with frequency. The electric parameters of rock can easily be measured in a laboratory to predict whether a radar measurement is feasible or not.

The conductivity of rocks and soils is more variable than the permittivity, but both are strongly influenced by water as shown in Figure 2.1, where the permittivity is seen to depend linearly on water content for concentrations less than 10%. Clays present particularly difficult obstacle because they release ions on absorbing water and this makes them almost impenetrable to radar waves. The conductivity of a rock will determine the attenuation of the pulse, though the geometrical spreading also plays a role.

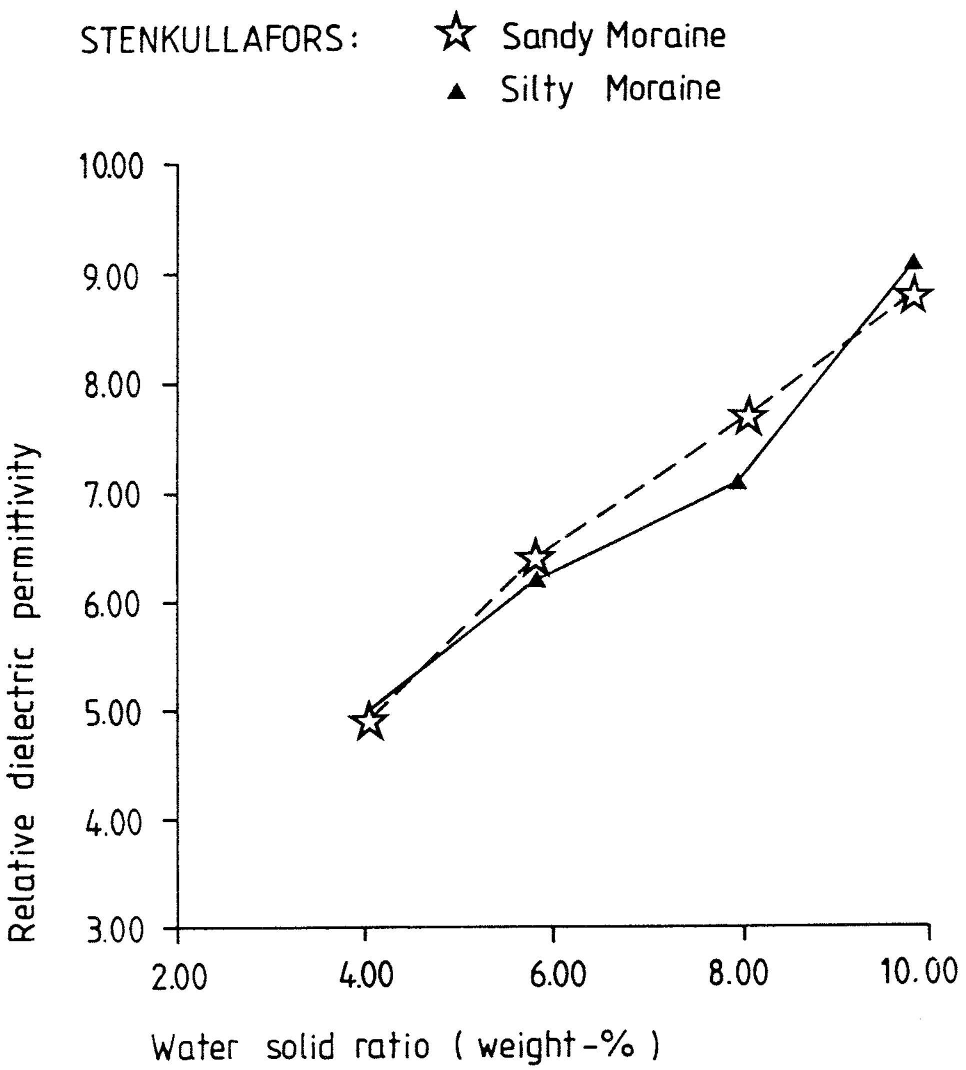


Figure 2.1 The relation between permittivity and water content for two moraines from northern Sweden.

In practice radar measurements from a tunnel are rarely attempted unless the electric resistivity of the rock is higher than 100 ohmm. This limit is determined by the condition that the pulse must propagate several wavelengths before it is significantly attenuated; otherwise there will only be diffusion of wave energy. This condition is easily satisfied in granite, but if there is an overburden of soil there may be problems. The thickness of the soil varies like its composition and water content. It is consequently necessary to construct antennas which will function reasonably well under different conditions rather than to construct antennas which work perfectly under welldefined circumstances.

2.3 Basic antenna types

The most important limitation imposed on the tunnel antennas is that they must be broadband even under variable external conditions. The wavelength is on the order of meters so aperture antennas can not be used in spite of their excellent broadband properties. The aperture must be several wavelengths in diameter and such antennas are consequently only used above 1 GHz.

Another restriction is imposed by the feed: the connection to the network is usually made by coaxial cables and their constant impedance must be matched to the antenna over a wide frequency band (Ramo et al., 1984). For this reason the antenna should have constant real impedance over the frequency band covered by the pulse.

Some candidates for ground radar antennas will be briefly reviewed. Historically true broadband antennas appeared only after the Second World War. Before the war the maximum bandwidth was about 2:1, but the development during the fifties produced antennas with bandwidth ratios 40:1 or more. The antennas that have been considered candidates for radar application can be separated into some typical classes (Balanis, 1982; Miller, 1986; Daniels et al, 1988).

2.3.1 Loaded dipoles

Dipole antennas were the first antennas used for radio transmission and the theory of wire antennas has since then been studied in detail. Approximate solutions can sometimes be obtained in analytical form but are usually calculated on computers. An important advantage of wire antennas is their low weight and ease of construction.

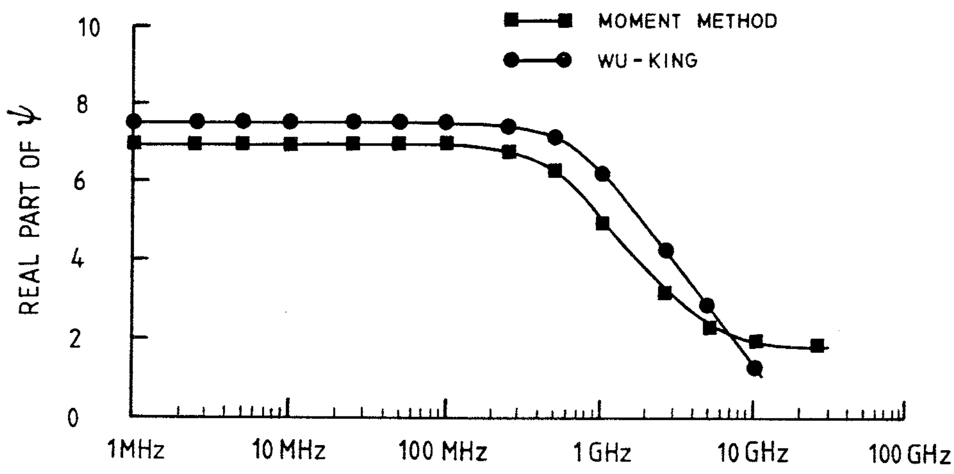
The standard halfwavelength dipole is an efficient antenna at resonance but the resonances are very narrow. Many different techniques have been suggested to increase the bandwidth. The simplest method is to increase the wire radius but the frequency broadening is insufficient for a ground penetrating radar (Balanis, 1982). A better strategem was devised by King and Wu who, following a suggestion by Altschuler, investigated a resistively loaded dipole antenna. They demonstrated theoretically that it can produce broadband radiation (Wu and King, 1965; Shen and King, 1965) and that the antenna impedance is real and constant in a wide frequency range. The antenna can thus be coupled directly to a coaxial line if a transformer is used to match the impedances of the antenna to the transmission line.

The Wu-King antenna is a dipole antenna loaded with resistors selected to make the current decrease towards the antenna end points. The idea is to eliminate current pulses reflected from the ends of the dipole which cause ringing and standing wave patterns characteristic of narrowband antennas. This idea succeeds remarkably well, if the resistance is inversely proportional to the distance from the antenna ends. The antenna properties do not depend critically on the level of impedance used in the Wu-King prescription (Shen and Wu, 1967). This was confirmed during the design of the RAMAC borehole antennas, where the Wu-King antenna has been used with great success (Olsson et al, 1987). The main disadvantage of this antenna is that part of the energy provided by the batteries is lost as heat to the resistors, but this is acceptable if measurements are stacked to improve the signal to noise ratio.

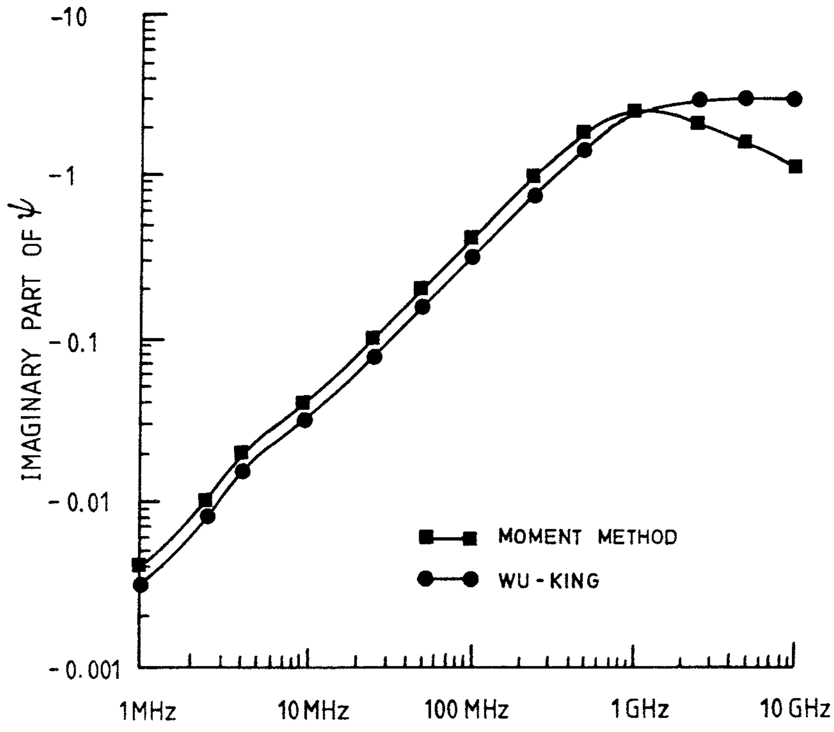
Theory and experiments for the Wu-King antenna were compared by Shen (Shen, 1967) and later by Kanda (Kanda, 1978; Miller, 1986), in general with excellent results. The impedance is constant and nearly real as predicted by theory; numerical confirmation is shown in Fig. 2.2. This agreement is remarkable since the original solution presented by Wu and King in 1965 was based on an apparently rather crude appoximation. King and Smith have later provided theoretical reasons why the approximation works so well (King and Smith, 1981).

Numerical calculations using the method of moments (Harrington, 1990) have demonstrated that the current on the antenna has the travelling wave behaviour predicted by Wu and King (Liu and Sengupta, 1974). The travelling wave was also demonstrated in Kanda's experiments. Kanda used a thin coal layer to produce variable resistance along a glass tube, but it is sufficient to use an approximation to this distribution consisting of lumped resistors. This method was demonstrated during the Stripa project when the antennas for the RAMAC system were developed (Olsson et al., 1987).

The travelling wave behaviour is very important because ringing in a dipole antenna is caused by reflections from the wire ends, which can generate resonant waves moving back and forth on the antenna. Ringing can be reduced by loading the dipole in such a way that the current becomes zero at the antenna ends. The Wu-King formula states that the conductivity of the wire should be proportional to the distance x from the antenna end. The required resistance per unit length, R, is thus determined by $R = K/x$.



(a)



(b)

Figure 2.2 The real and imaginary parts of the impedance K/60 used in the Wu-King formula according to theoretical and numerical calculations (Kanda 1978).

A small reactive part is neglected which must be included at high frequencies. The problem is to determine the level of resistance in such a way that a travelling wave is obtained. In vacuum the constant is approximately

$$K = 450 \text{ ohms},$$

if the frequency dependence is neglected. For an antenna in a dielectric the constant is reduced by the refractive index n,

$$R = K/n\ x \quad (\text{ohm/m})$$

The RAMAC antenna uses lumped resistors and suitable resistor values are obtained by averaging the distributed resistance over the interval between the resistors. According to the previous formula this corresponds to a logarithmic distribution after integration. The distance between the resistors must be much less than the minimum wavelength to produce the desired effect.

The emitted radiation will be centered around the dipole resonance frequency,

$$f = c\ /\ 2\ n\ l$$

where l is the antenna length.

We must also take into account that the tunnel antenna are used at the boundary between two media. It is difficult to determine a suitable resistivity distribution in this case: it is not even obvious that there exists one, since the approximation introduced by Wu and King does not apply directly. One can still hope that the Wu-King antenna will provide a reasonable solution to the problem and that a suitable value for K can be calculated by using the average permittivy of the two media.

This value is suggested by experiments showing that the antenna impedance and center frequency both scale approximately as the average of the permittivities. A theoretical justification can be found in the fact that at low frequencies the impedance is determined by the average of the two dielectric constants, for example in expression determining the static capacitance (Hill and Anderson, 1990). A better reason is that the resonant current modes on a long wire located between two media also scale as the average of the permittivity as shown by Wait in a simple manner (Wait 1972). One can assume that these formulas are approximately valid even when the antenna starts to radiate, since the radiation is small for a Wu-King antenna and can be regarded as a correction.

A similar conclusion was reached by James West who designed a ground penetrating radar for applications on the Antarctic ice (West 1986). This radar is narrowband so its design is only of limited interest to us: it is built as an array antenna with four active elements about three inches above the ice surface and four reflectors a quarter of a wavelength above at the working frequency 150 MHz. West found empirically that the lengths of the elements at the air-ice interface must be divided by the average of the refractive indexes of the air and the ice while their spacings should be divided by a slightly greater value for optimum performance. The directivity of the system was improved when the height and spacings of the parasitic reflector elements were reduced.

This design criterion agrees with our previous conclusions, because the parameters in this case are all close to 1: the dielectric permittivity of firn is about 1.8 and the refractive index $n = 1.34$. It thus does not matter whether the permittivity or the refractive index is used, but for larger values the permittivity is the correct choice.

The validity of the Wu-King concept was tested experimentally by measuring the current distribution on the antenna with a network analyzer. Several of these measurements are described in a report on the laboratory experiments which confirm the Wu-King theoretical analysis (Falk et al., November 1990).

2.3.2 Biconical antennas

The biconical antenna is traditionally analyzed as the first example of a broadband antenna. The infinite biconical antenna, consisting of two cones placed apex to apex at the feed point, is a perfect broadband antenna with constant input impedance for all frequencies. The fields and currents can also be determined in analytical form.

A bicone is awkward to handle and its length must be finite. When the cone is cut the new length defines the lowest useful frequency, while the high frequency limit is determined by the form and accuracy of the feed. Solid cones can be imitated by wire networks to reduce the antenna weight and in practice the bicone is often replaced by a monopole antenna, where a single cone is backed by a reflecting plane. This antenna is used as a standard in many laboratories.

The biconical antenna is inconvenient because of its size and the same idea has become more popular in two-dimensional form where it is called a bow-tie antenna. This antenna is used in many modern systems where the antennas are printed on a surface, e g as radiating elements in phased-array systems. The bow-tie antenna is not as broadband as the biconical antenna (Balanis, 1982), but this is not surprising because the symmetry of the bicone is partly destroyed when the bicone is compressed into a twodimensional structure.

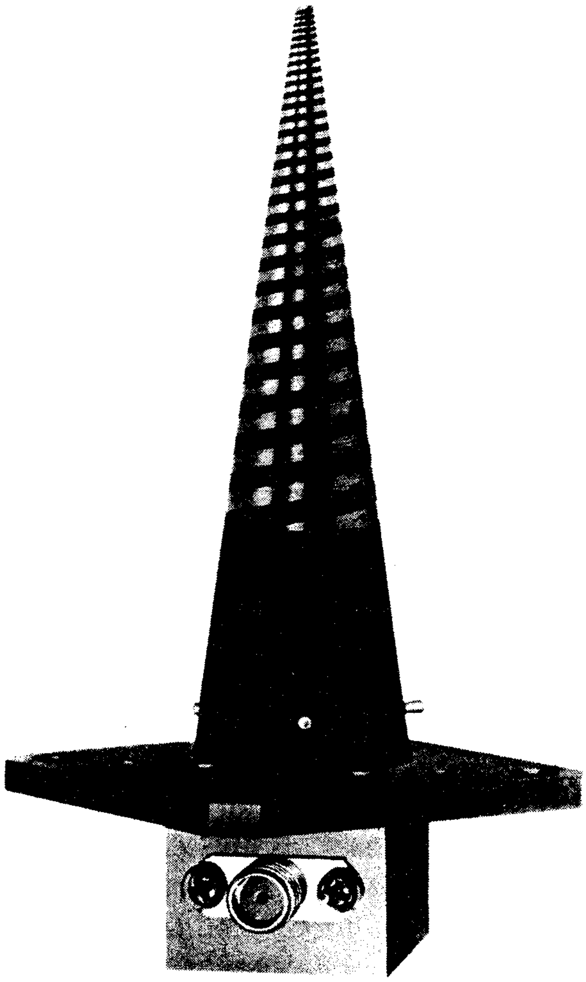
Like a dipole the bowtie can be loaded with resistors in order to reduce reflections from the antenna ends and eliminate standing waves. This principle is used in the GSSI ground penetrating radar system which produces well formed pulses. The theory of bowtie antennas has been worked out in detail and extensive calculations have been performed for input impedance as a function of bowtie angle (Balanis, 1982). The interesting case of a bowtie on a dielectric halfspace has recently also been investigated both theoretically and experimentally (Compton et al., 1987). An interesting feature of this work is that the antenna modes are different in character for wide and narrow angles.

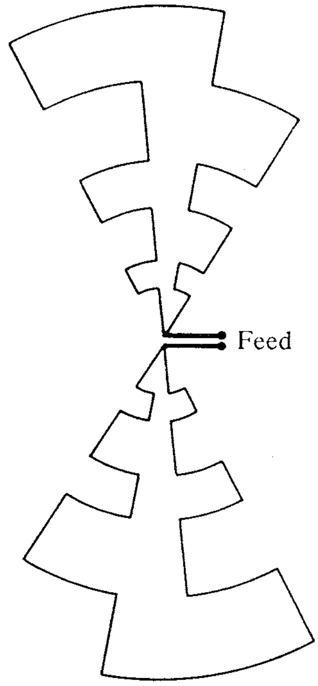
2.3.2 Frequency independent antennas

At the end of the fifties Rumsey suggested that broadband antennas can be designed by using geometrical structures that contain no characteristic lengths. A typical example is the infinite bicone discussed above. Such idealized antennas are perfectly broadband because the wavelength does not appear in the impedance formula unless there is a characteristic length. The antenna geometry can only depend on angles and a little consideration will show that this rule generates antennas that are spiral-shaped either in the plane or on a cone. The latter type is wellknown and widely used in air craft radars (Fig. 2.3); many calculations are found in the literature (Wang and Tripp, 1991)

The polarisation of this antenna will usually be circular. This is not a serious drawback, though most researchers favour linear polarization. The main disadvantage of the frequency independent antennas is that a phase distortion (usually called chirp) will accompany the pulse and tends to deform it. This phase distortion can be removed by compensating electronic circuits or by postprocessing. An example of data processing is given by Daniels (Daniels et al., 1988), but this type of processing is not popular and the antenna does not seem to be used in any commercial radar system. The chirp occurs because the signal is emitted by different antenna elements for each frequency. The active area will move over the antenna and this produces a phase variation in the pulse which is difficult to remove later.

Frequency independent antennas are attractive for broadband applications and many different constructions have been proposed and tested in practice. The best known is the logperiodic antenna, which is often used as a TV antenna (Fig. 2.3). The chirp does not produce any problems in these applications because the bandwidth is used to receive different channels at different times. This antenna has the additional advantage that it will produce a directed beam, unlike plane spiral antennas which radiate in both directions. Spiral antennas can, however, also be built on cones and a directed beam is then obtained.





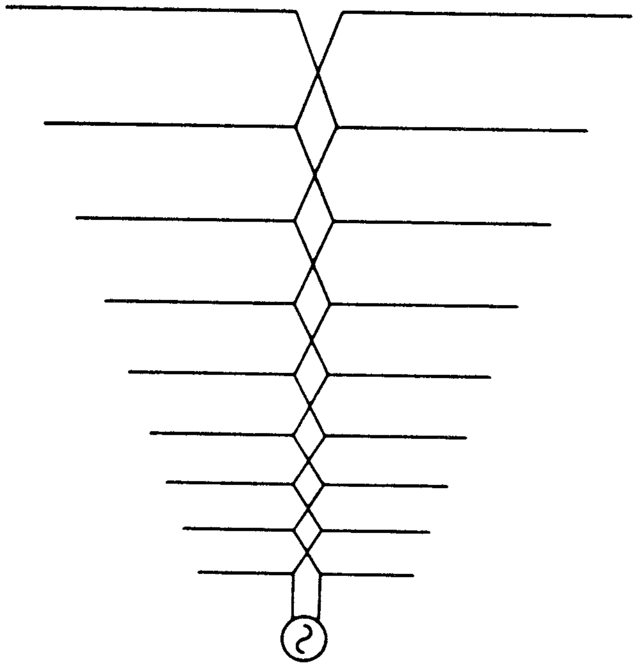


Figure 2.3 Three frequency independent antennas: a spiral cone and two logperiodic antennas.

2.3.4 Horn antennas

A smooth transition from wave guide to free air is obtained with a horn antenna. Horns have simple characteristics, they produce well directed beams and are broadband in frequency. For this reason horn antennas are often used as feeds in reflector antennas and as elements in phased array antennas. Horn antennas are often proposed in discussions on radar antenna designs, but they are always finally rejected because of their size. Horns must be at least half a wavelength wide to function well and they are many wavelengths wide in their typical applications. In practice they are often used at frequencies above 1 GHz, though some ground radar measurements have been reported down to a few hundred MHz with horns containing dielectric loading consisting of TiO_2 (Daniels et al., 1988). The horn is usually fed from a waveguide which can complicate the system design because the pulse will suffer phase dispersion in the waveguide. Kanda reports experiments with resistively loaded horns similar to Wu-King dipoles which appear to be very broadband (Miller, 1986).

2.4 Antennas near an interface

Tunnel radar is characterized by the fact that the antenna is situated at the interface between two media. It is well known that most antennas are sensitive to the distance from the ground. This effect will be important during analysis because the identification of a reflector depends on the fact that it can be identified in many different traces as the radar is successively moved in the tunnel. If the pulse form is constant the identification is simplified, but this may depend on the antenna and its coupling to the ground.

2.4.1 Sommerfeld's solution

Antennas near ground were studied intensively after long distance radio transmission had been demonstrated by Marconi. It was soon discovered that the Earth's finite conductivity influences radio wave propagation and that the power losses to the ground present a serious problem. The antenna design problem was solved by Norton in the thirties for antennas on ground. These numerical results were combined with extensive measurements to determine the electric properties of rocks and soils at radio frequencies (Hansen, 1989).

The mathematical problem was solved in 1909 by Sommerfeld (Sommerfeld, 1964) who tried to explain the unexpectedly large range obtained in Marconi's radio experiments. Before the ionosphere had been discovered many scientists thought that the excess range was related to the propagation of a surface wave. This wave has remained a controversial issue in radio science almost until our days but it has now finally been exorcized. The solution of the Sommerfeld problem can be found in many books

(Banos, 1966; Wait, 1987), but new articles constantly present approximations useful in certain parameter ranges (King and Brown, 1984; King, 1985).

Wait has treated the complicated problems that occur when the antenna is placed over a stratified earth (Kong, 1986; Wait, 1987). These formulas have been widely applied in geophysical investigations and are also of interest for ground penetrating radar. The analysis shows that the effect of several layers is described by an expression for the plane wave reflection coefficient at the interface, which contains all information about subsurface structures. In tunnel applications it is, however, more realistic to assume that the rock is homogeneous.

2.4.2 Numerical calculations

Sommerfeld's problem has received an almost mythical reputation for complexity due to the controversies surrounding the solution, but in fact it is not very difficult to derive and the analysis is straightforward. The far field can be obtained by a simple approximation, which leads to the geometrical optics case. The complications occur at grazing angles to the interface, a case which is of importance for radio communication on the Earth's surface, but rarely appears in radar, except when one considers how the direct pulse is transmitted between the transmitter and the receiver.

Numerical problems also appear near the current elements which are the sources of the field. The solution is difficult to approximate because it depends on many parameters, e g the antenna height and the electric permeability and conductivity of the ground. It is difficult to devise approximations which are valid in all different regions.

Numerical calculations of the field transmitted into the medium have been performed by Gary Smith at Georgia Tech (An and Smith, 1982; Smith, 1984). Originally An and Smith investigated a resonant antenna loop but the general features are simpler to describe if the dipole solutions are used, which can be expressed as a plane wave expansion. Similar results have been derived by other researchers (Engheta et al, 1982). Smith has continued to work on ground penetrating radar and has for example developed a material suitable for modelling the earth at higher frequencies in laboratory experiments (Smith and Scott, 1989).

Smith's numerical investigations provide a clear picture of the field transmitted into the ground by the antenna comparing it with the rest of the field, particularly the backlobe. The backlobe is important because it often happens that reflections in the air caused by lamp posts or trees are confused with subsurface reflections. Many radar workers are unaware of the fact that the backlobe is difficult to eliminate and for ground radar it is more or less impossible, because the relatively large wavelength allows the field to leak backwards even if metal screens or other means are used to direct it into ground.

The best help is provided by the ground itself. The dielectric constants of rocks and soils are much larger than for air, typically about ten times. If an antenna is placed near the interface the radiation will be directed in a sharp peak downwards. This effect is demonstrated for a resonant current loop in Figure 2.4, where curves are also shown for air and an interface between air and water (Smith, 1984).

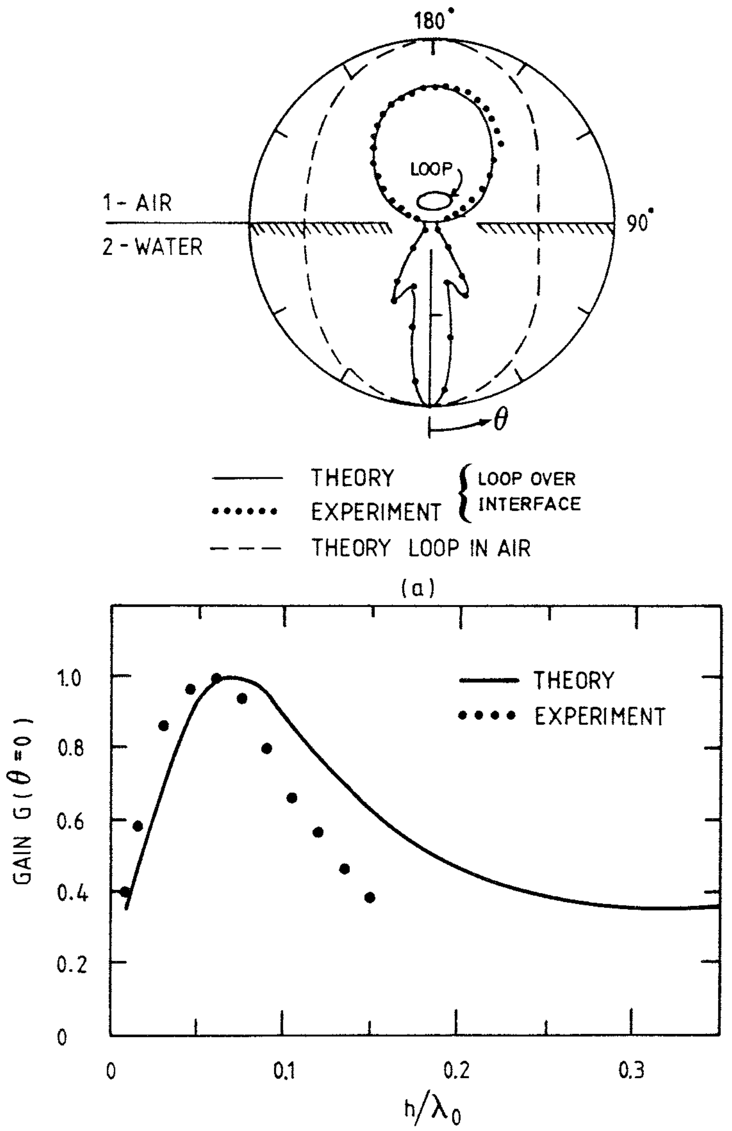


Figure 2.4. The radiation pattern of a resonant loop in air compared with the same loop parallel to an air-water interface. Below the gain as a function of antenna height (Smith, 1984).

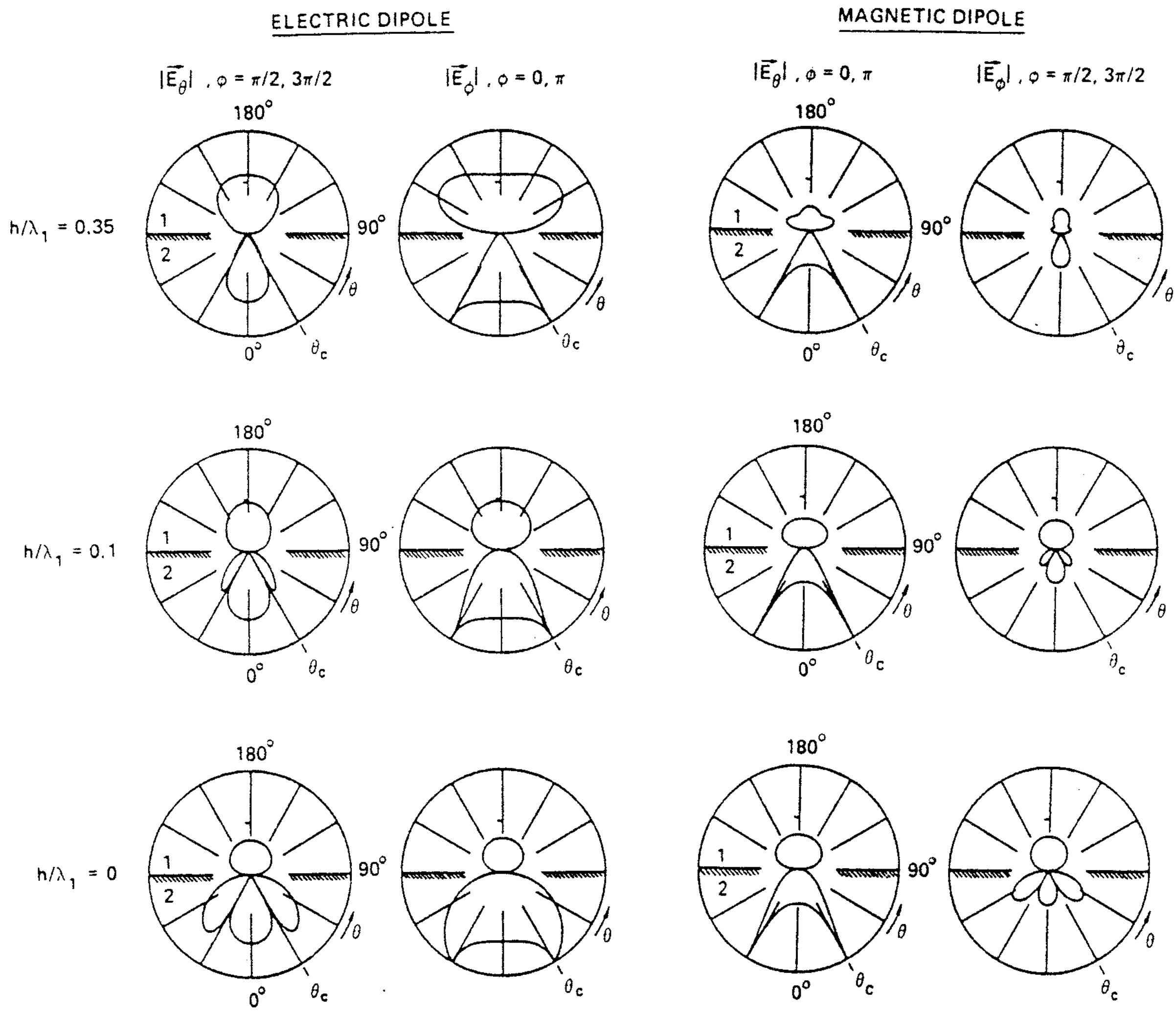


Figure 2.5. Radiation patterns for horizontal electric and magnetic dipoles over a dielectric with permittivity 4. Antenna height from top to bottom row: 0.35, 0.1, 0 wavelengths.

The increased directivity is shown in Figure 2.4 where theory and experiment are compared for a resonant loop antenna. Water has a large dielectric constant, 81, and the directive effect is very pronounced. The radiation pattern is clearly peaked along the normal but on the other hand nothing is observed near the interface. This is a phenomenon well known to anyone who has tried to look upwards when swimming under water, but here the effect is emphasized by the extreme polarizability of water at radio frequencies. The index of refraction is 9, so the critical angle in Figure 2.4 is θ_c = arcsin (1/9) = 6.4°. The lower part of the pictures compares theory and experiment for the gain as a function of antenna height over the surface.

Corresponding calculations for parameters characteristic of rock and soil show less sharp peaks. Figure 2.5 compares the radiation patterns for a medium with dielectric constant equal to 4, which can occur in rock. Two different polarizations are shown both for electric and magnetic dipole antennas. The important features are the directivity of the lobe and the sensitivity to antenna height. Results for three different antenna heights are presented: 0, 0.1, 0.35 wavelengths and the differences are obvious. When the antenna is near the surface a large part of the energy passes into the medium in a wide beam and the backlobe is small but already when the antenna is raised a tenth of a wavelength the pattern changes considerably. This effect is particularly noticeable for the electric dipole, but can be seen in both antennas. The critical angle θ_c of the radiation lobe is 30°; for Stripa granite the corresponding angle is 24°.

The effect of antenna height is also observed in the input impedance because the total power emitted by the antenna is affected. Some data demonstrating this effect are displayed in Figure 2.6: curve A shows the result of an experiment with a resonant dipole over wet ground, while B is the theoretical curve for a small dipole over a medium with permittivity 15. Curve C is the magnetic dipole. The input resistance varies rapidly below a tenth of a wavelength as expected. This property easily be demonstrated by raising and lowering a small transmitting antenna over ground and measuring the reflected pulsed with a network analyzer.

The input resistivity has been calculated for a Wu-King antenna placed at different heights in Figure 2.7 using a computer program based on the method of moments. Only for antennas near the interface is there any significant difference compared with the free space curve. This trend is seen in all computer calculations (Falk et al., November 1990).

Another quantity of interest is the proportion of the energy that passes into the rock. Figure 2.8 shows that even in granite where the dielectric constant is about 6 a large part of the energy will pass into the rock and this reduces secondary reflections in the tunnel.

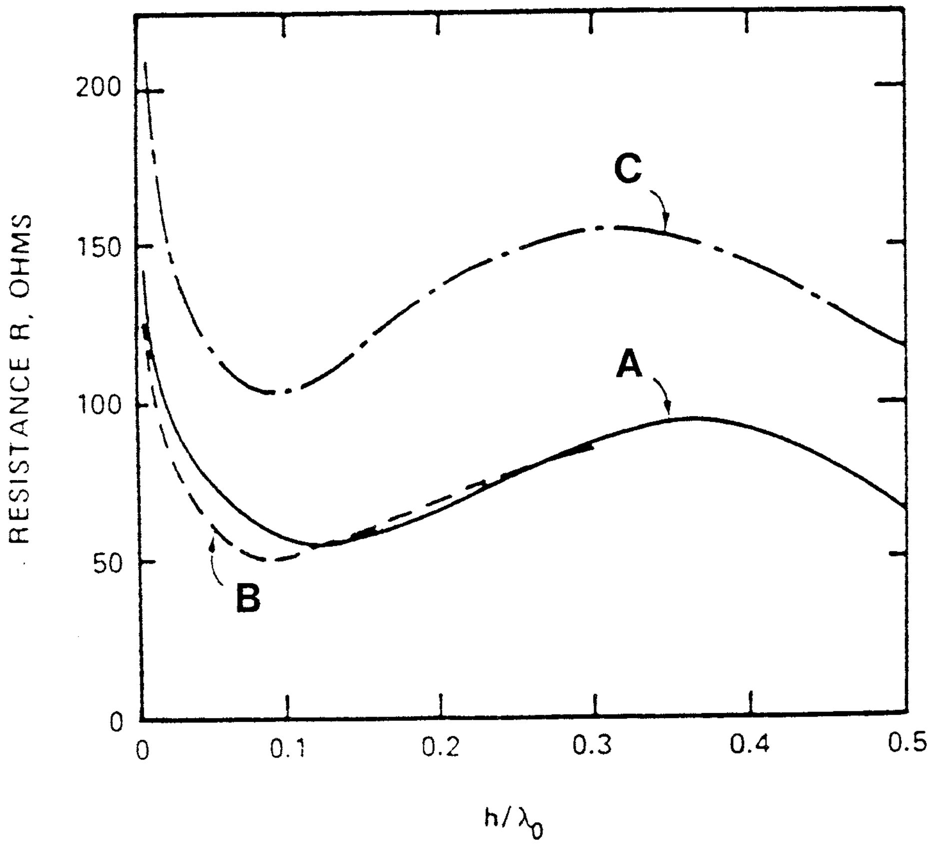


Figure 2.6 Input impedance as a function of antenna height in wavelengts for a horizontal electric dipole (A experiment, B theory) and calculated for a magnetic dipole, C.

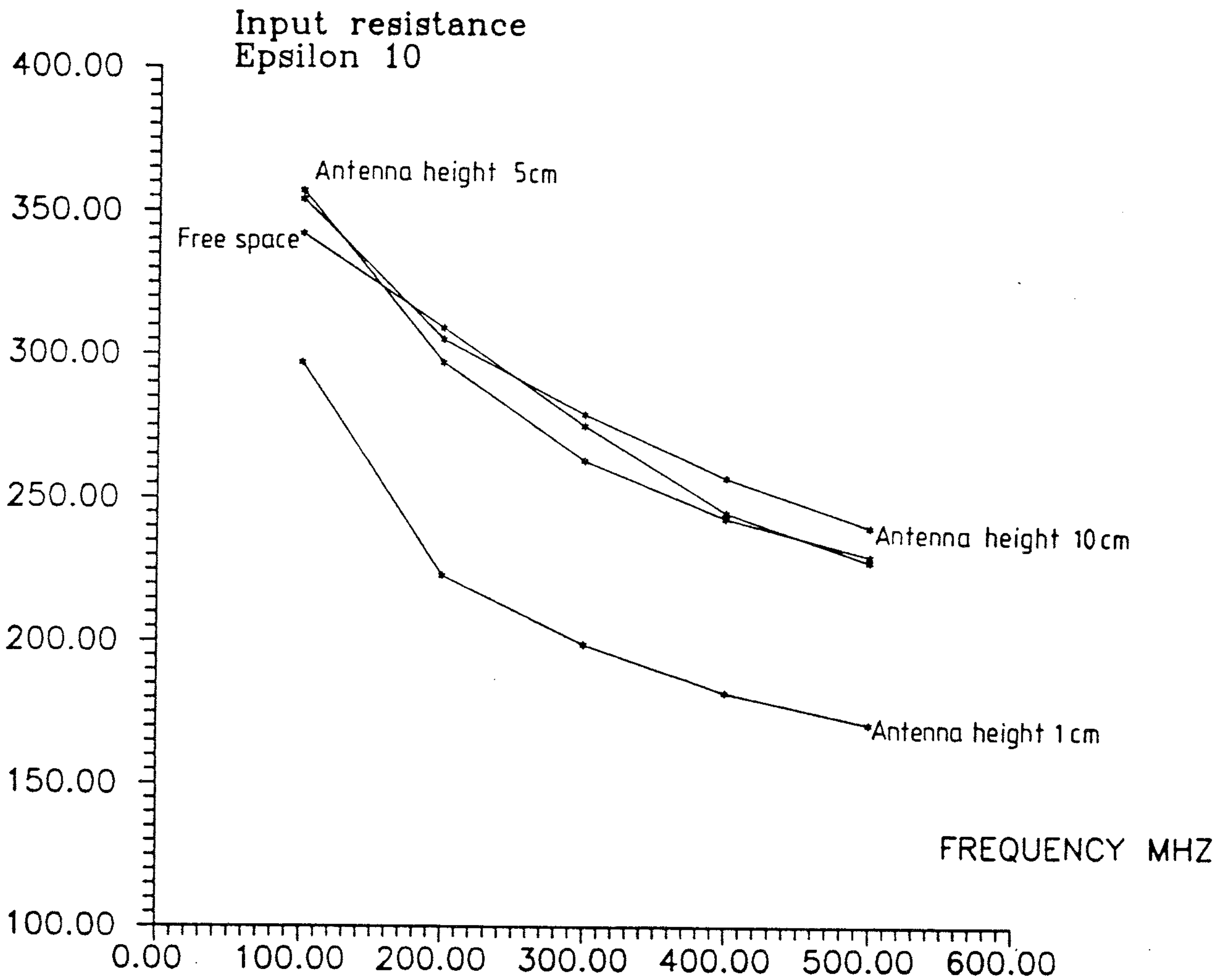


Figure 2.7 Input resistance computed for a Wu-King antenna over a dielectric medium with permittivity 10 for different heights (Falk, November 1990).

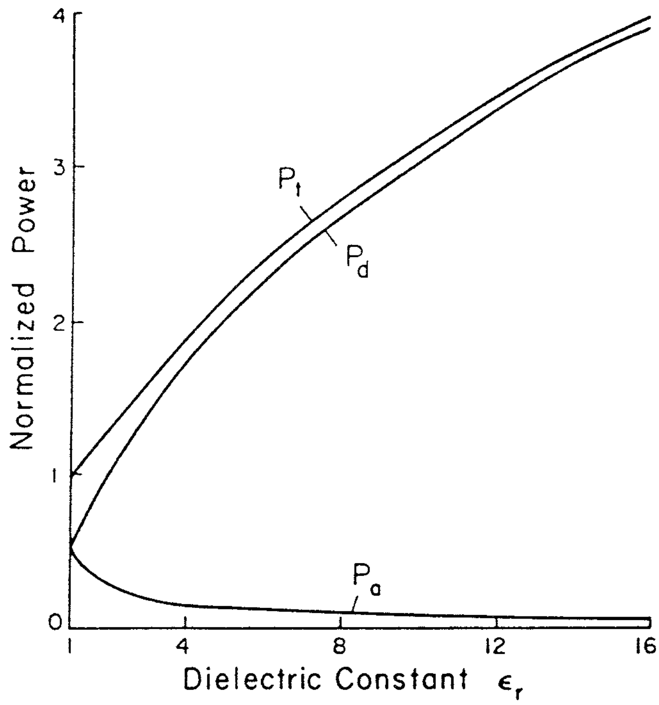


Figure 2.8 The power radiated by a horizontal electric dipole at an interface; subscript a refers to air, d to the dielectric and t is the total power (Rutledge et al., 1983).

2.5 Computer programs

Starting in the sixties several computer programs have been developed, which solve antenna problems numerically by different versions of the method of moments (Harrington, 1990). Programs are mainly written for wire antennas but metal surfaces or surfaces with a constant impedance can also be included in some programs. Antenna programs of this type were used to optimize the RAMAC borehole radar antenna.

Program that can handle an antenna situated over a dielectric halfspace are rare. The required programs have been developed in the US by military agencies, but are not available to the public. Some specail cases have been investigated in cooperation with the Swedish Defence Research Institute. These calculations have been very informative, since they can be compared directly with data provided by a network analyzer. Several examples of such calculations are shown in this report, e g Figure 2.7 and in a previous report (Falk et al., November 1990).

2.6 Antennas in related applications

Antennas near the interfaces between two media have been studied in many application and we will briefly review the existing literature which can provide information about antenna design and performance.

Long radio waves can penetrate the earth to considerable depths and even enter salt water. The literature on communication with submarines is extensive and King and Smith have investigated trailing wire antennas placed slightly below the sea surface in great detail (King and Smith, 1981). The book by King and Smith is the most comprehensive source on antennas near an interface between two media. Unfortunately the numerical results are not directly applicable to antennas over ground, because salt water has a much larger dielectric constant, 81, than soil or rock (5-20) and the conductivity is also much higher. The electric contrast at the interface is sharper for antennas in sea water than for ground antennas and the conductive losses in water make some approximations effective which would not work otherwise.

Underwater antennas as well as antennas designed for geophysical investigations at great depth are usually much smaller than the wavelength. This is an important difference compared with radar tunnel antennas which are about half a wavelength long.

Antennas near an interface have also been studied at high frequencies in the GHz region. Electromagnetic waves can be used to treat cancer tumors using the same principle of heating as in a microwave oven. In order to focus the radiation on the tumor and avoid other tissues arrays of antennas have been tested (Hansen, 1989). The problem can be handled analytically, but it is very complex for a medium consisting of many layers. Hansen has made detailed studies of the resulting formulas and his book is an excellent source on activities in this field, but the numerical calculations are displayed in a manner which makes them almost impenetrable. The medical applications are restricted to narrowband radiation.

The best sources on antenna problems near an interface are presently papers on antennas printed on a dielectric substrate, e g the microstrip and the micropatch. This antenna is simple to construct, but it is not a candidate for a tunnel antenna since it is inherently narrowband (James et al, 1981). The numerical calculations performed in microstrip investigation are of great interest: dipole, slots and bowtie antennas have been investigated in this way (Compton et al., 1987). The review papers by Jackson, Rutledge, Alexopoulos and Pozar in the reference list provide solutions for antennas at an interface. The exact solutions and approximations derived by these authors are particularly interesting because the dielectric constant of the dielectric is rather close to values typical for rock.

3. ANTENNA DESIGN

3.1 Antenna tests

The first experiments with tunnel radar produced results of mixed quality. The measurements in Kamaishi (Olsson, 1989) contain more detail than those obtained in Stripa in 1988, but there is considerable ringing and the reflections are diffuse compared with most borehole measurements.

The antenna unit used at Kamaishi is shown in Figure 3.1. The electronics and batteries were placed in a housing over the antenna to screen the electronics. The antennas were loaded dipoles of a type previously used in borehole probes. The pulses were fairly well shaped but ringing occurred as seen in Figure 3.2. Ringing makes it difficult to observe reflections, but at least three fracture zones can be discerned in Figure 3.3. The amount of ringing varied with polarization and measurements on the smooth floor of the mine produced better results, possibly due to the presence of water (Olsson, 1989). It was, however, felt that the reason for these difficulties were rather obscure. Apparently the antennas were sensitive to the distance to the wall but other parameters might also be involved.

Theory suggests that radar pulses can be affected by small changes in antenna position and numerical calculations support this conclusion, but most calculations are based on idealized assumptions: the antenna is small and the interface between the two media is a plane. Field tests were therefore started to investigate real antennas over ground. Most of the tests were performed in the parameter laboratory in Malå, since there is no steel in the concrete floor, and tests were also performed on a lawn outside the laboratory.

The first experiments used the RAMAC equipment connecting the antennas to the electronic units with coaxial cables. This method was soon abandoned because the cable screens coupled to the antennas and the results were unstable. An HP network analyzer was used instead and based on work with this instrument several antenna types were excluded, such as transmission lines, which are too difficult to balance, and many types of plane metal sheets which showed no advantage over Wu-King or bowtie antennas.

Laboratory experiments of this type are insufficient to make decisions about which antennas to use. A radar system should measure reflected pulses rather than the pulses propagating directly between the antennas. It is also very important to work in an environment where only a few reflectors are available. A network analyzer is too complicated to move around, so a couple of prototype antennas were built where the antennas had been separated from the electronics but the preamplifiers were at the antenna feeds. It was, however, soon obvious that this construction was insufficient to handle the interference problem. In a dramatic experiment we successively removed all antenna elements and still registered a strong signal. Further testing showed that the signal originated in radiation fields which coupled to battery wires, screens of coaxes, etc. A complete revision of the antenna units was consequently required.

The network analyzer can also be affected by this type of interference and it is interesting to consider the differences. The coaxes used with this instrument are of very high quality and well screened. Several tests and calibration measurements have shown that the measurements performed with this instrument never went seriously wrong, at least for the signal propagating directly between the antennas. It is more difficult to say what happens with the weak signals, which are of interest when the analyzer is used as a radar. There is no doubt that some of the radar experiments performed with network analyzers by other radar groups have been disturbed by interference.

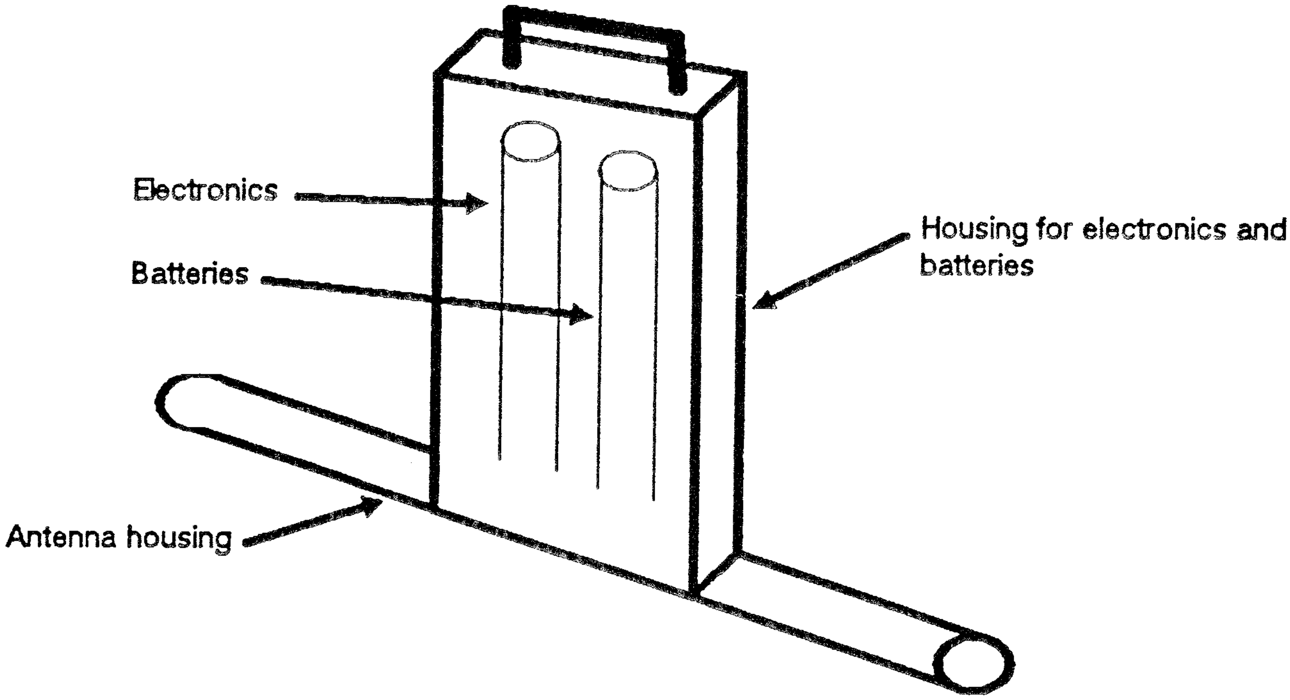


Figure 3.1 The antenna unit used in the Kamaishi measurements (Olsson, 1989).

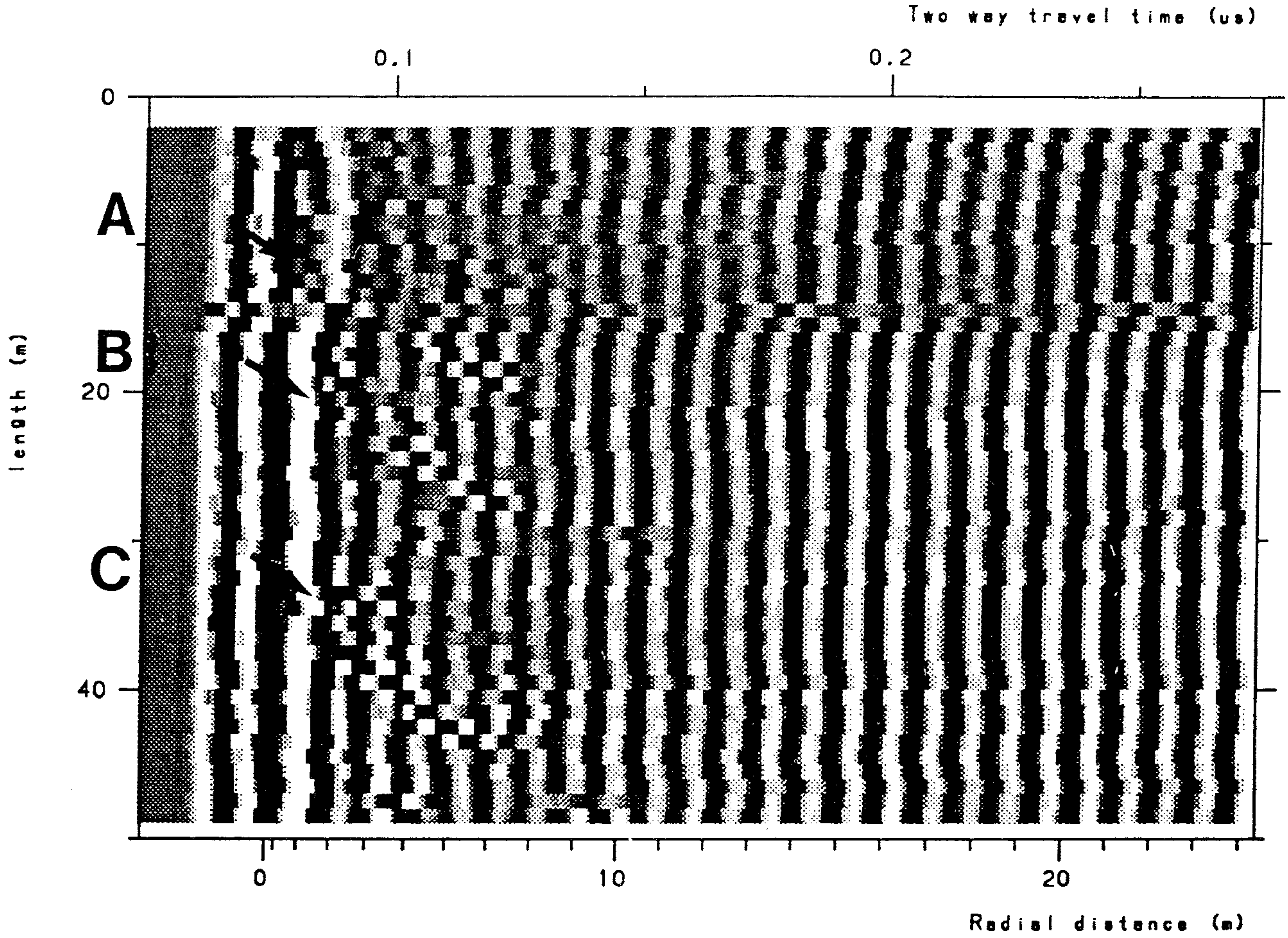


Figure 3.2 Radar reflection profile from the Side Tunnel in Kamaishi with the antennas at the tunnel wall perpendicular to the tunnel (Olsson, 1989).

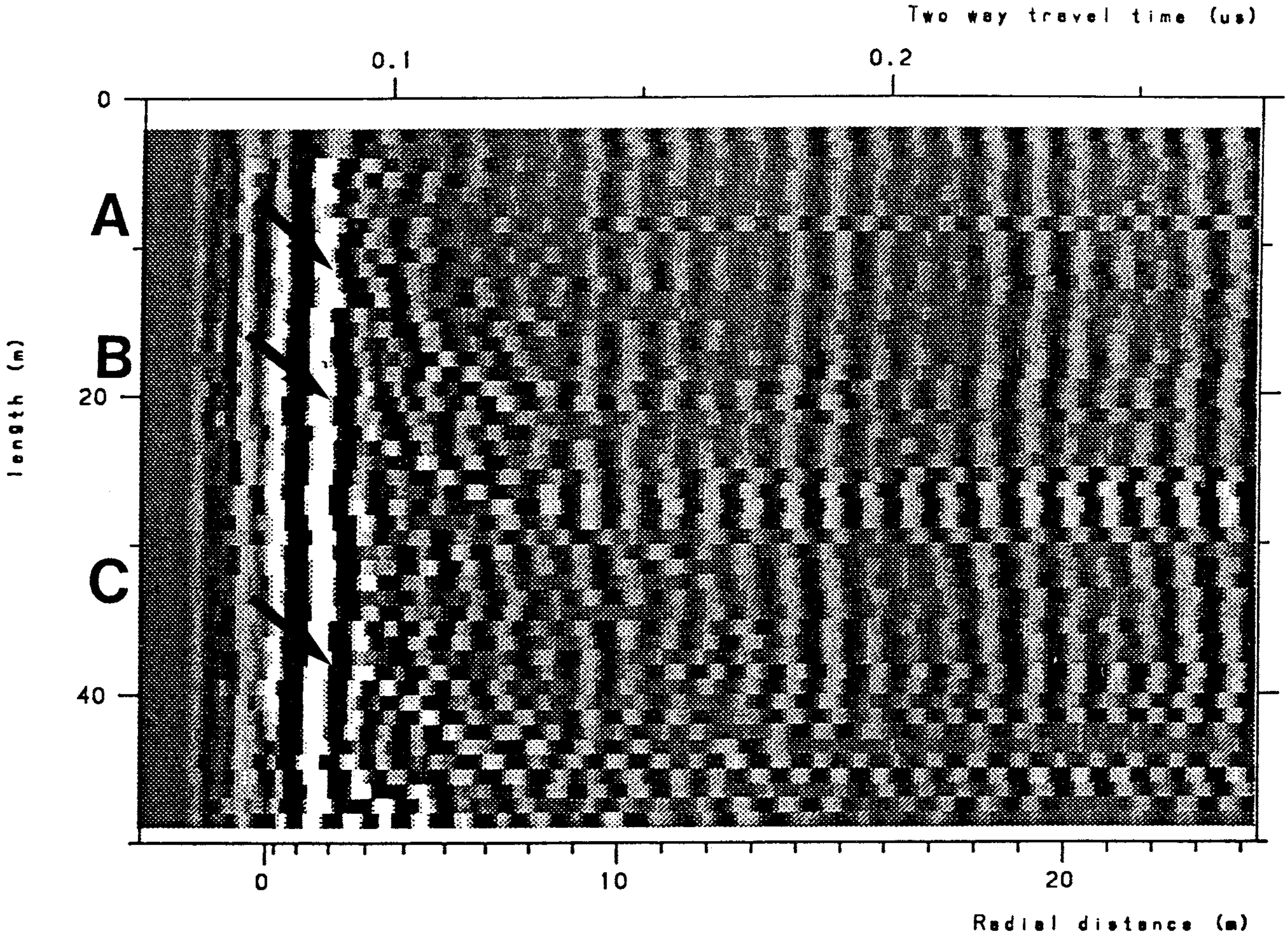


Figure 3.3 Radar reflection profile from the Side Tunnel in Kamaishi with antennas parallel to the tunnel in a ditch of water (Olsson, 1989).

3.2 Radar design

The radar units were rebuilt by placing the RAMAC electronics in special metal boxes. The electronic cards of the transmitter and the receiver were placed in the boxes with the batteries above the components as shown in Figure 3.4. The electronic components are the standard RAMAC cards, which were placed in plastic tubes. The first card of the receiver contains the optoreceiver for the trig pulse. This pulse causes the sampler units on the second card to register a sample at a well-defined moment and the A/D converter then produces a digitized signal of the measured voltage which is transmitted to the control unit on an optical fibre.

The electronic circuits are connected to the antennas by short coaxial lines which end at the antenna feeds on the surface of the screening box. The box acts as a ground plane and was placed in the middle of the antenna with the batteries in the box on top of the electronics. The metal box is a part of the antenna shortening the center piece and the antenna feeds are located symmetrically at each end of the boxes. This construction is similar to the RAMAC borehole radar, where the electronics is contained in a metal tube of small diameter; the cards are placed after each other and back-to-back to reduce the length of the high frequency antennas. This explains why the borehole antennas have proved to be rather good tunnel antennas in previous experiments in spite of their size and weight. By increasing the height of the metal container one can place the cards side by side and add the six batteries without affecting the antenna performance. This construction is outlined in drawings 3.4 and 3.5. The antennas can easily be taken off and replaced with others, which makes the equipment ideal for antenna tests and measurements in an unknown environment, where it is sometimes necessary to modify the antenna to adapt it to the resistivity of the rock.

3.3 Antenna construction

The previously tested resistively loaded antennas were investigated with the new radar equipment with good results. About fifteen different resistive loadings were tested using the network analyzer to check the antenna impedance and the standing wave ratio at all frequencies. The best antennas have a fairly slowly varying impedance near the resonance frequency where the radar pulse will have its center frequency. The best antennas were tested by performing ground radar measurements outside the laboratory on the snow covered lawn. The measurements showed several reflections, but unfortunately little is known about the reflectors, so the tests had only an indicative value by demonstrating which antennas provide the sharpest pictures.

The best antennas were close to the Wu-King recipe. After measurements in Stripa with the network analyzer and after several tunnel radar experiments the following parameters were found to be the best. Each of the two antenna sections consist of plastic tubes 2 cm in diameter: metal tubes of different lengths are placed on the plastic and the resistors are welded on in the gaps between them. This structure is shown in Figure 3.5, though the number of resistors has been reduced to simplify the picture; in addition their lengths have been exaggerated; the gaps are actually only about 1-2 mm.

Tests have demonstrated that it does not matter much whether the metal tubes are joined in one or more points; efforts to distribute the current around the tubes would thus be misdirected. The current and voltage distibution on an antenna can be studied directly with a network analyzer; a typical example is shown in the second interim report where the function of a Wu-King antenna is demonstrated in detail (Falk et al., November 1990).

Low frequency antenna

The parameters of the low frequency antenna were optimized as follows: counting from the midpoint of the metal box in Figure 3.4 at the symmetry center of the antenna the length of the metal sections were

15 cm (half the length of the metal box), antenna feed, 17 cm, 11 cm, 7 cm, 5 cm, 3.4 cm, 2.2 cm, 1.5 cm

The total length of this antenna is 1.24 m.

The following resistors are welded across the gaps, starting with 120 ohm in the gap between the 17 and 11 cm metal sections:

120, 120, 150, 180, 220, 330 ohms.

The antenna is not very sensitive to small variations in resistor values. One can test this by moving a finger or a conductor over the antenna. The sensitive points are situated about halfways between the antenna ends and the feeds. The resistors have been selected from a standard set since there is no point in obtaining a perfect fit to the Wu-King antenna.

The construction of the antenna feeds is shown in Figure 3.5. Balun transformers are used to match the system to the 50 ohm coaxial cables connecting the feeds to the electronics. Baluns x3 were found to be the best choice. The two coaxes join at a power splitter which transmits the pulse to the preamplifier. The pulse then reaches the sampler where one sample is measured from each pulse.

High frequency antenna

Both in Malå and Stripa high frequency antennas were tested. The best results in Stripa were obtained with the following parameters:

15 cm, feed, 5 cm, 3 cm, 3 cm

and the resistors

120, 220, 370 ohms.

The effect of the metal box is considerable in this case, since the unloaded central part becomes relatively long, and the quality of the data obtained with this antenna can not be compared with the low frequency measurements. If an effective high frequency antenna is desired it is recommended to start by reducing the size of the metal box, which can be done without great difficulty.

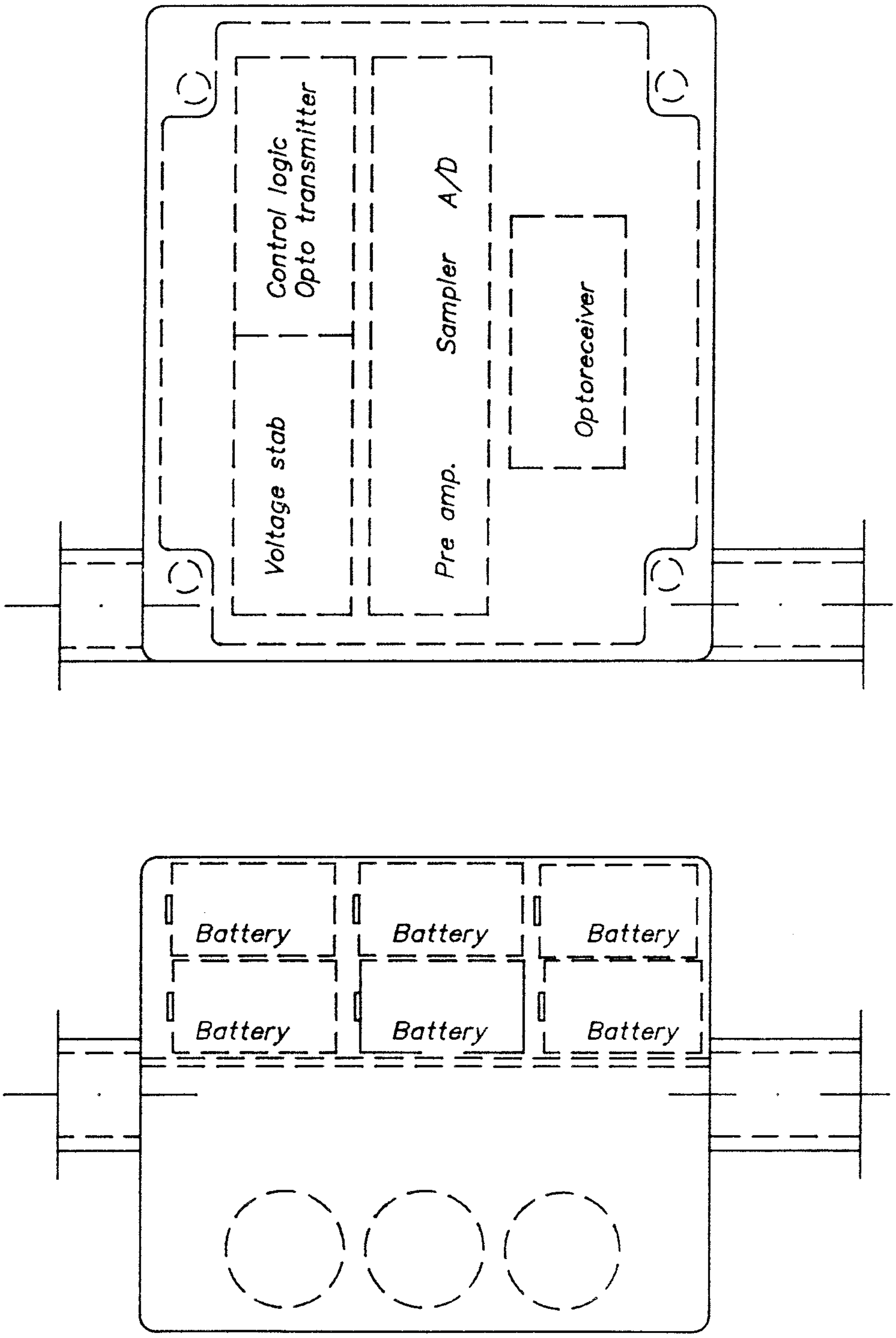


Figure 3.4 The arrangement of the RAMAC electronic cards and the batteries in the metal box of the low frequency receiver.

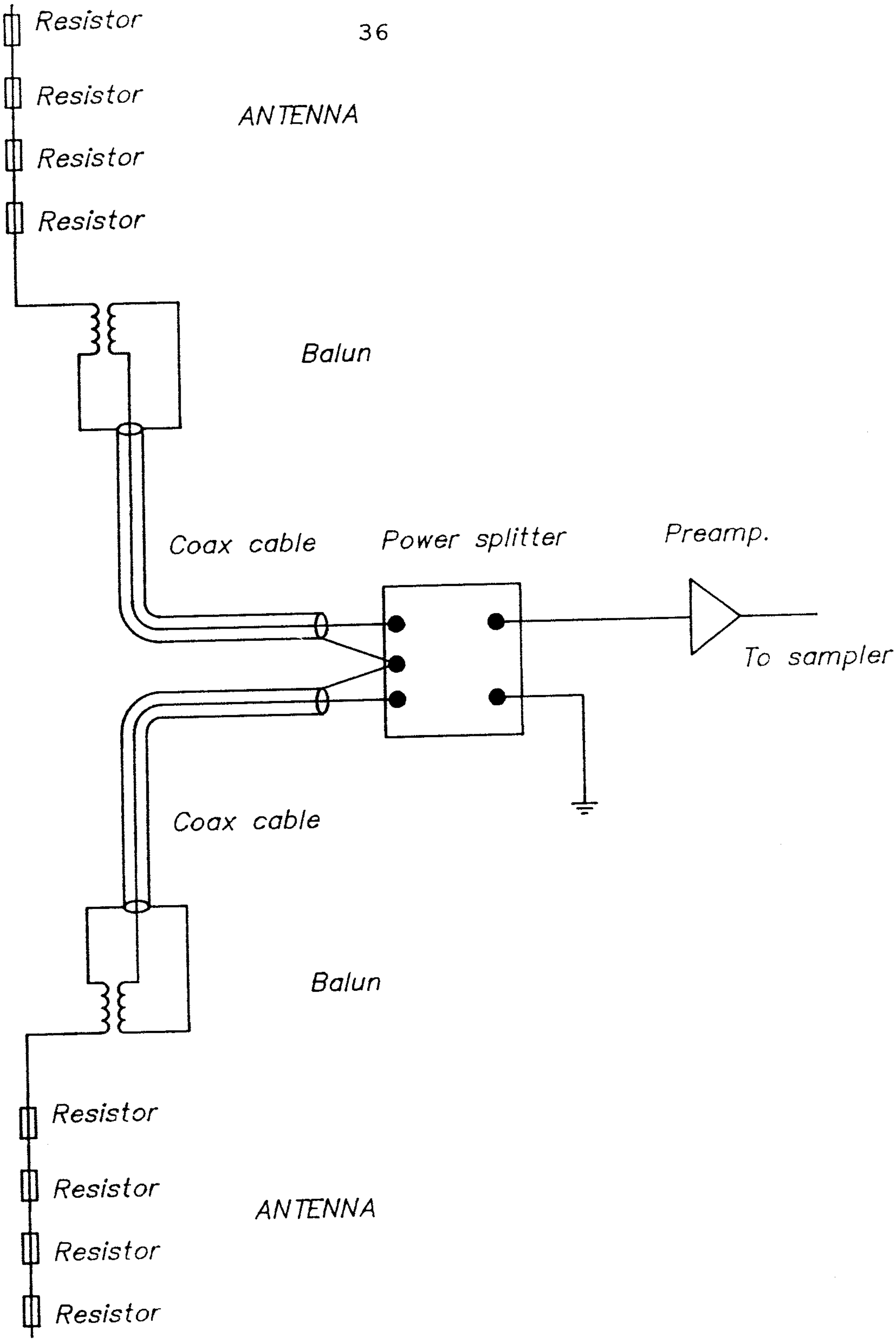


Figure 3.5 Schematic of the tunnel antenna.

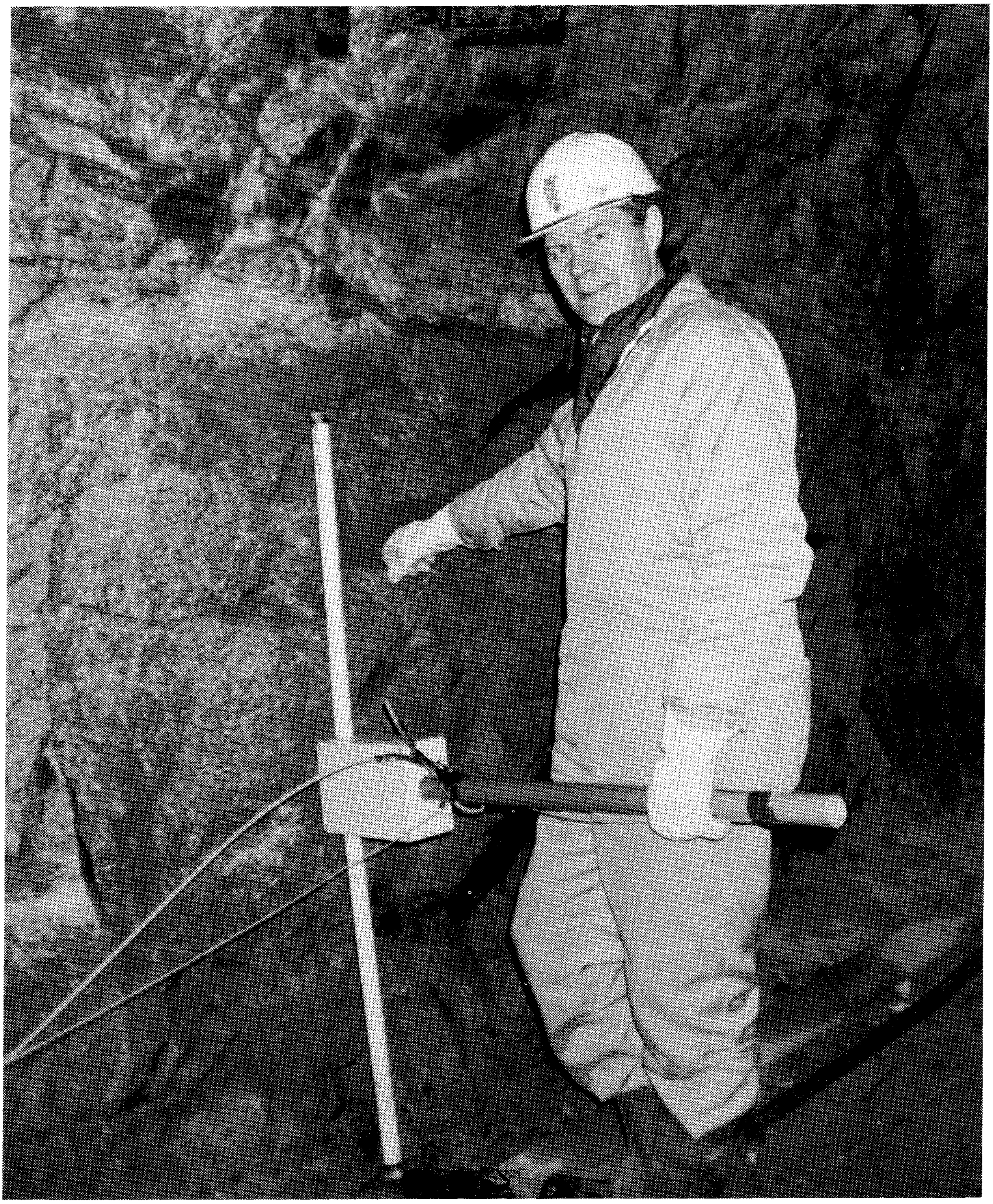


Figure 3.6 The low frequency antenna unit during tests in Stripa.

4. ANTENNA EXPERIMENTS IN STRIPA

Stripa mine is an excellent test place for radar work: the wave attenuation in Stripa granite is low, about 0.3 dB/m and the area is thoroughly known from previous radar work within the Stripa project. The antennas were studied by performing radar measurements along two tunnels, but the pulse was also investigated in special experiments, where the radar signal was monitored trace by trace. The tests showed that the radar worked successfully in a wide frequency range and also in geometries previously tested only in boreholes: single tunnel, borehole to tunnel, tunnel to tunnel and tomography. These experiments provided detailed information about the system.

4.1 Calibration of the radar pulse

In order to calibrate the radar signal a well-defined reflector is required. An excellent target was found about 15 m from the Crosshole site in the form of a neighbouring tunnel. The geometry of the area used during the tests is shown in the map in Figure 5.1 in the following section describing the radar measurements. The reflecting parallel tunnel has at this point widened into a cavity which was previously used for tracer tests.

The transmitter and receiver antennas were placed on the floor near the tunnel wall orthogonal to the tunnel and 2 m from each other. Figure 4.1 shows a reflection from the tunnel running parallel to the crosshole tunnel. The signal arrives about 160 nanoseconds after the direct signal, corresponding to 10 meters in Stripa granite, where the velocity is 0.128 m/nsec. This distance agrees very well with the map in Figure 5.1. The reflection is in phase with the direct signal as expected for a pulse reflected from a medium with low dielectric constant.

The radar signal changes as the equipment is moved along the tunnel. The direct signal fluctuates, but it is more important for the radar analysis that the reflected signal does not change rapidly. The direct signal in Figure 4.2 is well formed but the reflection is more complicated than in Figure 4.1, probably because the reflector has widened to a chamber at this point. The next signal, in Figure 4.3, is entirely different: it was measured when the antennas passed the opening connecting the two parallel tunnels shown in Figure 5.1. The signal consequently starts to ring when the external conditions change too much, since the antennas have been adapted to rock.

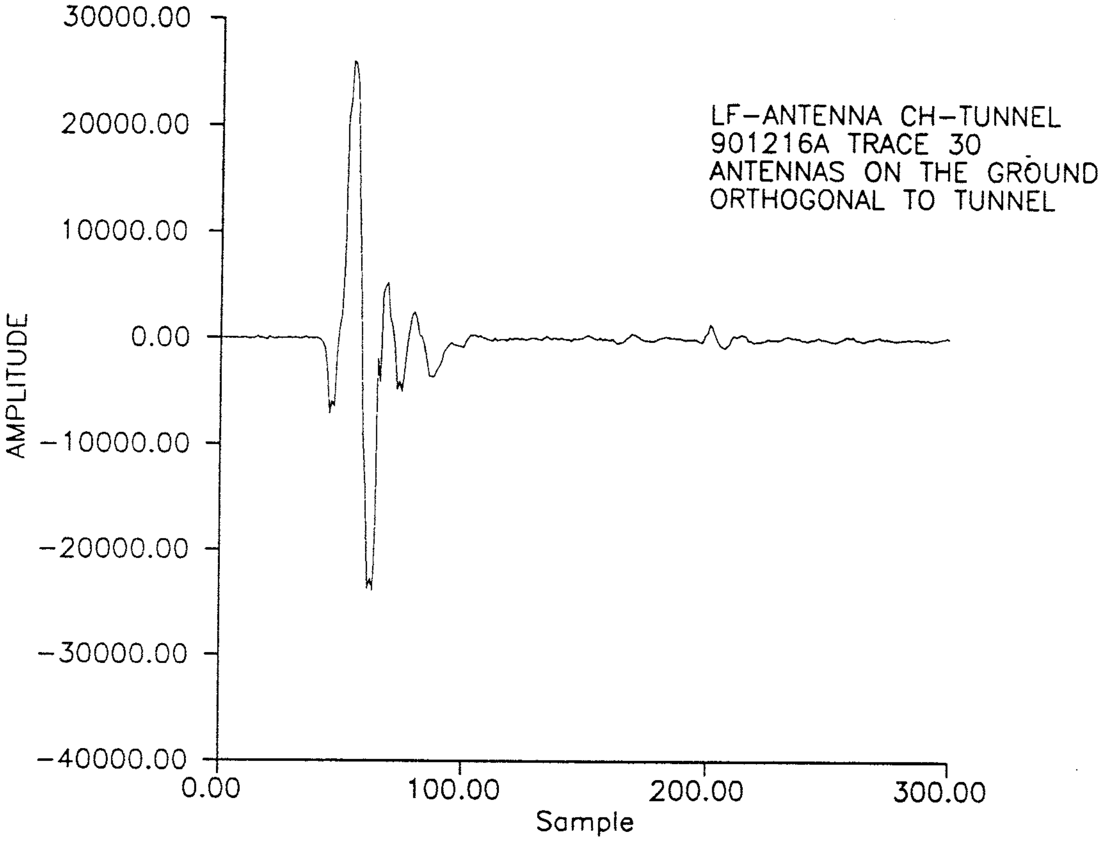


Figure 4.1 Two low frequency antennas 2 m apart on the ground orthogonal to tunnel.

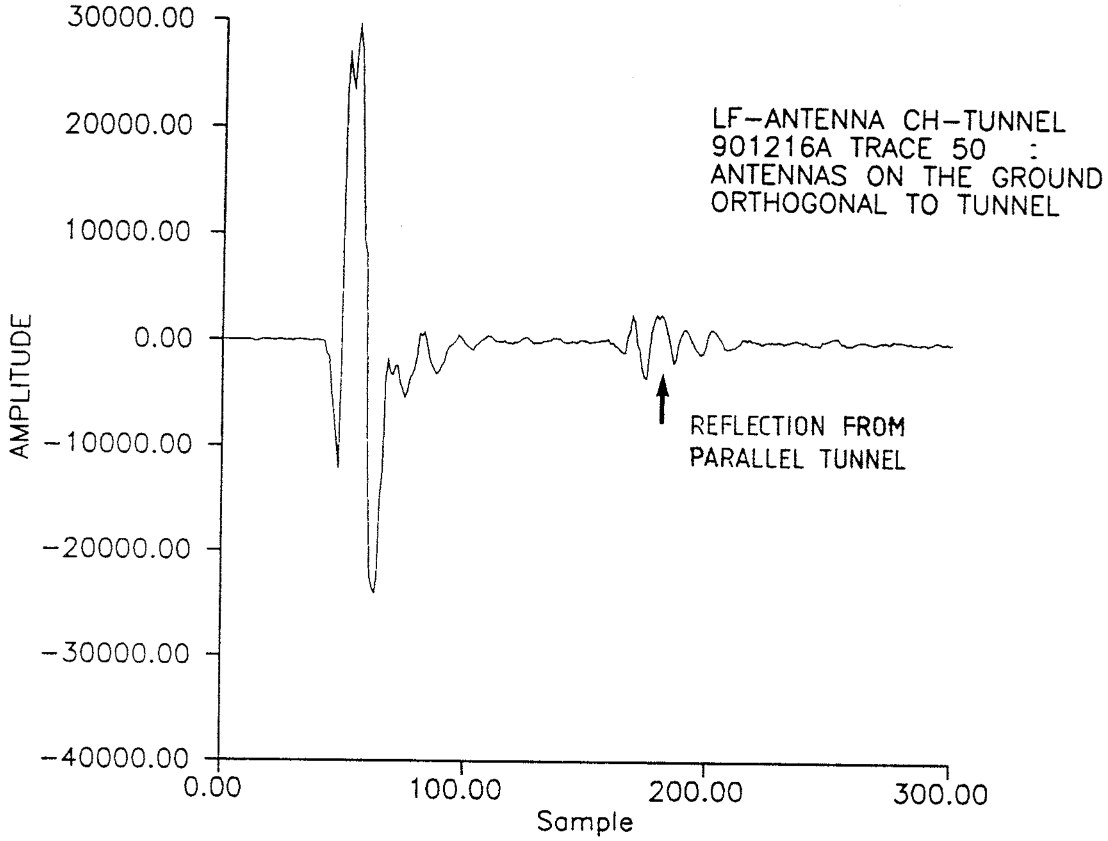


Figure 4.2 Two antennas 2 m apart on the ground orthogonal to tunnel showing a reflection from the parallel tunnel.

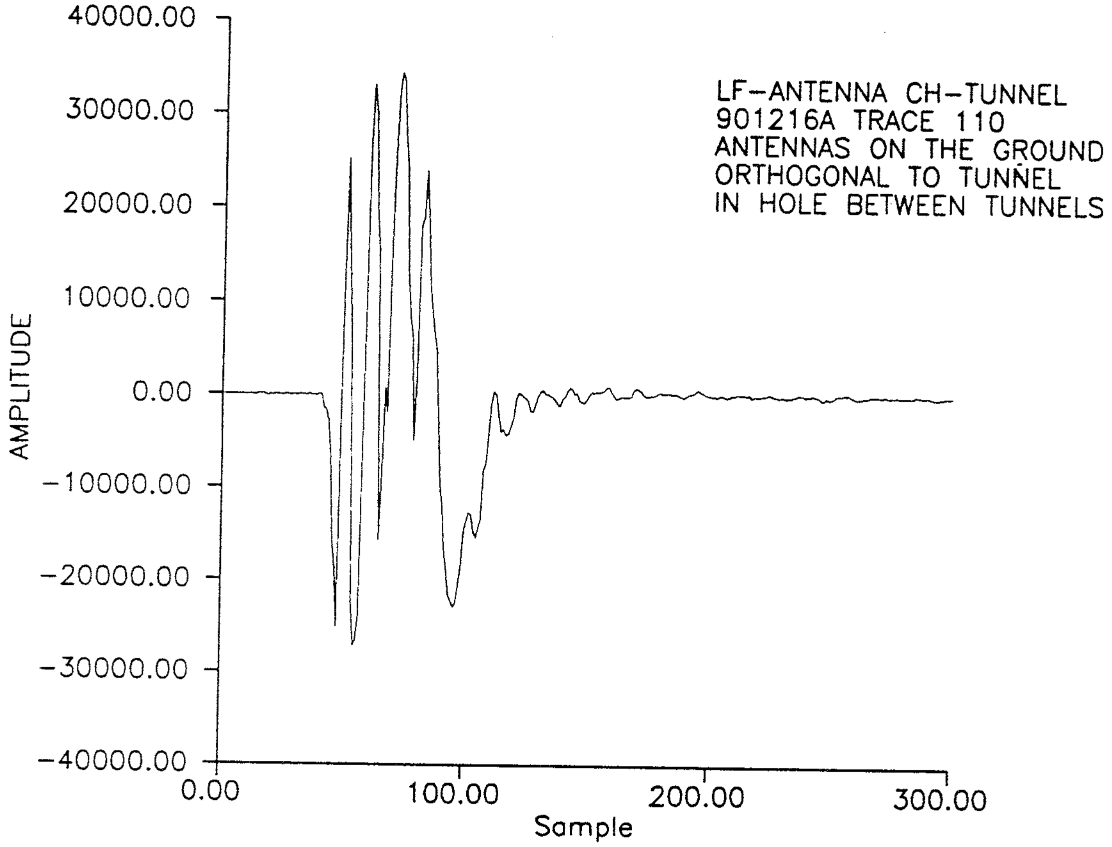


Figure 4.3 Two antennas 2 m apart on the ground and orthogonal to the tunnel passing the hole between the tunnels.

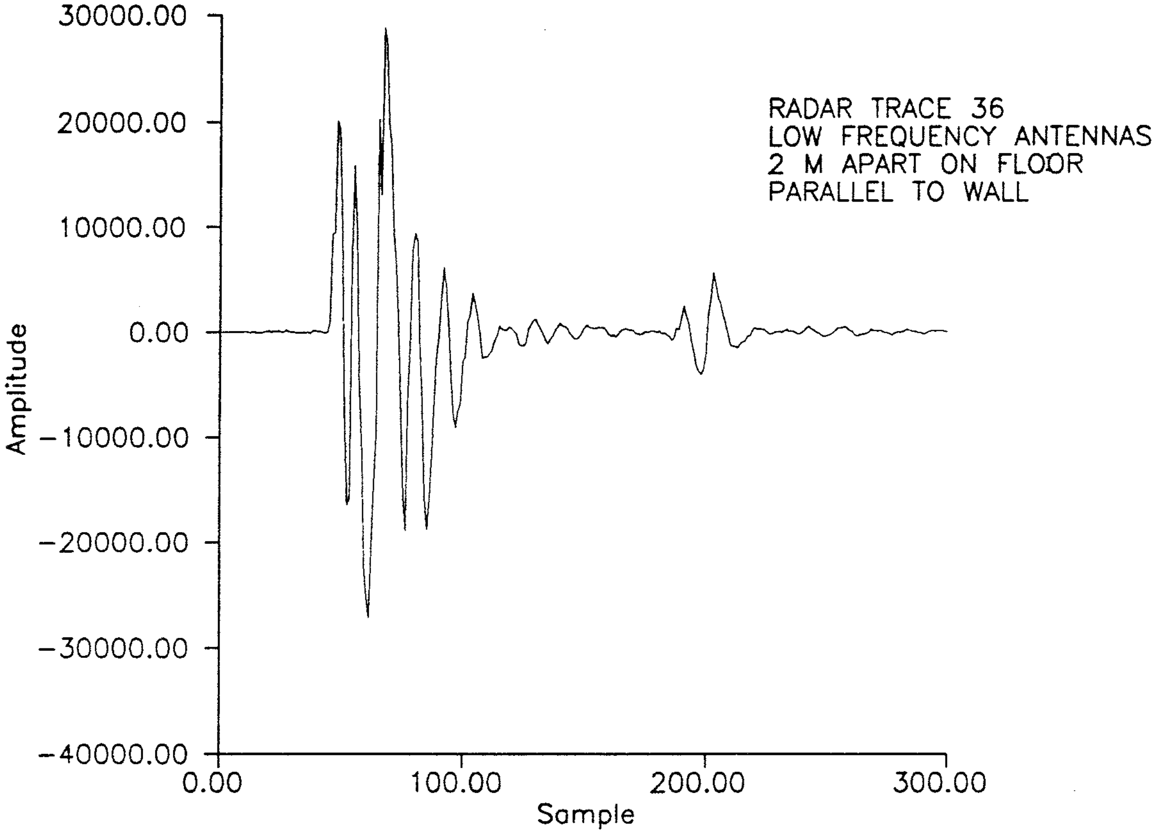


Figure 4.4 Antennas 2 m apart on the ground parallel to the wall of the Crosshole tunnel showing a reflection from the parallel tunnel.

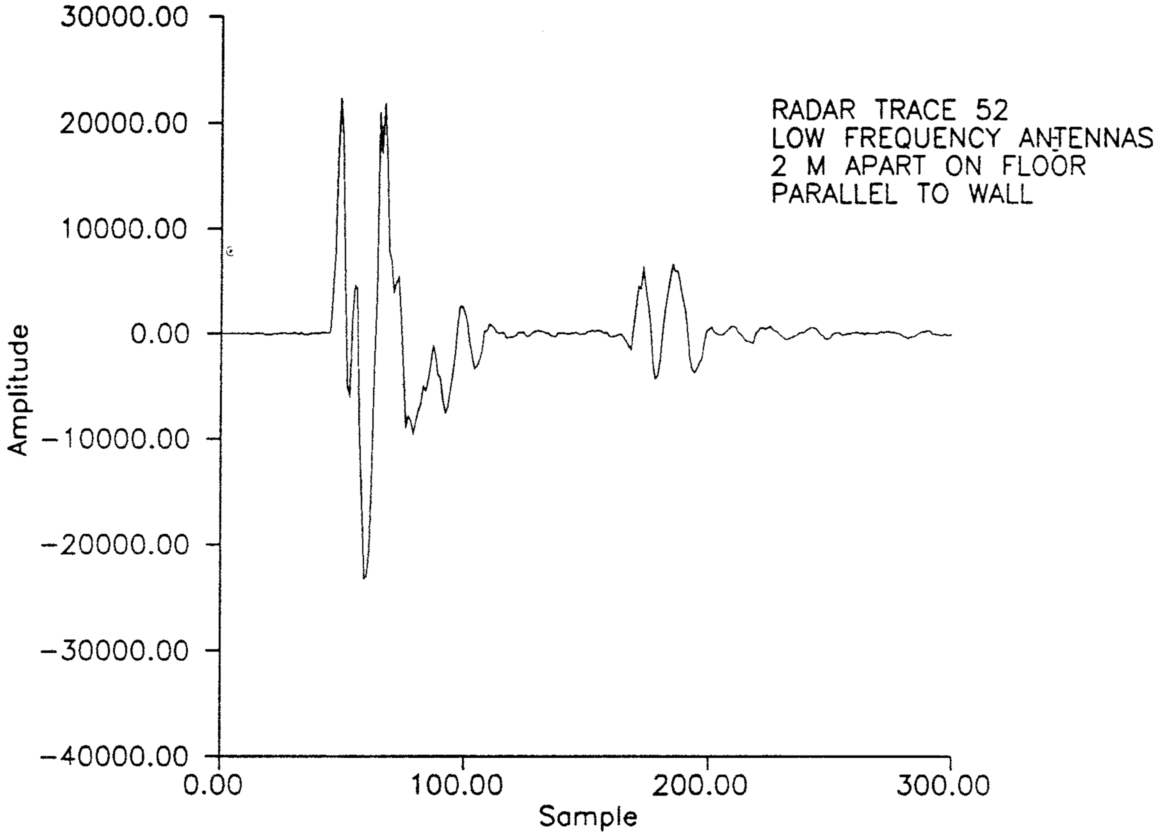


Figure 4.5 Two antennas 2 m apart on the ground parallel to tunnel with a reflection from the parallel tunnel.

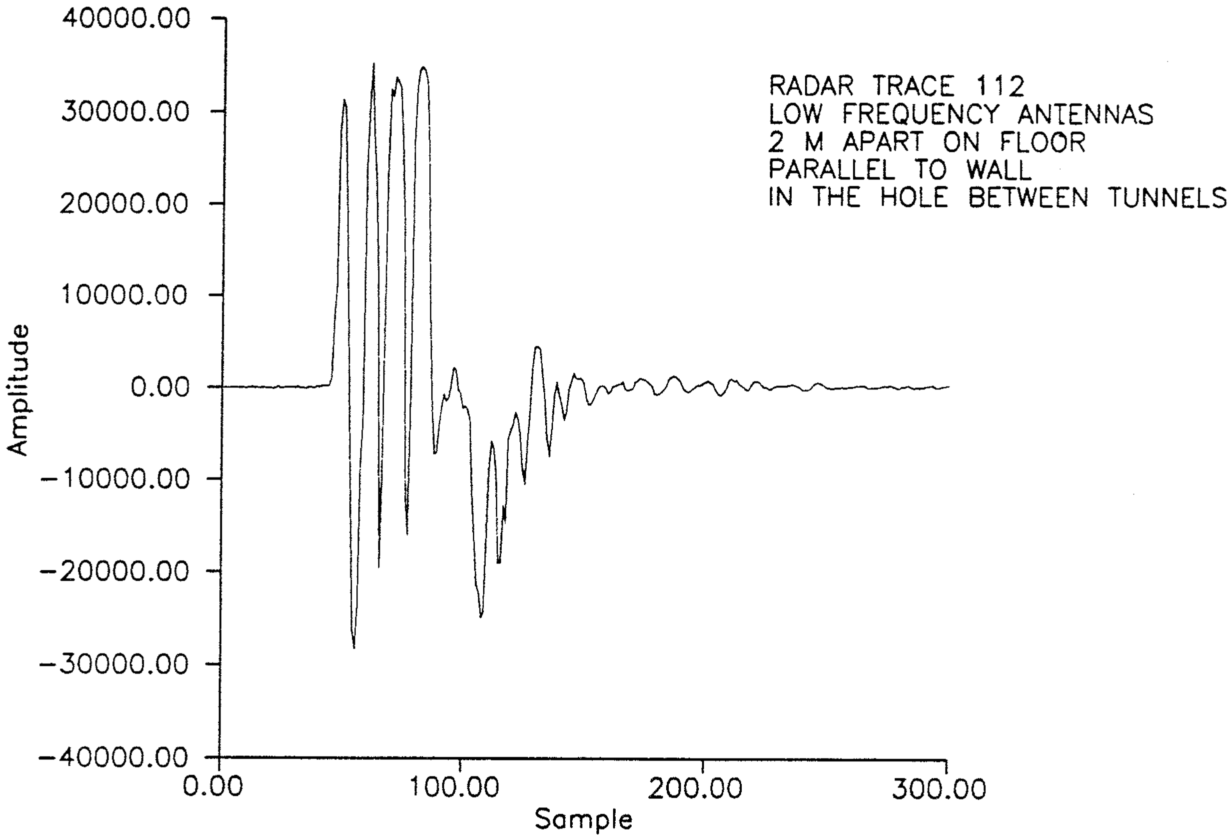


Figure 4.6 Two antennas 2 m apart on the ground parallel to tunnel in the hole between the tunnels.

The three signal traces should be compared with the three following signals shown in Figures 4.4-4.6, which were measured in similar positions but with the antennas placed parallel to the tunnel and held close to the wall. The signal in Figure 4.5 is ringing, but the reflected signal is still well shaped, confirming that wave propagation along the tunnel wall has little to do with the propagation of reflected signals in the rock. The amplitude of the reflected signal has increased dramatically, because the dipole antenna is now orientated with its radiation maximum towards the target. In the previous case the minimum, which is along the antenna axis, was directed towards the target. This example shows how important it is to select a suitable antenna orientation. One must be prepared to change orientation if circumstances so require, particularly if a conductor happens to be parallel to the antenna. This was the reason for making the antenna units as light as possible: dipole antennas were favoured because they are easy to move around and have a well defined linear polarization.

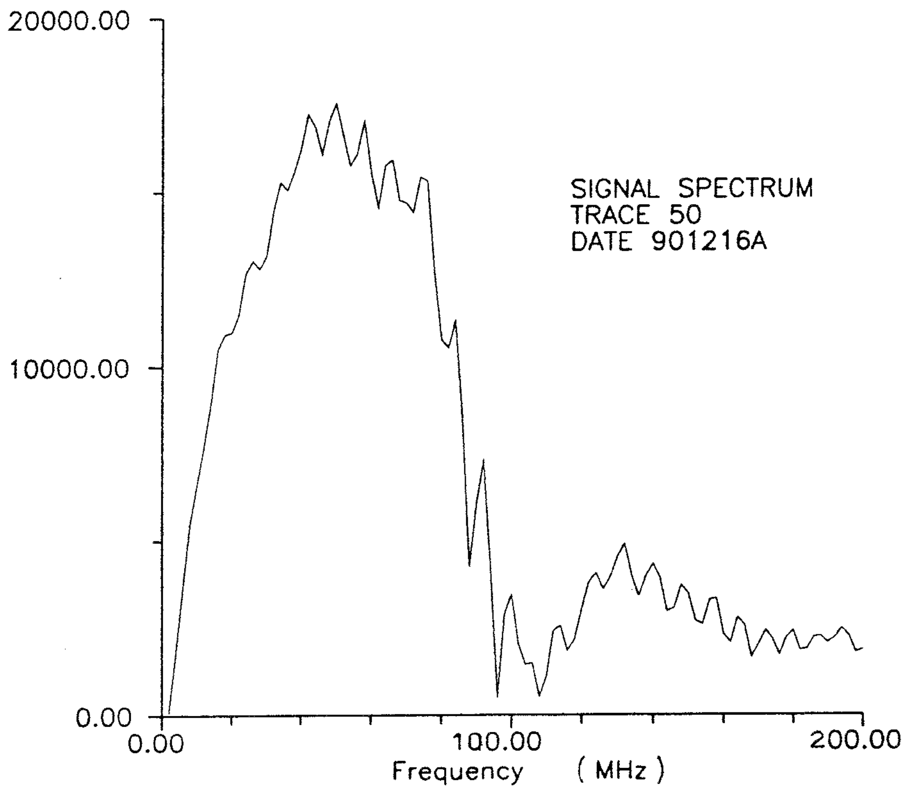


Figure 4.7 Signal spectrum of the signal in Figure 4.2.

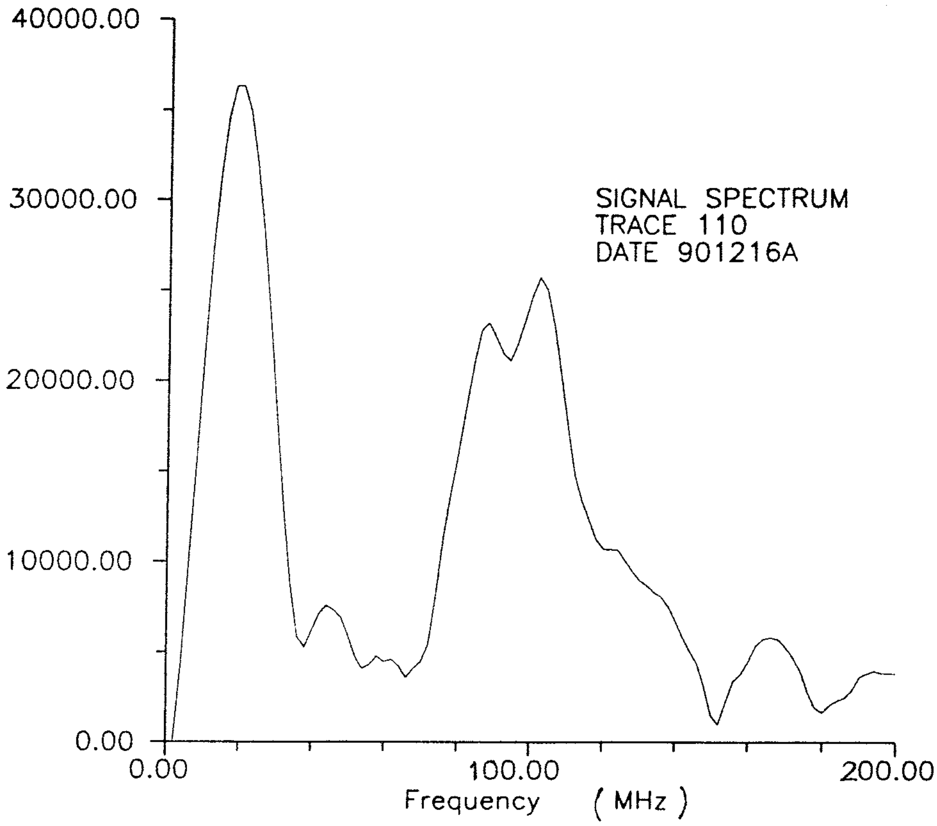


Figure 4.8 Signal spectrum of the signal in Figure 4.3.

4.2 Signal frequency spectrum

The spectrum of the signal in Figure 4.2 is shown in Figure 4.7. The spectrum is broad as expected from a Wu-King antenna and centered around 50-55 MHz. The peak is very wide and it is difficult to define a resonance frequency, which makes the pulse suitable for ground probing radar.

This spectrum can be compared with the spectrum of the ringing signal obtained in the open space in Figure 4.3. The frequency spectrum is shown in Figure 4.8 and contains two peaks: the lower is caused by the electronics, which creates a slow movement at the end of the pulse, while the higher frequency is a new natural frequency of the antenna occurring at about 100 MHz.

This effect can only be explained by the open space surrounding the antenna. The large space around the antenna effects the direct wave which, however, is of little consequence for a radar measurement. The antenna behaves more or less as if it had been placed in free space. Since the frequency has doubled one can assume that the permittivity experienced by the tunnel antenna is about 4, bacause wavelengths scale as the squareroot of the permittivity.

This approximative reasoning can be checked by calculating the central frequency for a pulse which has propagated undisturbed through rock. Pulses of this type are obtained in cross tunnel measurements as shown in Figure 4.9. The signal has travelled about 10 m in rock and has not attenuated significantly. The corresponding spectrum shown in Figure 4.10 has a peak at 59 MHz and since the antenna length is 1.2 meter, which should correspond to half the wavelength, the equivalent permittivity is about 4.3, in good agreement with the previously obtained value 4.

It is well known that the permittivity of the Stripa granite is 5.5-6 for the radar frequencies, which suggests that the tunnel acts according to the rough formula suggested by theory: the equivalent permittivity 4 is not far from the average value for air and granite, $(6+1)/2 = 3.5$. This idea can be tested further, e g by performing cross tunnel mesurements where pulses from antennas placed away from the tunnel wall are studied or by measuring the resonance frequencies of an antenna in different media.

The Wu-King antenna formula was checked by constructing a high frequency antenna half as long as the low frequency version. The signal from this antenna was centered at twice the frequency, but the quality of the pulse suffered from the fact that the metal box covers a large part of the middle section of the short antenna, which consequently does not quite fit into the Wu-King recipe.

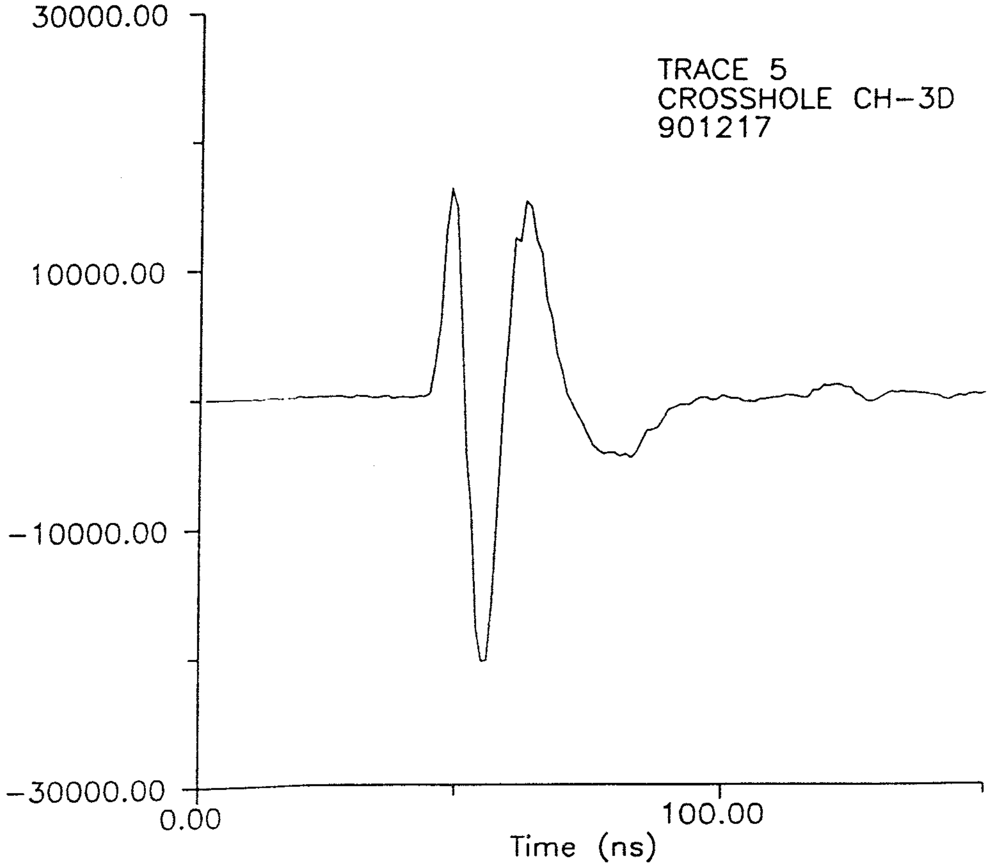


Figure 4.9 Radar pulse after propagating 10 m between the Crosshole tunnel and the 3D-tunnel.

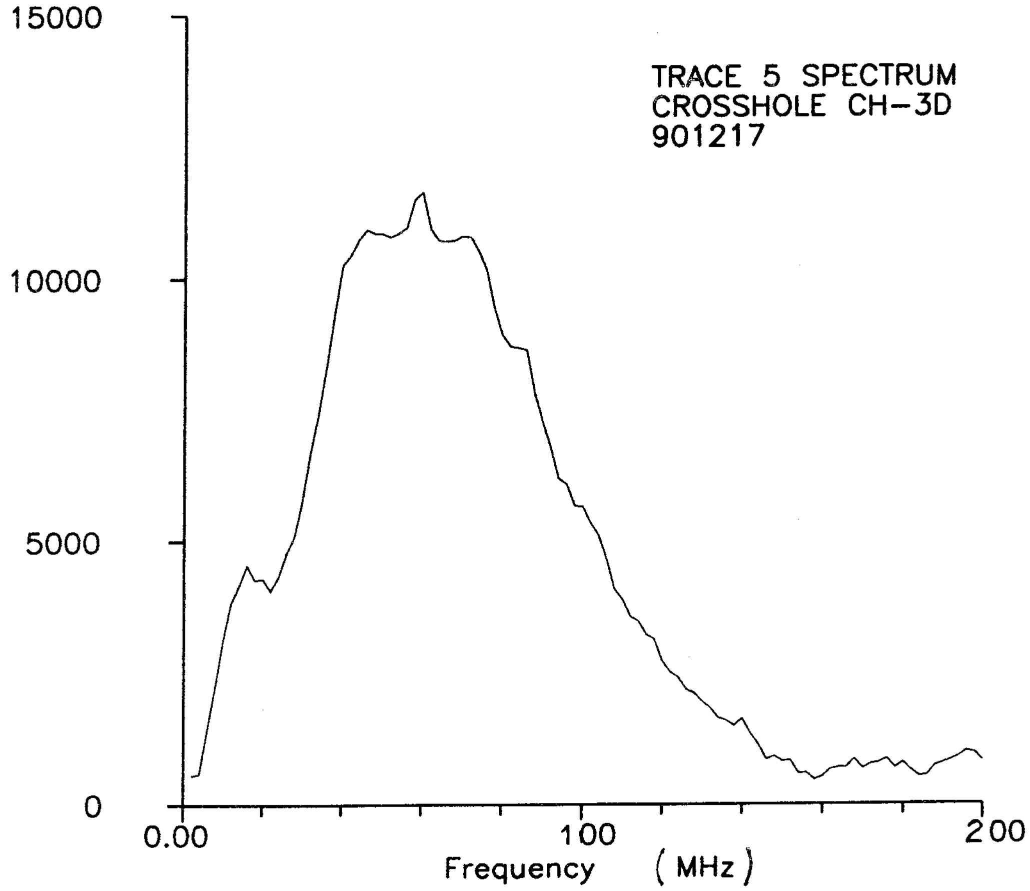
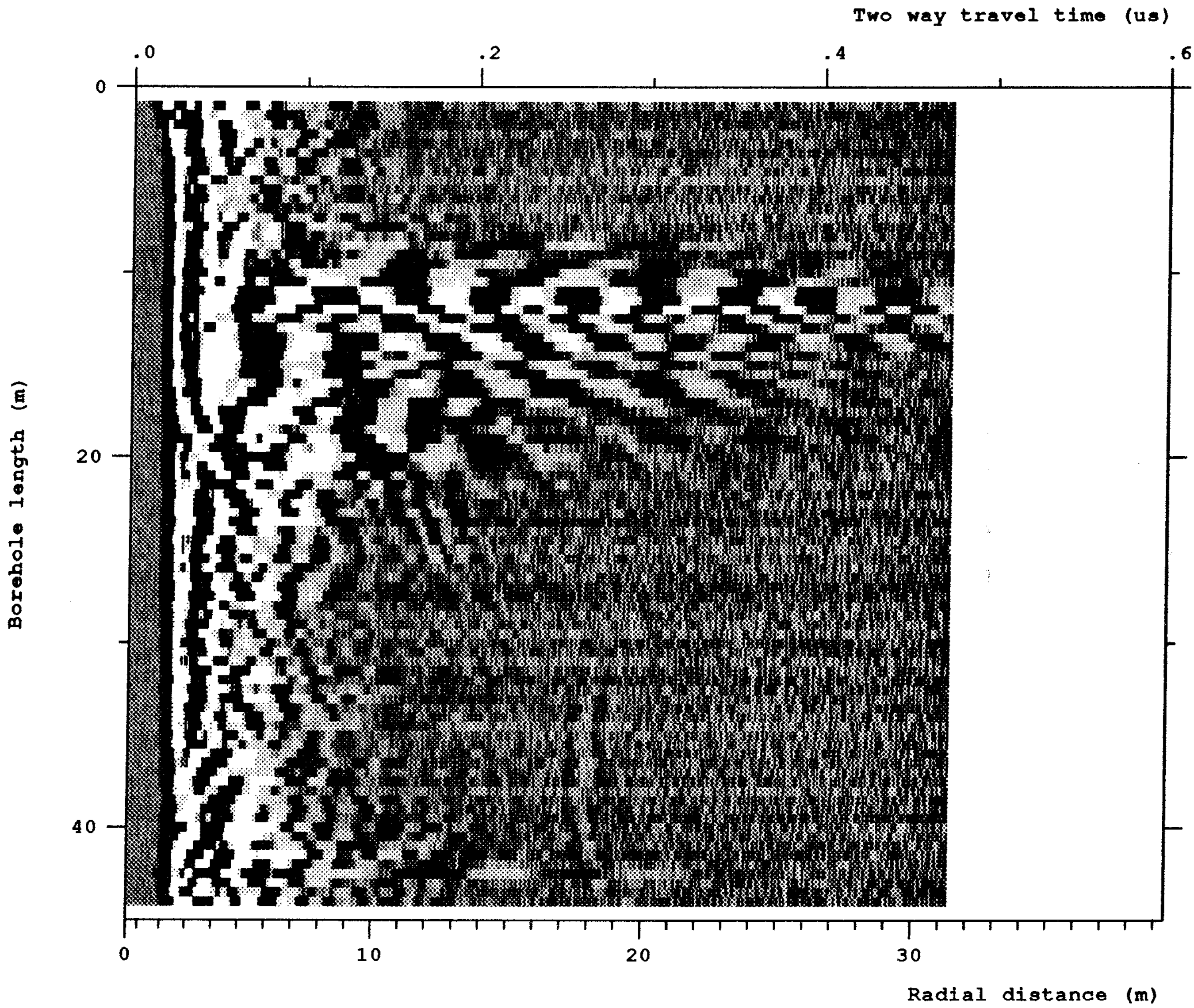


Figure 4.10 Spectrum of the previous trace.



Site and borehole:stripa tunnel to d3
Date:901217
T-R Distance:2
Equipment name:tunnel

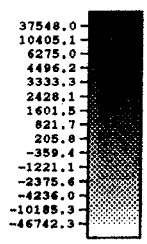


Figure 4.11 Measurement in the 3D-tunnel starting at the tunnel intersection. 60 MHz antennas on floor, orthogonal to tunnel.

4.3 Polarisation

The polarisation of a radar pulse will to a large extent decide what is seen in a radar measurement. The reflected signal depends on polarisation, particularly if the reflector is a linear structure, e g a metal cased or waterfilled borehole. In both cases the coupling is strongest when the wave is polarized with the electric field parallel to the conductor.

This effect can cause serious problems when measurements are performed in a tunnel. In practice there are always metallic conductors present in a tunnel in the form of cables, railways and ventilation drums. The multiple reflections generated between an antenna and the conductor can completely mask other reflections. This effect is well known in ground penetrating radar where it is used to separate pipes and cables from other objects. Figure 4.11 shows an example of a radar picture where the polarisation has been poorly selected. The antennas were placed on the tunnel floor orthogonally to the wall and a strong coupling occured when the antennas were parallel to an electric conductor hidden under the tunnel floor. It is consequently necessary to use antennas which can be freely lifted and rotated to reduce coupling.

Figures 4.12-4.16 illustrate the effect of antenna orientation on the signal. Both antennas were held vertically near the wall and 2 m apart parallel to each other at a point where a clear reflection was obtained from the parallel tunnel. When one of the antennas is rotated the signal strength is reduced as expected. A simple model suggests that there should be a sinusoidal decrease in amplitude and in fact the signal is reduced to half its amplitude when the antenna has been rotated 60° in agreement with the formula cos 60° = 0.5. The signal almost disappears when the antenna has been rotated 90° in Figure 4.14 though some peaks remain. The model works best for the reflected signal while the direct pulse does not quite obey the simplified picture. Almost the whole pulse disappears but the first peak remains high, indicating that it may be caused by some other coupling. This explanation is supported by the observation that the direct signal is not perfectly inverted when the antenna has been rotated 180°. Measurements of this type are a valuable diagnostic tool in antenna tests.

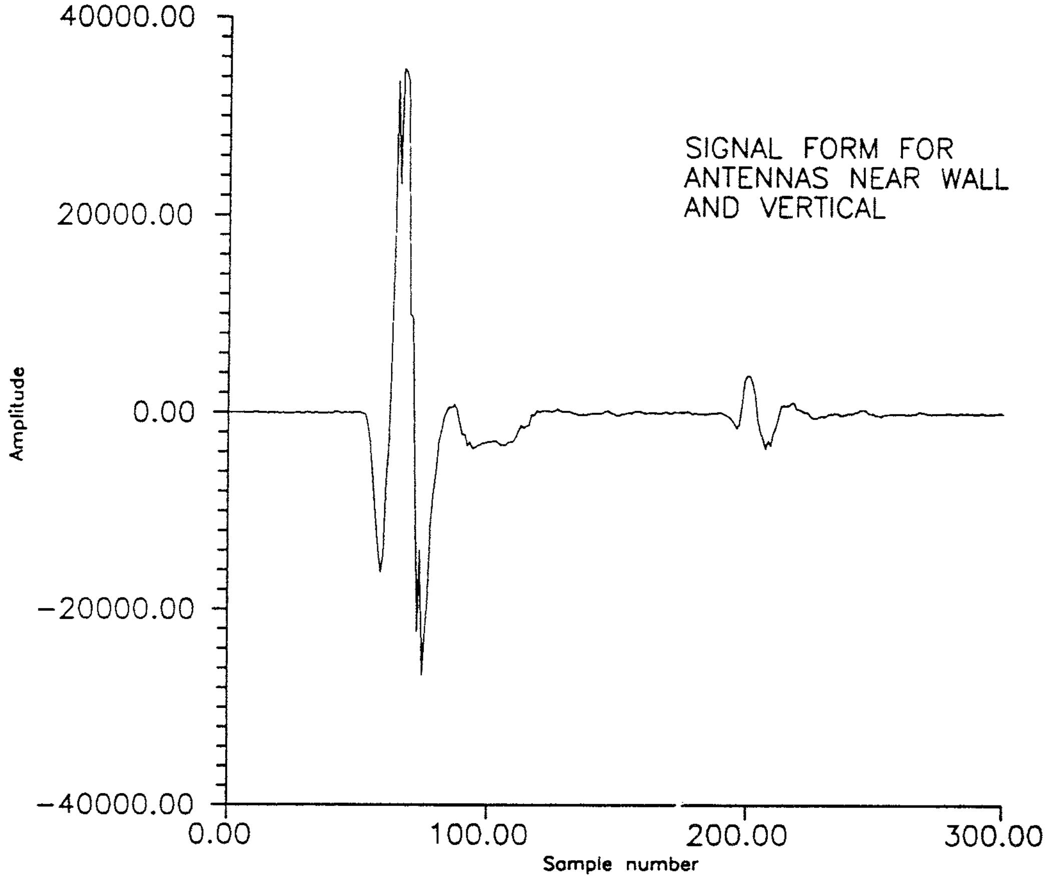


Figure 4.12 Two 60 MHz antennas held vertically against the tunnel wall. Reflection from the parallel tunnel.

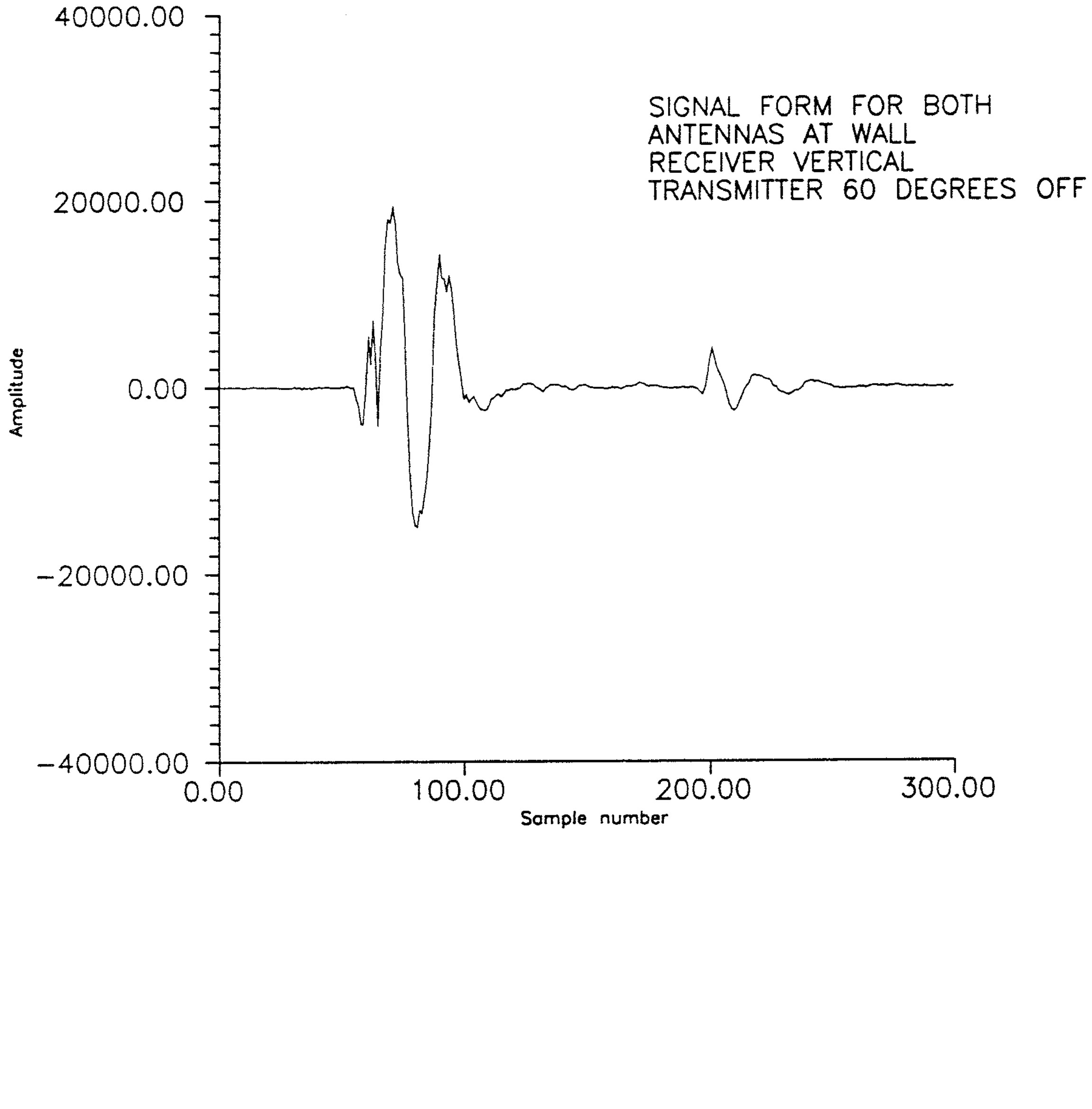


Figure 4.13 Both 60 MHz antennas near wall, receiver vertical, transmitter rotated 60°.

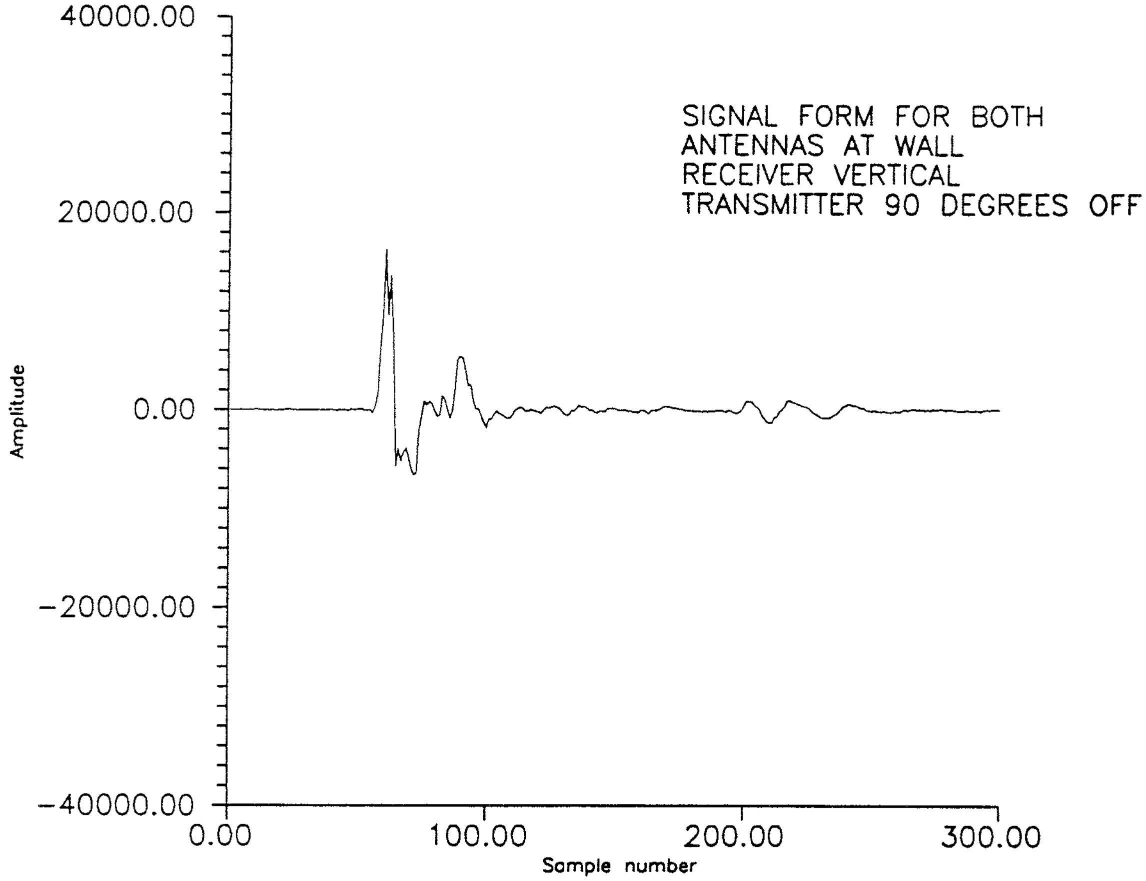


Figure 4.14 Both 60 MHz antennas near wall, receiver vertical, transmitter rotated 90°.

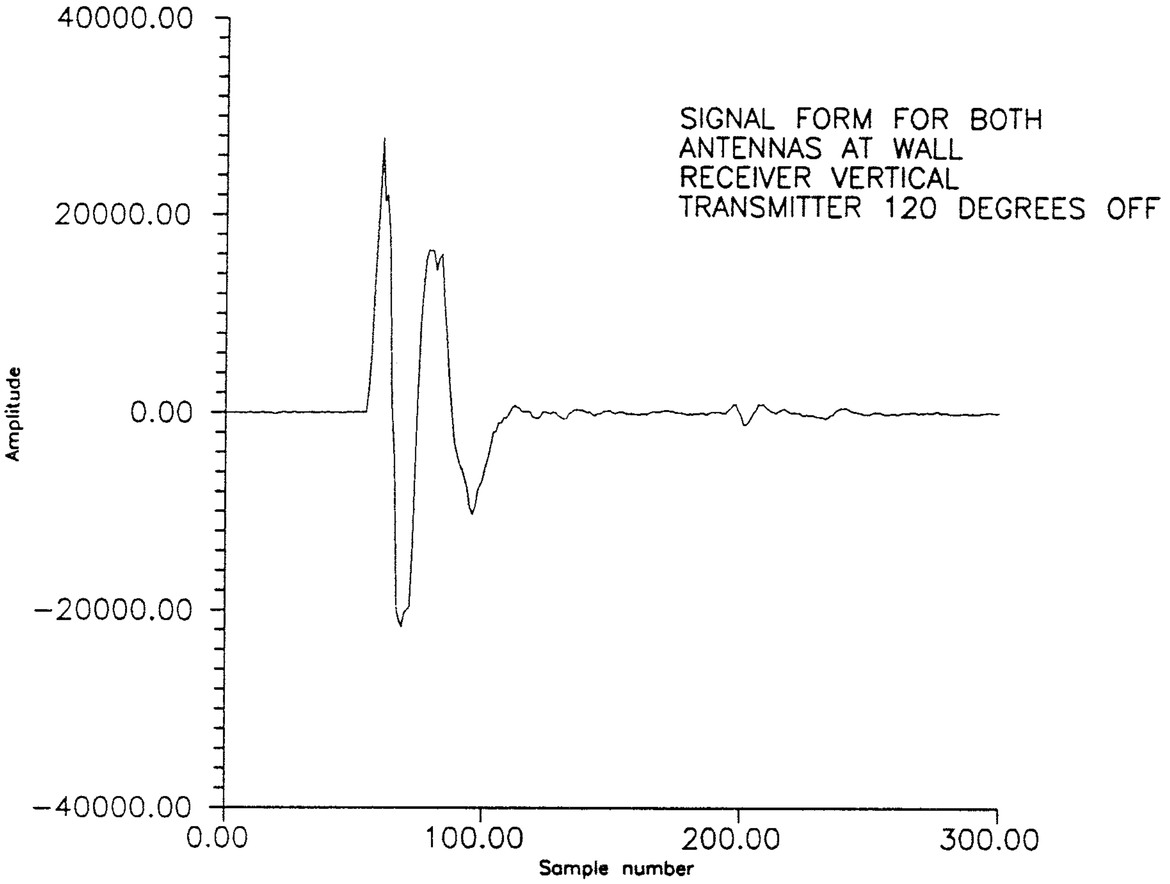


Figure 4.15 Both 60 MHz antennas near wall, receiver vertical, transmitter rotated 120°.

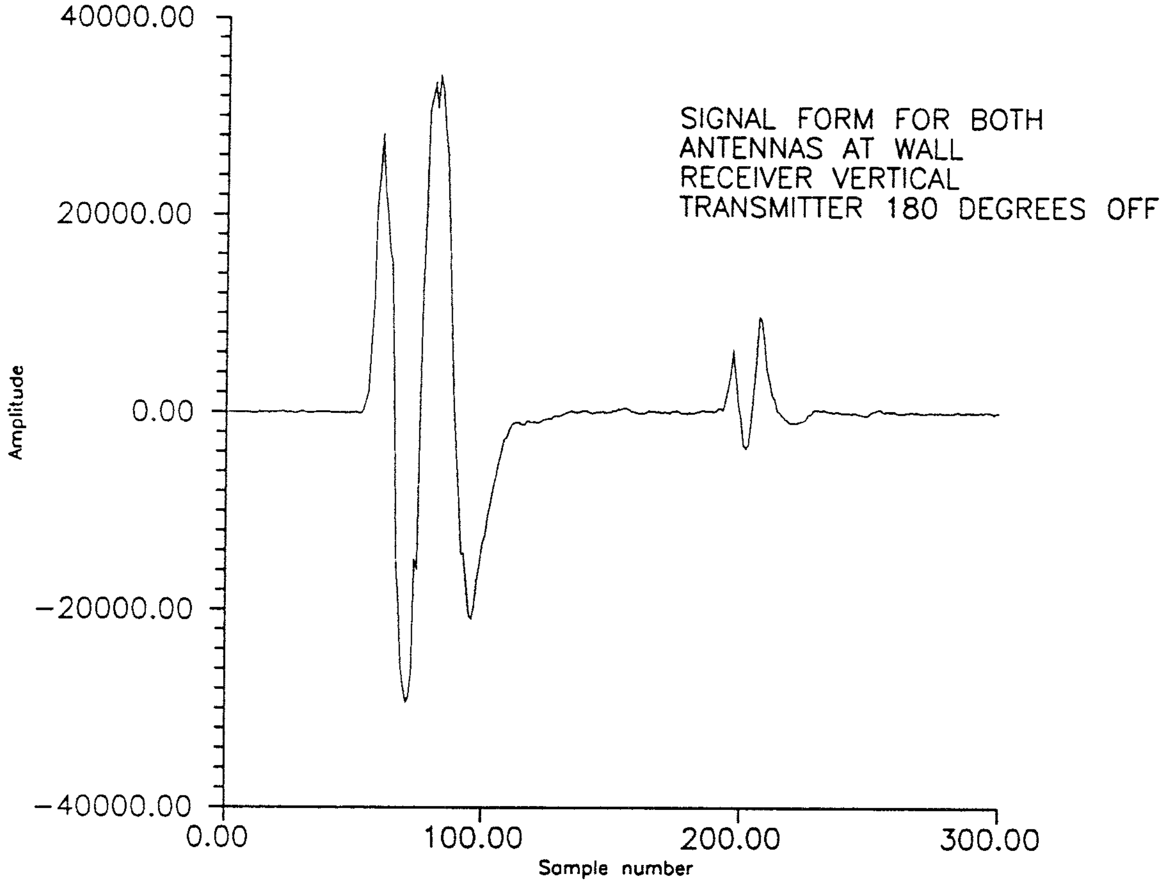


Figure 4.16 Both 60 MHz antennas near wall, receiver vertical, transmitter rotated 180°.

4.4 Distance dependence

The most important property of a ground penetrating radar is that the pulse is short and reasonably free from ringing. In a tunnel the permittivity of rock is fairly constant and offers less variation than in the ground, where the overburden presents a problem. The dependence on antenna height is rather difficult to predict: the theoretical calculations for a dipole over an interface suggest that a dipole is sensitive to antenna height. The antenna is located in a transition zone between two media with different wave velocities and impedances and a rapid change must take place over a distance on the order of a wavelength.

Calculations indicate that the transition zone for a dipole near a plane is narrow. The antennas are sensitive to the distance to the interface; this was confirmed in laboratory tests with small antennas and a network analyzer (Falk et al., 1990). A clear difference was noticed when the antenna was placed on the ground and then lifted 30 cm upwards. These experiments suggest that the properties of the pulse depend on how the antenna is placed as indicated by calculations but the calculations are based on simplifications which may be inapplicable in a real tunnel (Smith, 1984).

The antennas are specifically designed for tunnel applications and considering that the wavelength and the antenna length both are on the order of a tunnel diameter (2-3 m) the previous calculation can only have an indicative value. Exact calculations of antenna performance in a tunnel are difficult to obtain: the closest case in the literature is perhaps an investigation by Hill and Wait who studied electric and magnetic dipoles in a cylindrical tunnel (Hill and Wait, 1977). Their calculations do not cover parameters applicable to radar frequencies but are still of interest, because they also consider the case where electric and magnetic dipoles radiate in the presence of a metal cable in a tunnel. In general the effect of coupling to the cable turns out to be less than might have been feared. This result agrees with our experimental results, where ventilator drums and the railway rails had remarkably little effect on the signal.

The calculations describes so far refer to short antennas and it is necessary to perform experiments to obtain data for a real antenna. The experiments showed that conditions are more favorable than we might have hoped for. Measurements with a network analyzer demonstrated that the impedance of most of our antennas was insensitive to the distance from the tunnel wall as long as it did not exceed 0.5 m. This effect is particularly pronounces for Wu-King antennas: the impedance curves on the Smith chart were almost unaffected when the antennas were moved away from the tunnel wall or placed on the gravel of the tunnel floor, in marked contrast to tests previously performed on the laboratory floor. There were, however, some changes in resonance frequencies as might be expected from considerations of continuity between the two media.

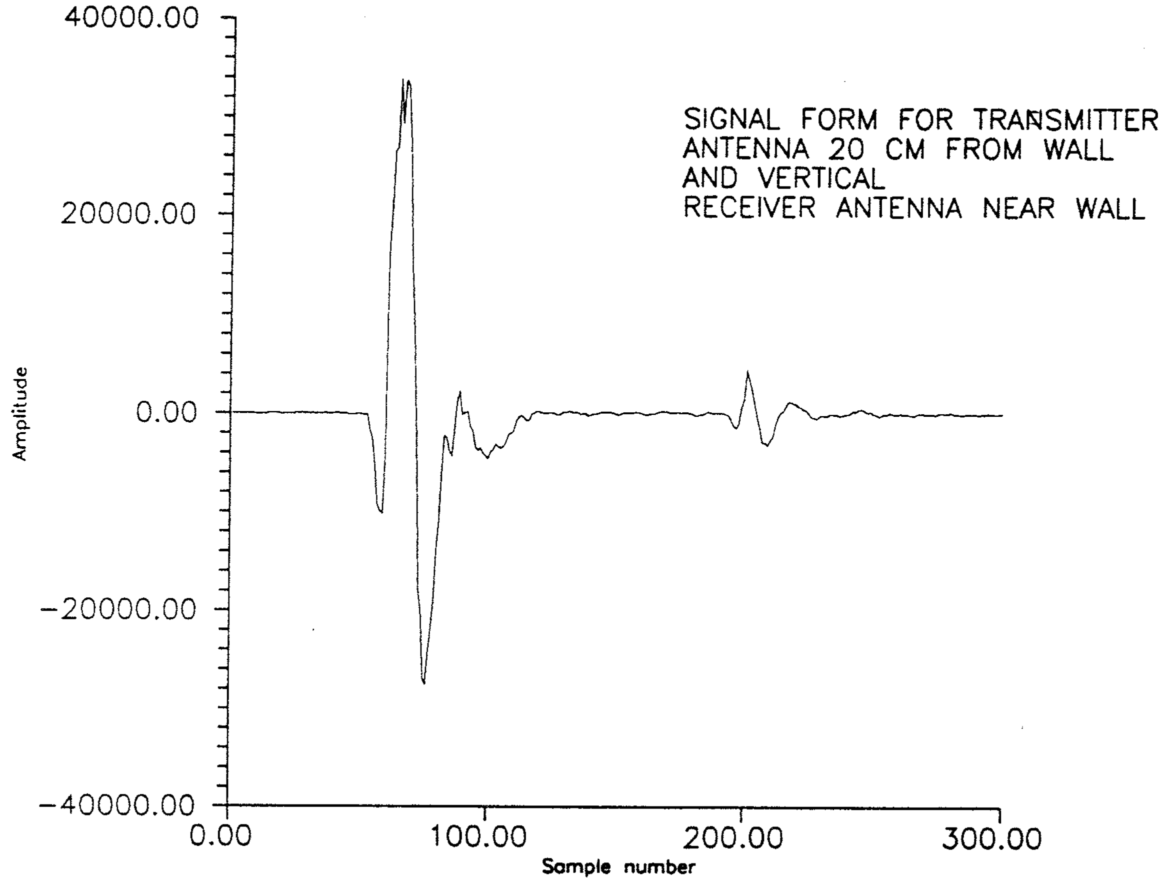


Figure 4.17 Both 60 MHz antennas vertical, receiver near wall, transmitter 20 cm from wall. Reflection from the parallel tunnel.

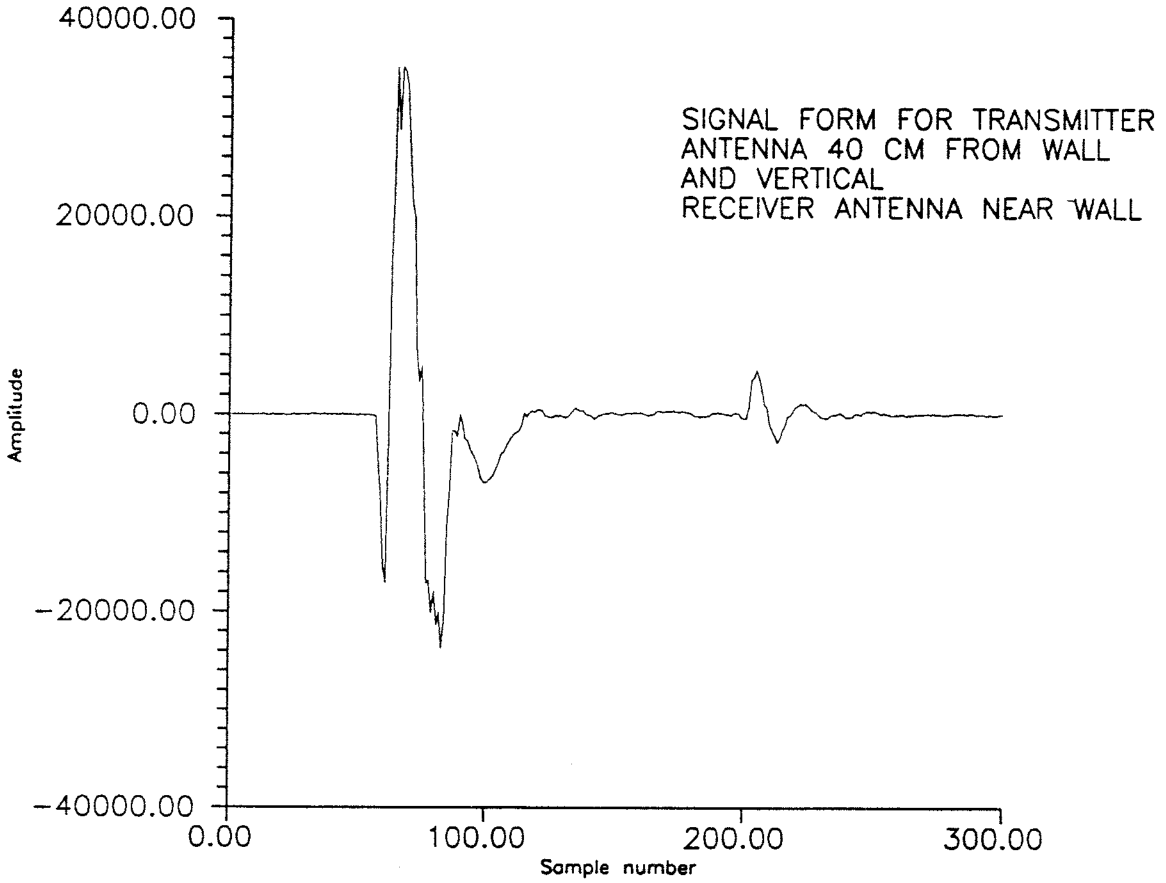


Figure 4.18 Both 60 MHz antennas vertical, receiver near wall, transmitter 40 cm from wall.

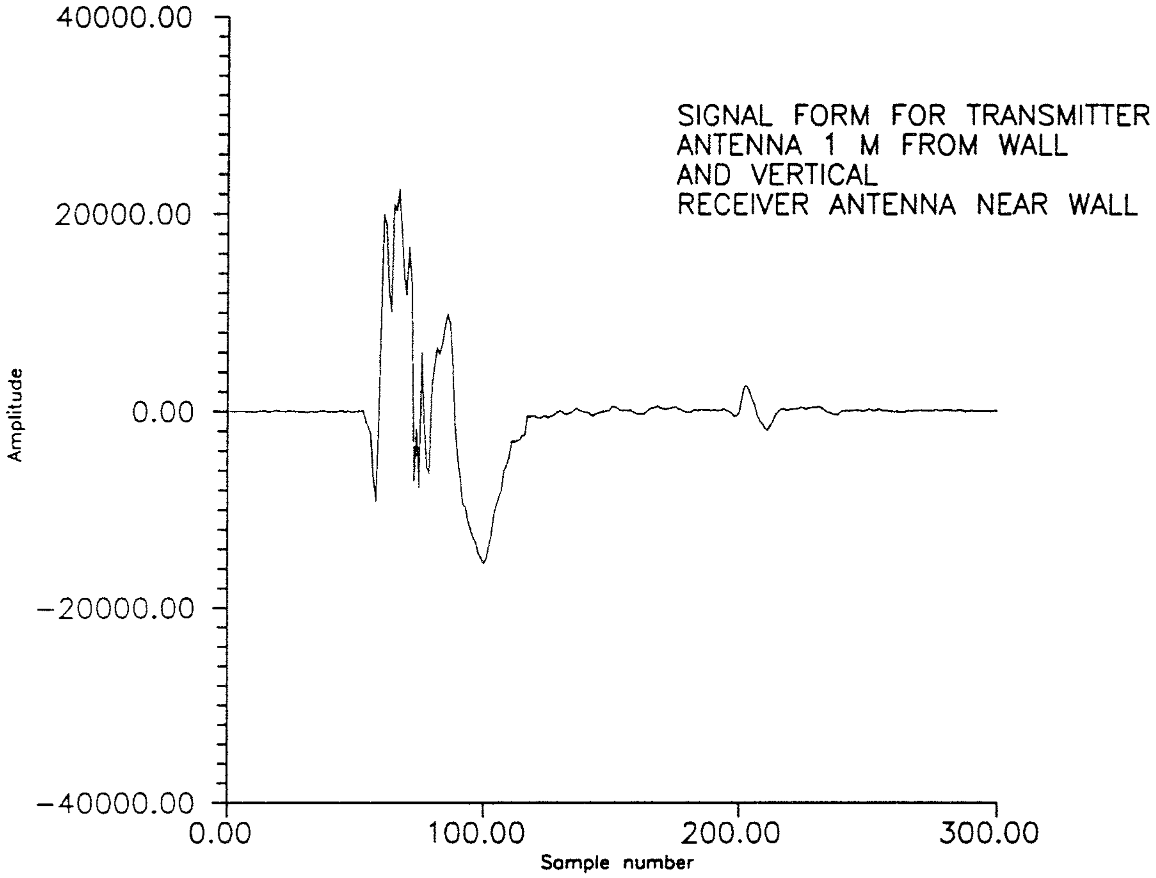


Figure 4.19 Both 60 MHz antennas vertical, receiver near wall, transmitter 1 m from wall.

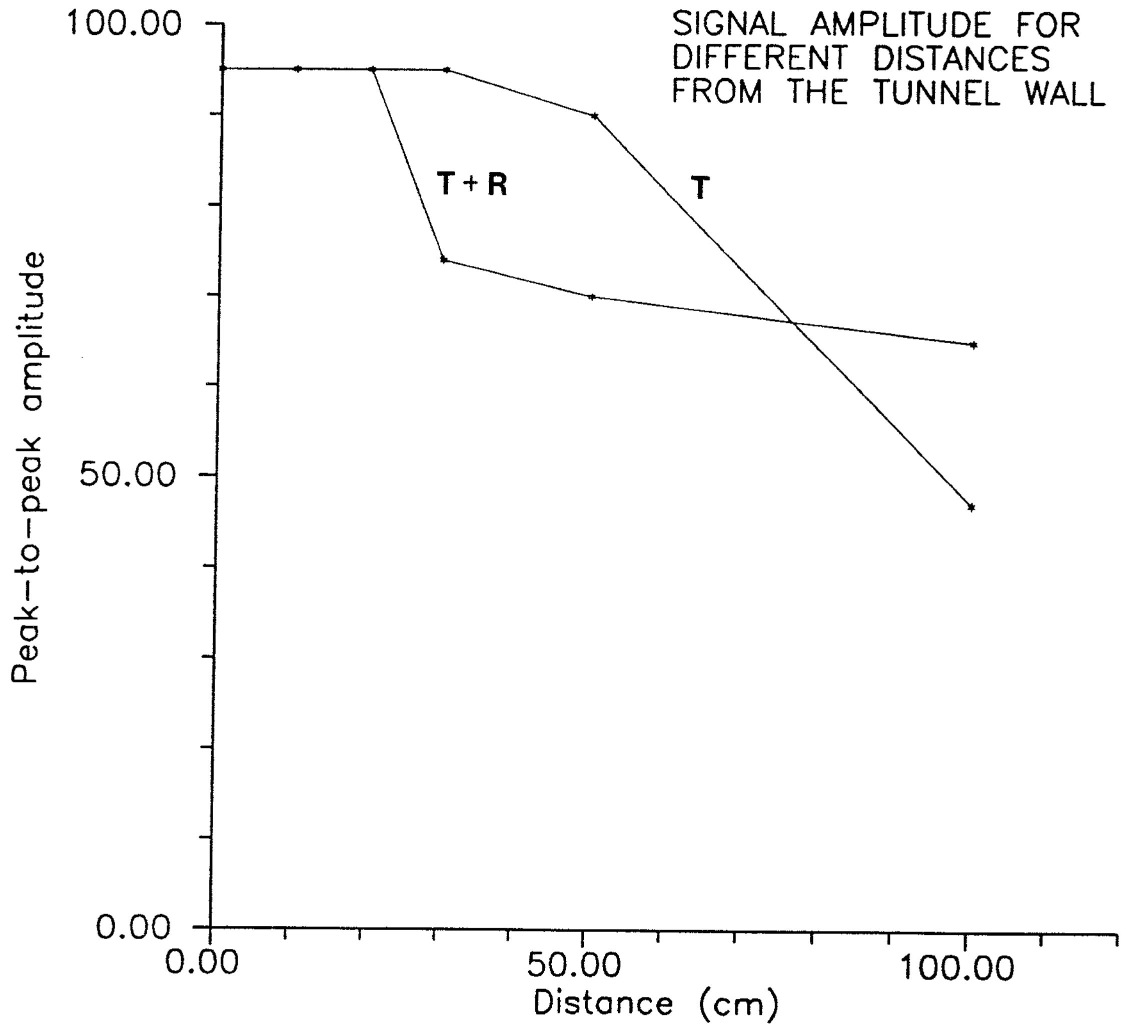


Figure 4.20 Signal amplitude for direct wave as a function of antenna distance from wall. T: only transmitter. T + R: both antennas moved.

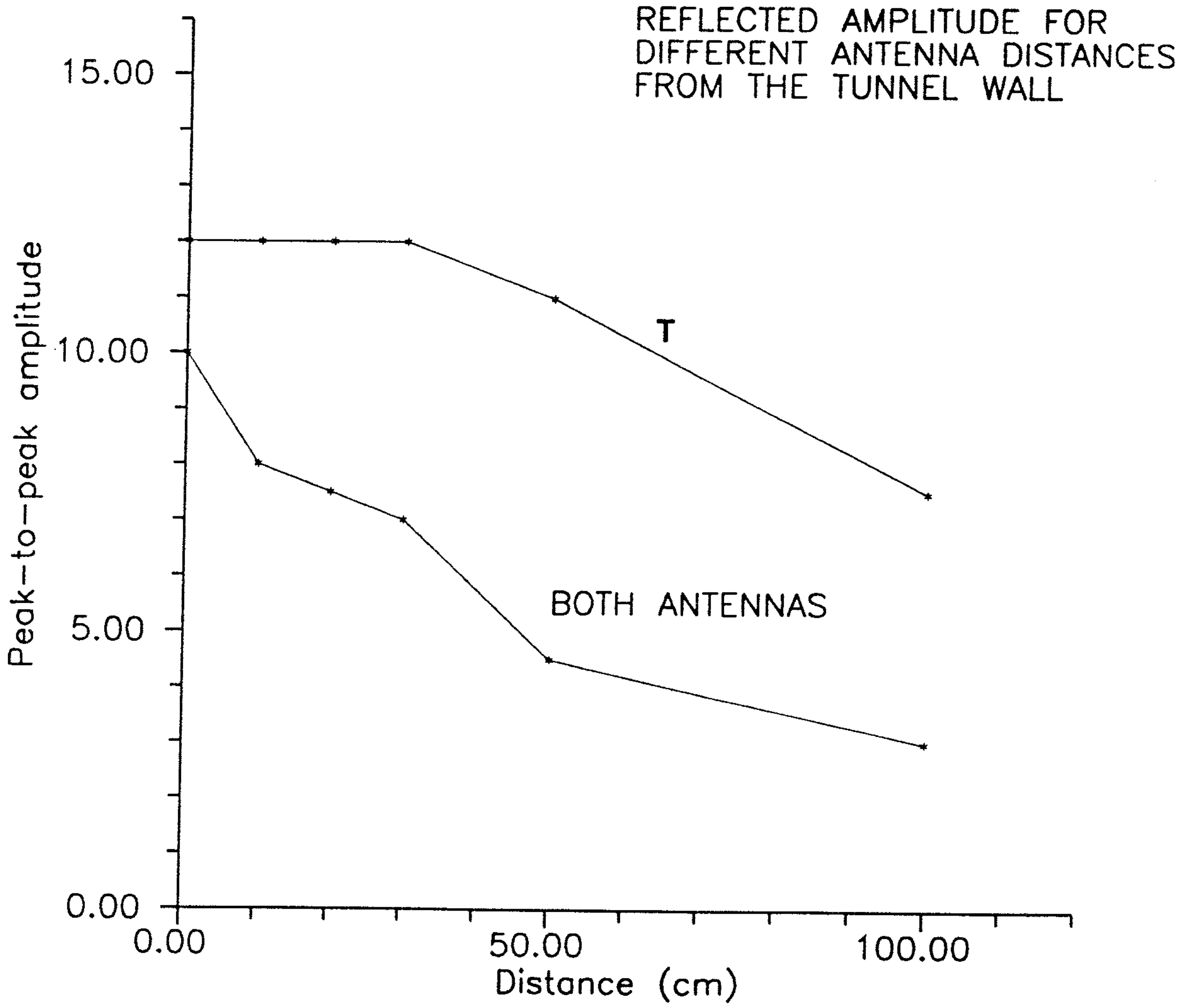


Figure 4.21 Signal amplitude for reflected pulse as a function of distance from wall. T: only transmitter. Lower: both antennas moved.

Figures 4.17 - 4.21 show similar result obtained with the radar equipment. Both antennas were held vertically and placed near the wall 2 m from each other. As the antennas were moved from the wall the traces were compared and the effect on the signals was remarkably small. Diagrams 4.20 and 4.21 show how the peak-to-peak amplitude falls off when either the transmitter or both antennas are moved out from the wall. The reflected pulse is less affected than the direct pulse. The reason for this is clearly that direct pulse is disturbed by scattering in the tunnel, which will gradually interfere with the pulse as the antenna is moved outwards. When the antenna has reached the center of the tunnel the wave breaks up into several components and it becomes difficult to define the position and amplitude of the pulse.

The results of these tests are fundamental for tunnel work: tunnel antennas are insensitive to variations in distance which are less than 30 cm. In practice there are no great difficulties in applying them to tunnel walls even if the surface is rough.

4.5 Screening

Radar measurements can excite waves which propagate along the tunnel. This effect is similar to tube waves in seismics. It happens occasionally that wave guide modes are excited in boreholes, but the frequency must be very high, usually over 200 MHz depending on the borehole radius. There are no real propagating modes in a tunnel without conductors because the permittivity is lower than in the rock, but waves can be guided by metal conductors, like wires and ventilation drums. Such modes can be excited and reflected back from obstacles in the tunnel and may confuse the radar interpretation in the same way as tube waves disturb borehole seismics.

Most of the radiated energy will propagate in the rock because of its high dielectric constant. In fact the tests showed no effects of waves reflected along the tunnel, though their existence could be deduced from the air waves observed when measuring between tunnels. The measurements showed that air waves disperse very quickly. In order to investigate the influence of objects in the tunnel railway trolleys and other metal objects were brought up behind the antennas, which were held near the wall. The effect on the pulse was very small as shown in Figure 4.22. A screen of metal net was also placed behind the antenna in various positions as shown in Figure 4.23, but the difference was negligible as seen in Figures 4.24 and 4.25. The metal net reduces the signal amplitude if it is sufficiently close to a dipole, but otherwise there were no significant effects of the screen as shown in Figure 4.25. The antenna are consequently best used without screens or reflectors.

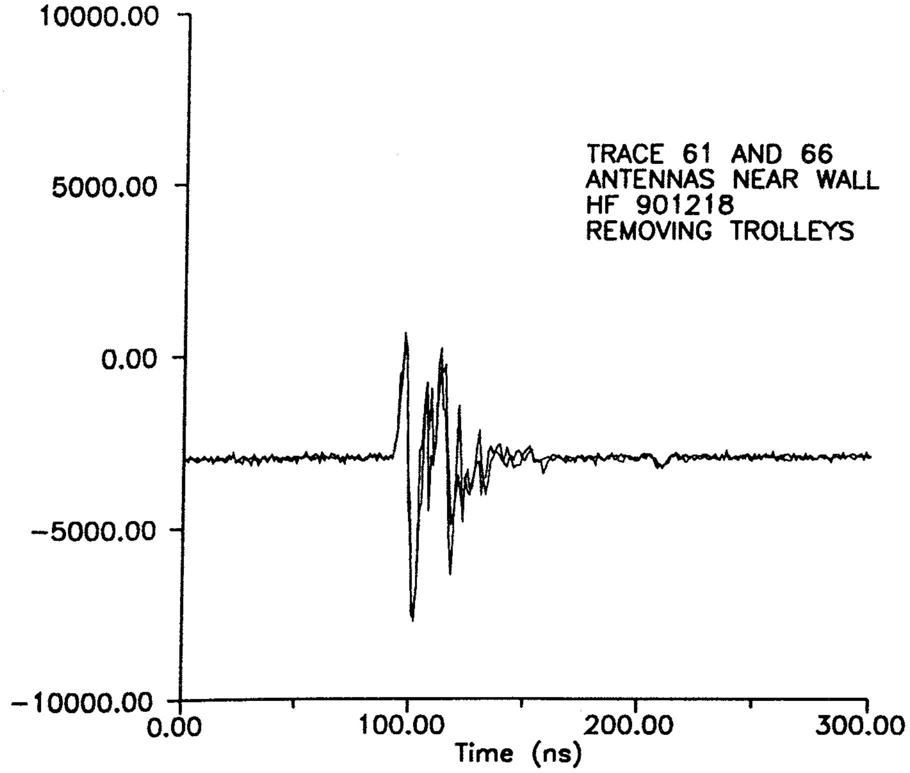


Figure 4.22 Comparison of antenna signals with and without a railway trolley behind the high frequency antennas.

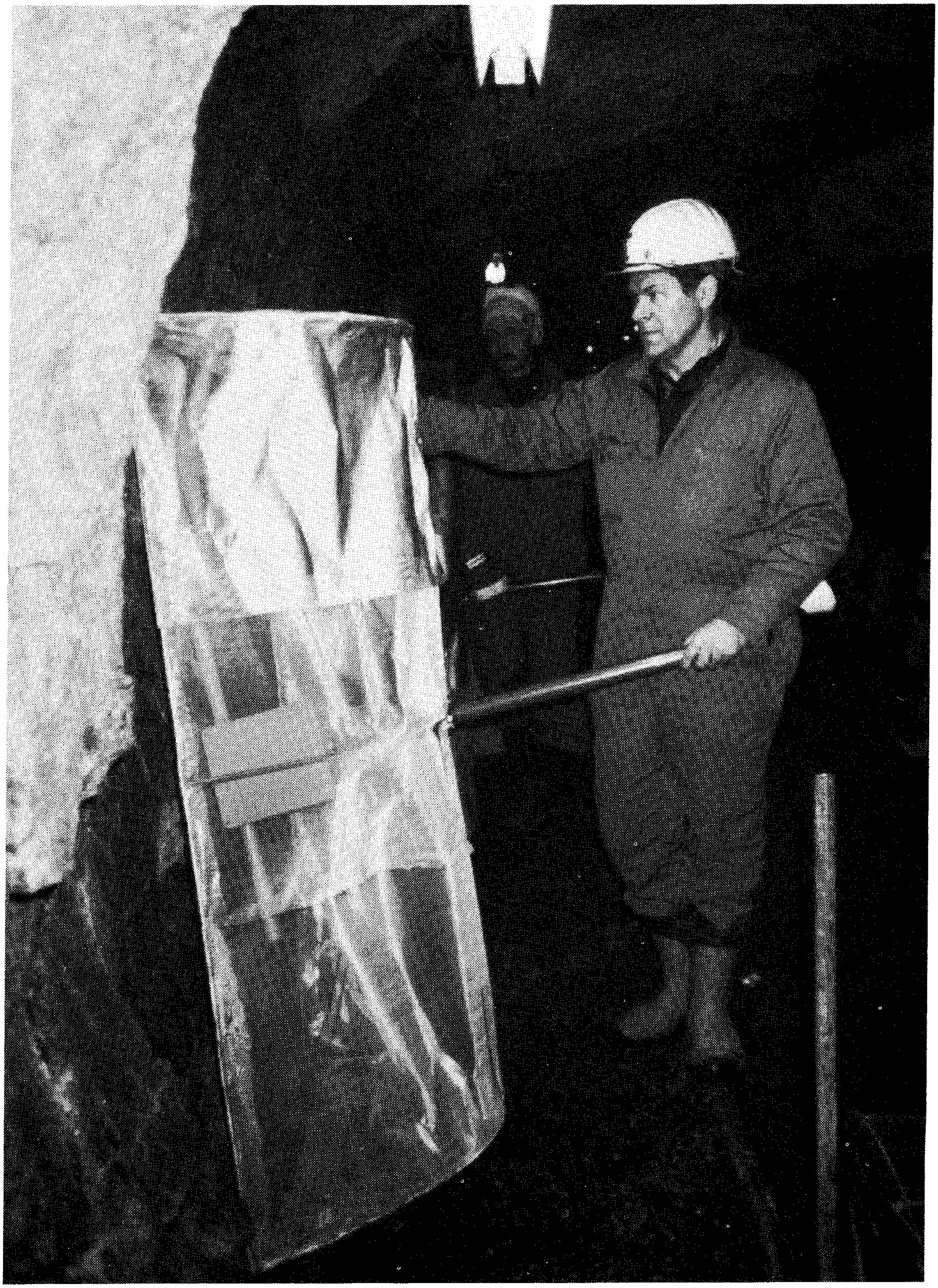


Figure 4.23 Metal net used as a screen to test the antennas.

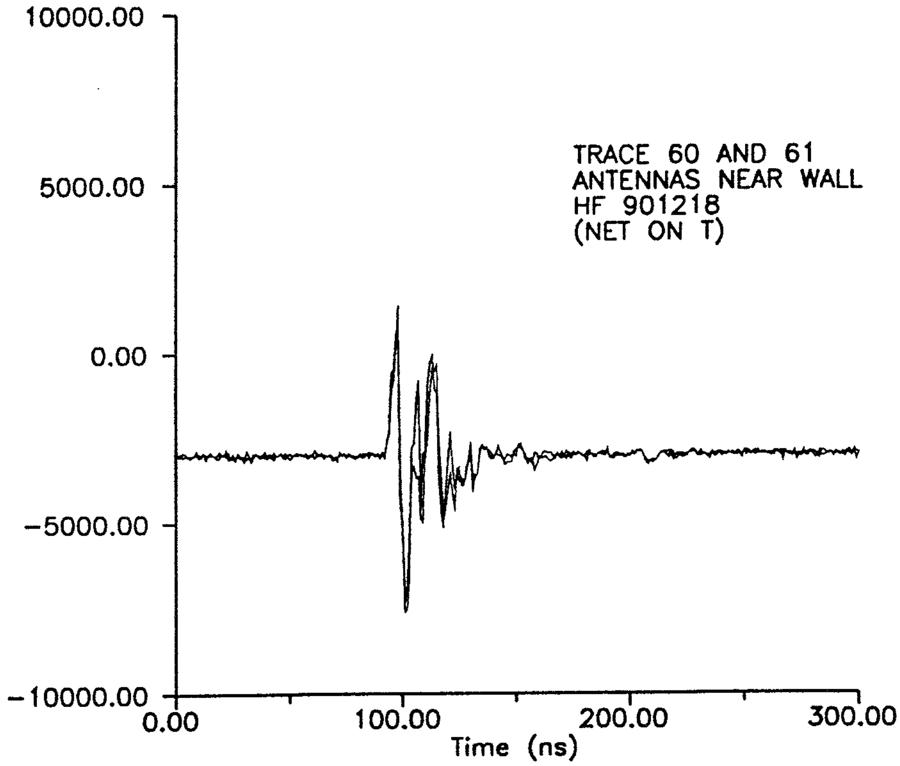


Figure 4.24 Comparison of antenna signals with and without metal screen behind the high frequency transmitter.

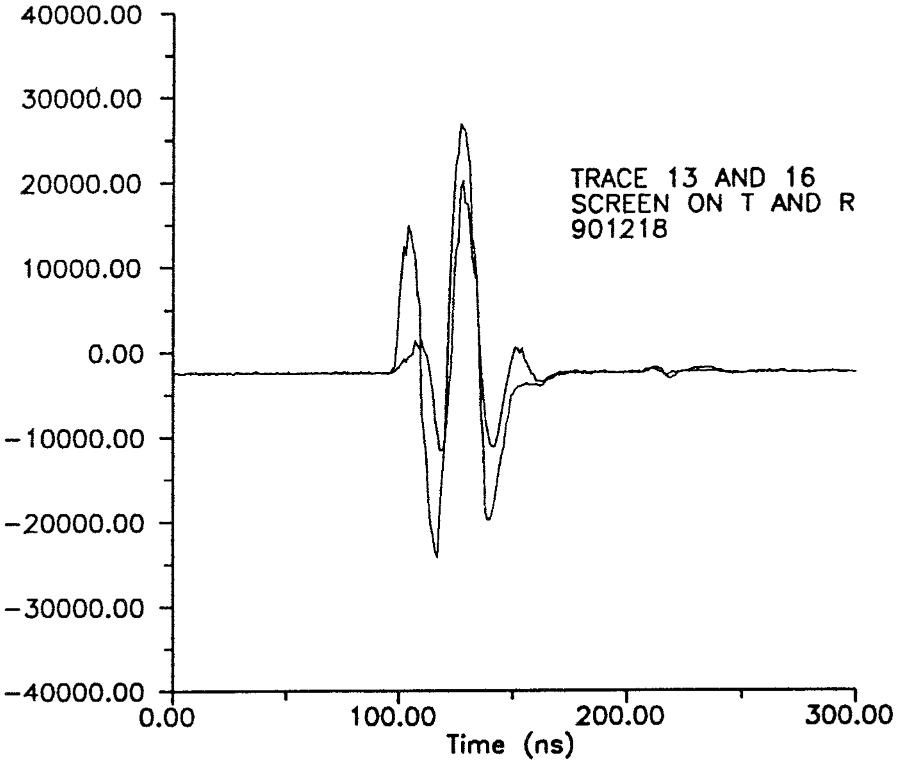


Figure 4.25 Antenna signals with and without screen behind antennas. The screen reduces the pulse amplitude slightly.

5. TUNNEL RADAR MEASUREMENTS

5.1 Description of the Crosshole tunnel

Most experiments in Stripa took place in the tunnel leading up to the Crosshole site and called the Crosshole tunnel in Figure 5.1. Measurements were also performed in the tunnel leading to the 3D-site and called the 3D-tunnel in the same map. In order to facilitate a comparison of measured data with structures in the tunnel a brief description will be given of the Crosshole tunnel. The tunnel is about 2.5 m high and 2.5 m wide; it contains a railway track, a few electric cables and a ventilation drum about 30 cm in diameter as shown in Figure 5.2. Starting from the Crosshole site the following features may be noted:

Distance	
-3 m	Fracture zone to the left.
0 m	The tunnel bend, where most mesurements started.
10	Iron waste starts.
20	Iron waste ends.
29	The pilot borehole.
37	Beginning of concrete on left side; the ventilation drum is here in the middle of the roof.
40	Borehole N2. End of concrete.
47	Start of next concrete section to the left.
50	The ventilation drum turns over to the left.
52	Beginning of hole between tunnels.
60	End of hole between tunnels (8 m wide).
70-78	Zone H. Most fractured around 78 m.
100	Start of the Crosshole tunnel. Electric display board.
106	Ventilation drum turns towards 3D-site.

5.2 Description of radar measurements

Several radar measurements were performed in the Crosshole tunnel to test the equipment. Major reflectors have been indicated in the radar pictures to simplify a comparison with the map in Figure 5.1.

Figure 5.3

The radar map in Figure 5.3 was measured with the 60 MHz antennas held vertically against the left wall of the Crosshole tunnel starting from the point 0 near the Crosshole site. The radar picture shows the parallel tunnel, which joins the Crosshole tunnel at an open hole, which is also seen in the radar picture. The reflection near the origin is probably caused by the Crosshole site. The concrete wall covering a small shaft is seen as a curved reflection typical for point targets. Two fracture zones are visible, the stronger of these is caused by zone H. The maximum range is about 25 m.

Figure 5.4

A similar measurement performed with the high frequency antennas is shown in Figure 5.4. This measurement was performed over a larger distance, but it shows few features because the range is reduced to 10 m and also because of the poor quality of the signal. The parallel tunnel and the hole between the two tunnels are clearly seen, while the concrete walls and fracture zone H appear as very weak reflectors.

Figure 5.5

The three crosshole measurement in Figures 5.5 were performed between the Crosshole tunnel and the 3D-tunnel. The fixed receiver antenna was held vertically in the Crosshole tunnel at points 12, 30, 55 m from the intersection of the tunnels and near the wall closest to the 3D-tunnel. In the third case the antenna was opposite the hole between the parallel tunnels. The transmitter antenna was also moved in a vertical position along the 3D-tunnel starting 5 m from the tunnel intersection and measurements were performed for a length of 47, 38, 63 m in the three different cases. The directly propagated pulse is seen as a hyperbola in each measurement obtained when the transmitter approaches the receiver and then is removed again.

In the first two measurements air waves appear. These pulses have propagated part of their way through the tunnels and can thus arrive before the pulses which propagate through the rock along a straight line, since the velocity in granite is a factor 2.3 lower than in air. The waves propagated along the tunnels are highly dispersive and do not provide any useful information. A few fracture zones are seen behind the direct wave, but zone H was not observed. Crosshole reflections can be analysed in a manner similar to single hole reflections. The mathematical formalism was developed during the Stripa project and has been converted into a computer program (Sandberg et al., 1991).

Figure 5.6

Figure 5.6 shows a borehole-to-tunnel measurement performed with a 60 MHz borehole transmitter antenna placed 6 m into the pilot borehole which start from the Crosshole tunnel (see Figure 5.1). The receiver was carried with antenna held vertically along the right side of the Crosshole tunnel starting at point 0 and finishing at 73 m. This measurement also produced air waves, showing that some energy is propagated along the tunnels from which it can then diffract to antennas in the boreholes. Features of interest include zone H, borehole N2 and the hole between the tunnels, which is a very weak structure in this picture. The reason is that the hole is on the opposite side of the tunnel and tunnel radar antennas radiate very little power into the backlobe. The directivity is demonstrated in an even more striking fashion in the following measurements from the 3D-tunnel.

Figure 5.7

The most detailed pictures were obtained for measurements in the 3D-tunnel, which showed a marked difference between the right and left sides. The first attempt to measure with the antennas at right angles to the tunnel on the floor failed completely due to coupling to electric cables which caused ringing all over the radar map. The 3D-tunnel was instead measured with vertical antennas held against the wall, 2 m apart and in 0.5 m steps. Measurements started at point 0 in Figure 5.1 and went on for 73 m. A characteristic example of multiple reflections between an antenna and a cable is seen in the middle of the picture. This type of reflection is wellknown in ground penetrating radar. Zone H can be seen in this measurement and probably also borehole N3 at the top of the picture. There are several other reflectors in the picture, but they can not be identified because the area has not been investigated previously.

Figure 5.7 is the most detailed picture obtained during the field tests of the antennas. The maximum range is 25 m and the reflectors are very clear due to the homogeneity of the rock. The phase of the reflected pulses indicates that most of the reflectors are fracture zones or waterfilled boreholes since the reflections are out of phase with the direct wave; an air-filled tunnel would instead reflect the pulse in phase as seen in Figure 4.2.

Figure 5.8

A corresponding measurement was performed along the left side of the 3D-tunnel with quite different results. This demonstrates again the directive character of the radiation when the antennas are held against the wall. The measured distance was 94 m starting from point 0 in the 3D-tunnel, but very few reflectors of interest can be seen in the picture. There are instead several electric conductors producing complicated interferences. In fact the measurement was ended when the antennas coupled strongly to the scatterer seen at the bottom of the picture. At this position in the tunnel appears a complicated system of pipes and wires, which pass vertically through the left side of the tunnel.

Figure 5.9

The slowness tomogram in Figure 5.9 was calculated from mesurements performed with 4 m distance between the antenna positions in both tunnels. The maximum distance propagated by the pulse is nearly 60 m. The H-zone appears in its correct position in both tunnels: this is particularly interesting since the intersection with the Crosshole tunnel obtained by extending the zone from the SCV site should be around 35 m. In fact fracture zone H is clearly seen in the tunnel at 25 m as indicated by the tomogram, which also shows how the fracture zone changes direction. The section between 25-35 m consists of altered granite.

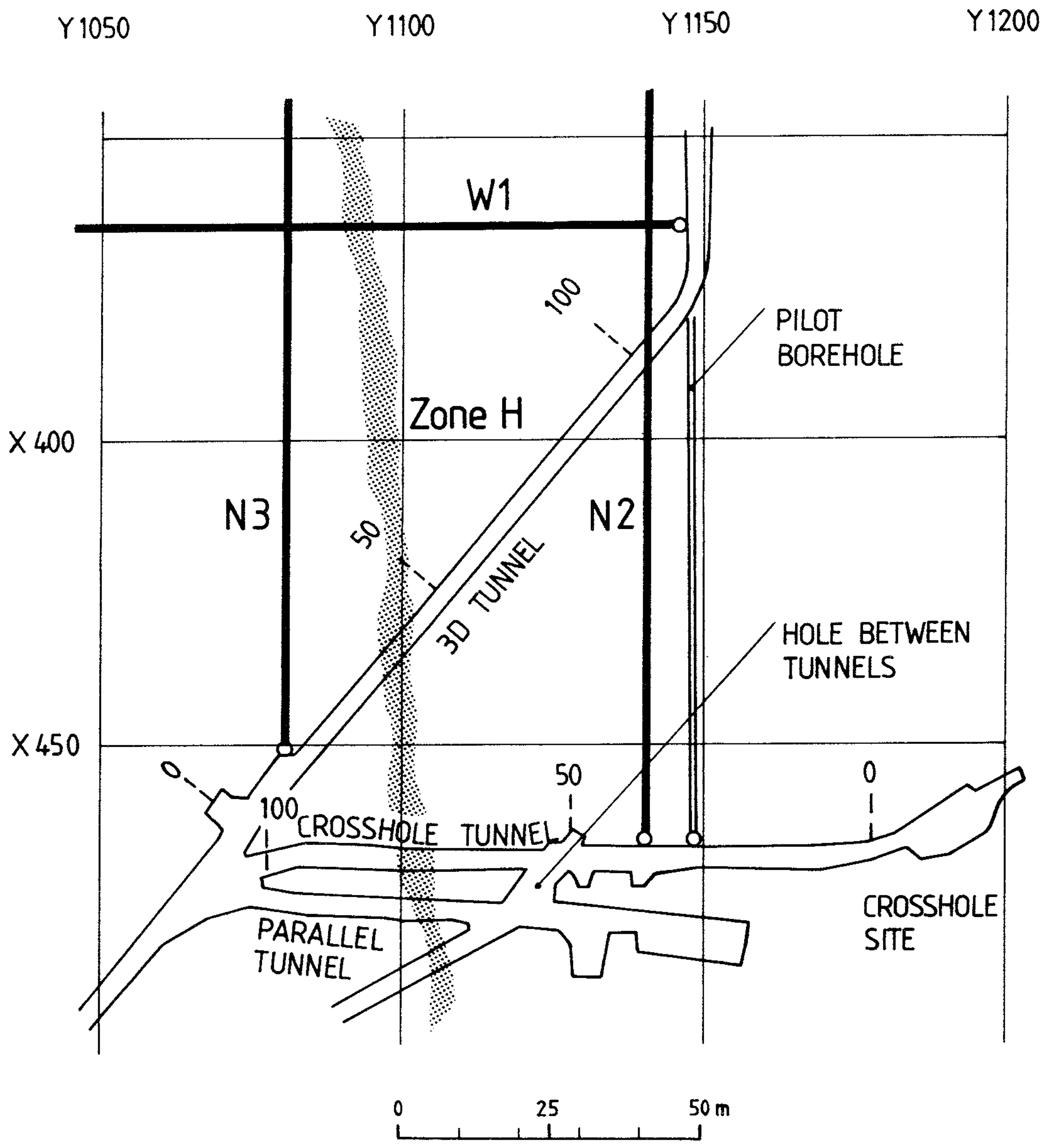


Figure 5.1 The measurement site at 360 m depth in Stripa with the Crosshole tunnel and the 3D-tunnel.

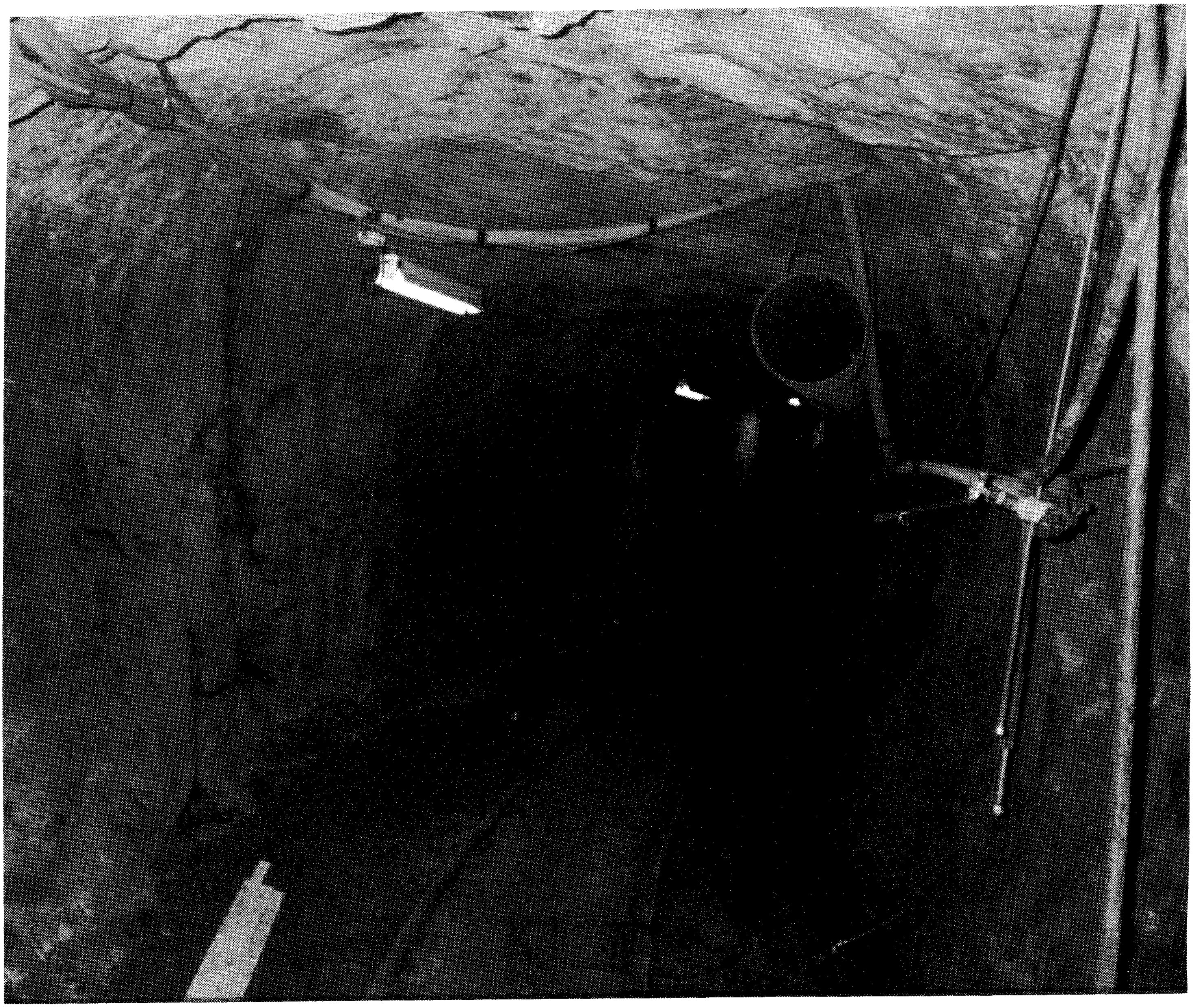


Figure 5.2 View of the Crosshole tunnel from the Crosshole site.

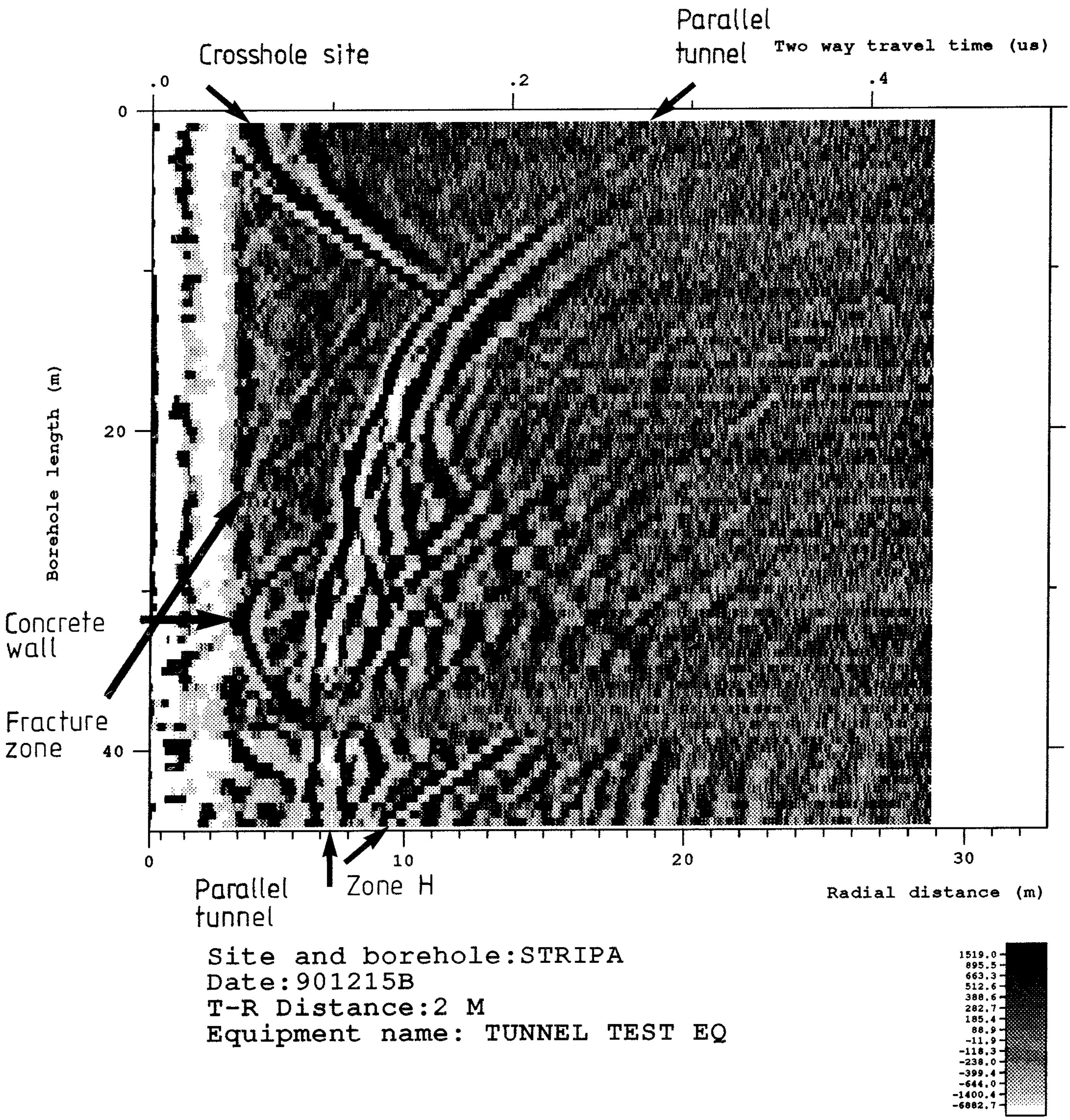


Figure 5.3 Tunnel radar measurement performed in the Crosshole tunnel with 60 MHz antenna held vertically. T-R distance 2 m.

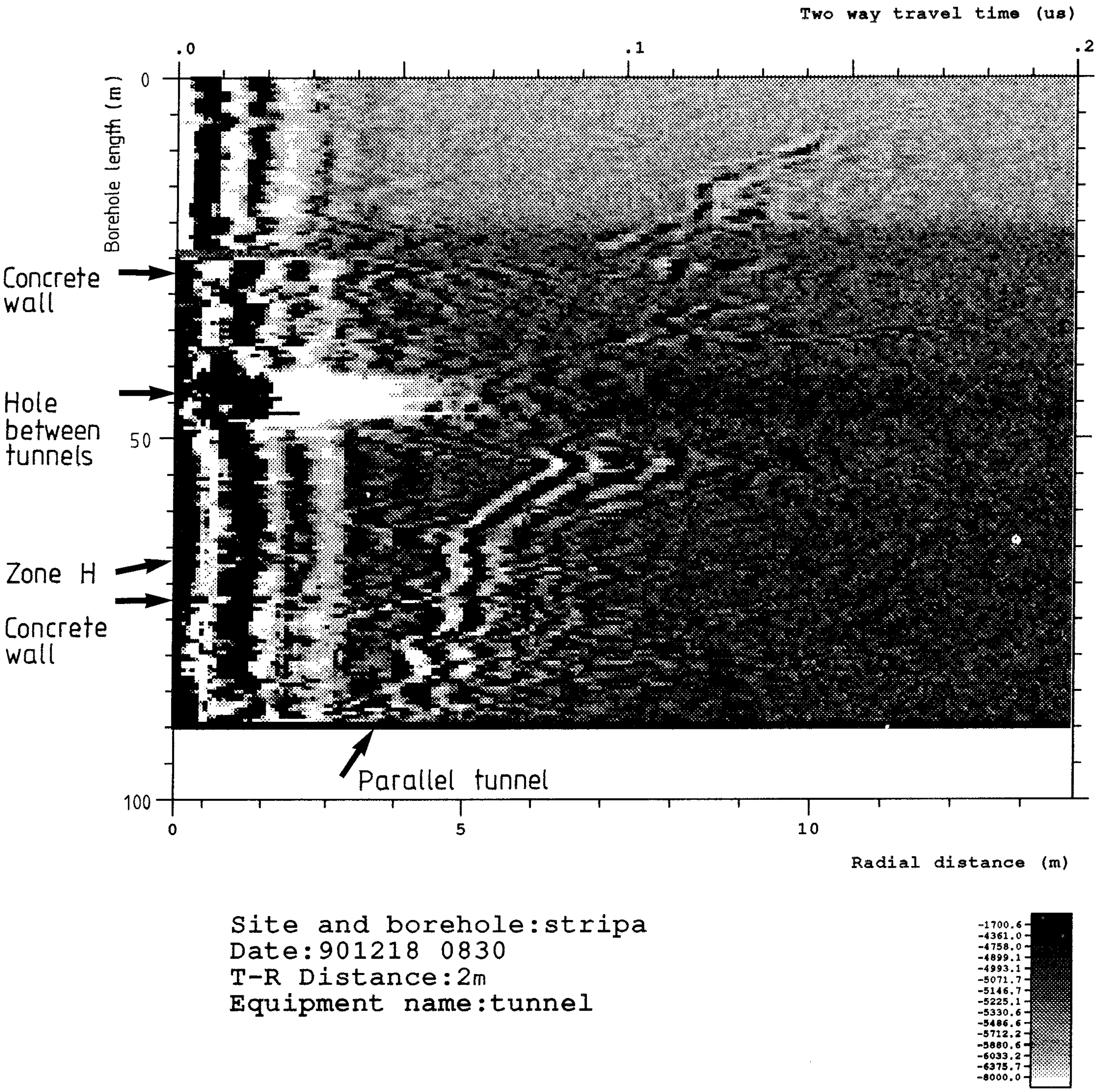


Figure 5.4 Tunnel radar measurement in Crosshole tunnel with 120 MHz antennas held vertically. T-R distance 2 m.

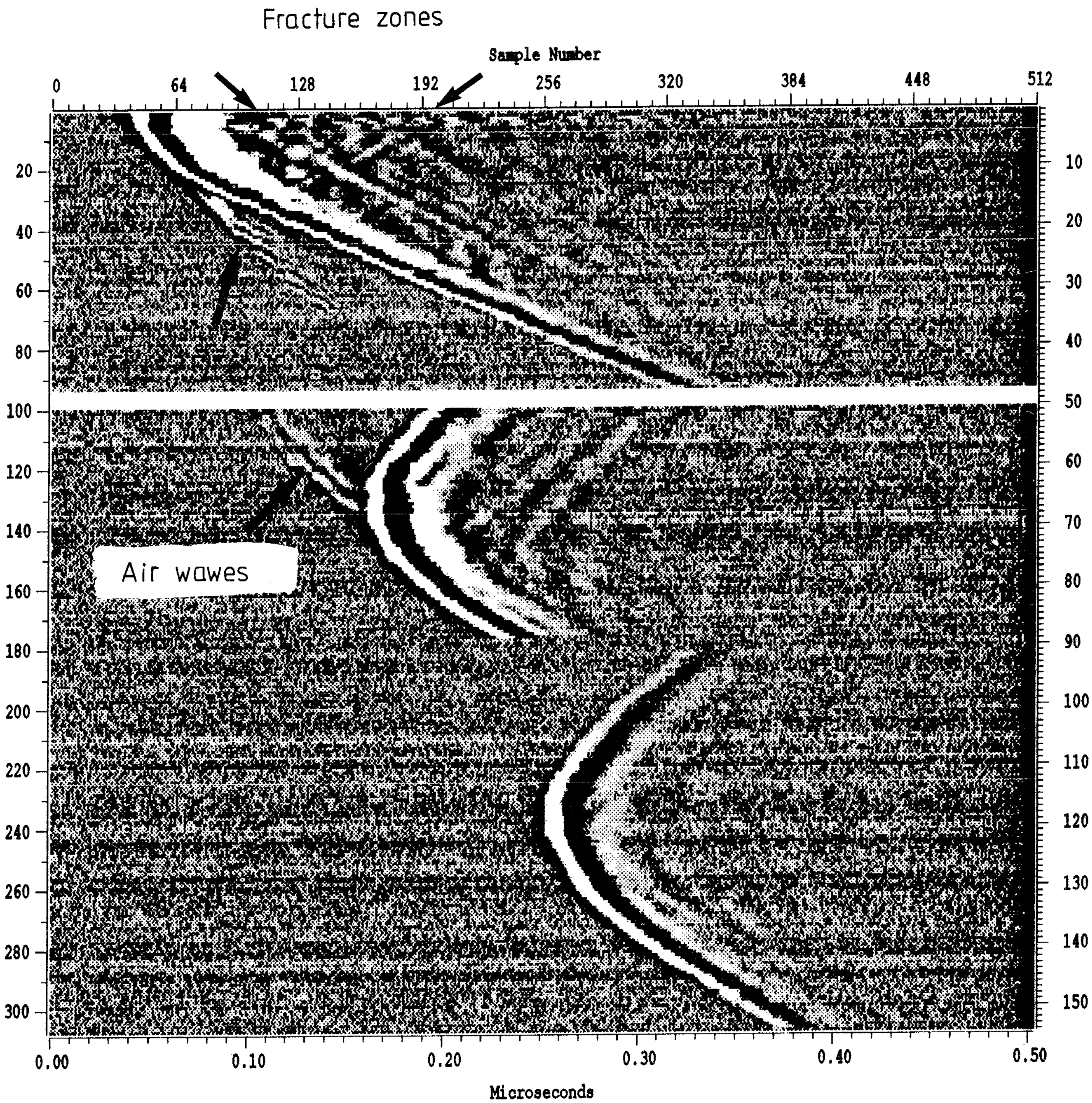


Figure 5.5 Three crosshole measurements performed with the receiver in the Crosshole tunnel at 12, 30, 55 m from the tunnel intersection. Transmitter carried in 3D-tunnel. 60 MHz antennas.

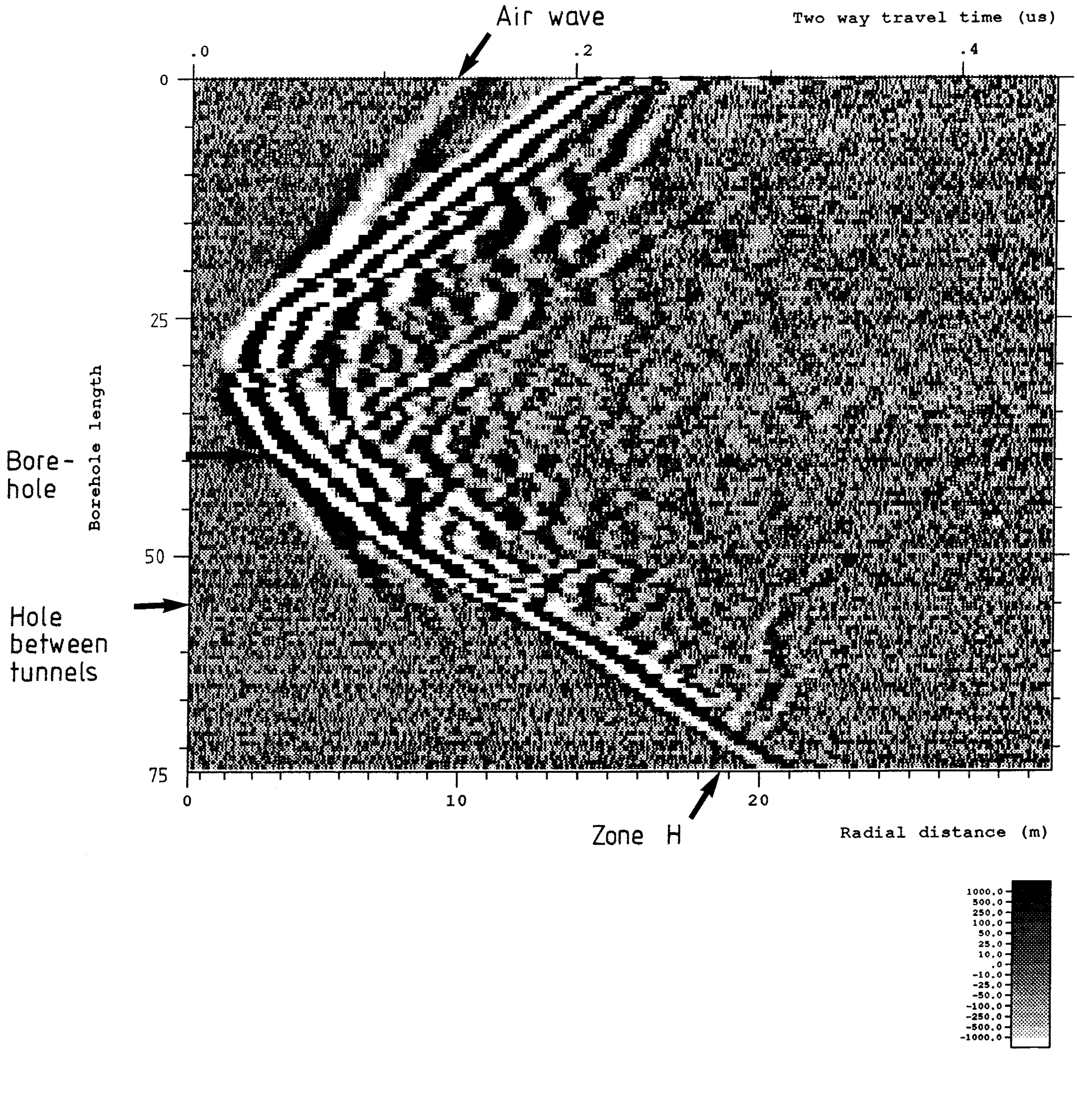


Figure 5.6 Tunnel-to-borehole mesurement. 60 MHz transmitter 6 m into pilot borehole. 60 MHz receiver in Crosshole tunnel.

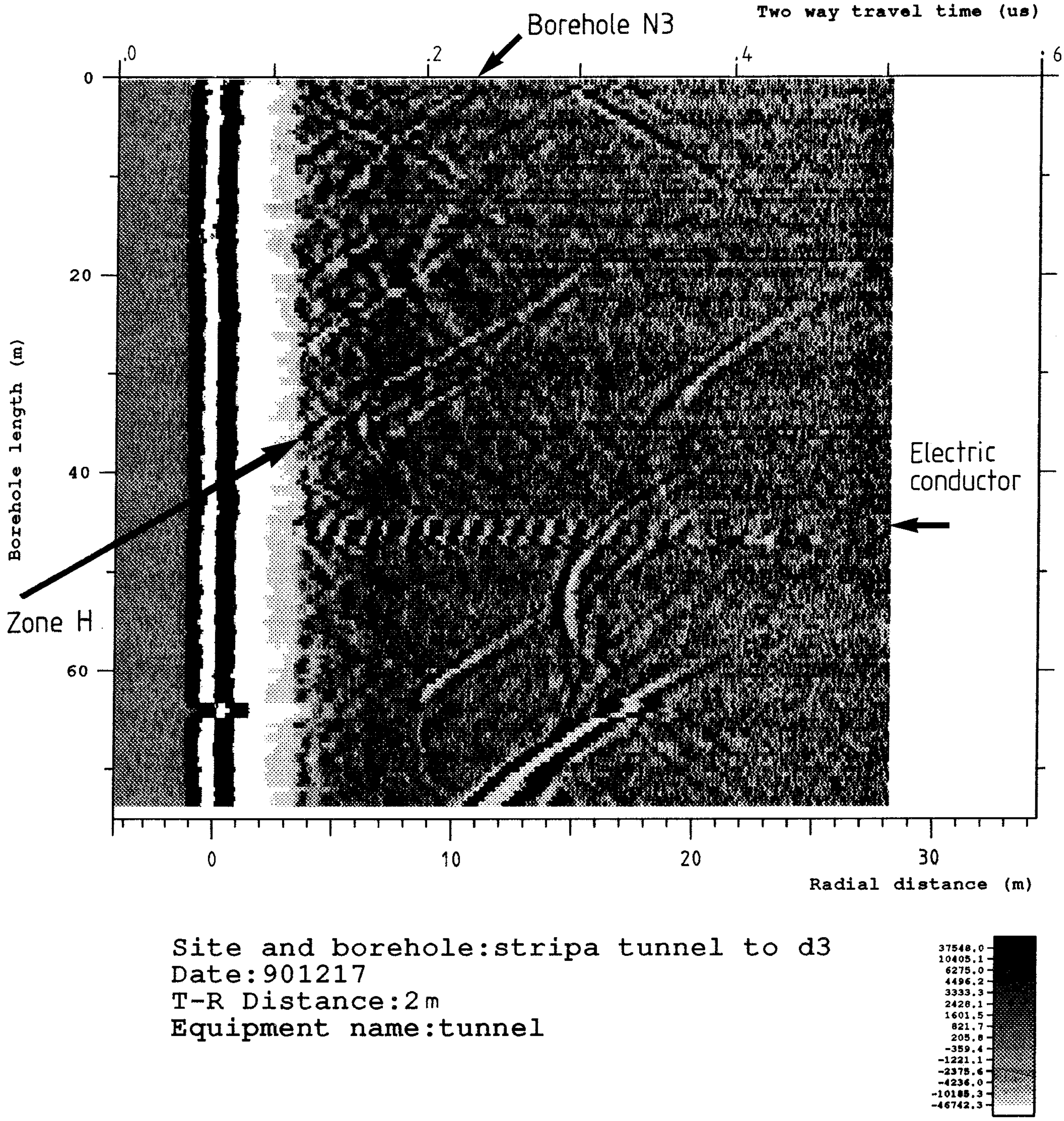


Figure 5.7 Right side of 3D-tunnel measured with 60 MHz tunnel antennas held vertically against the wall. Start at point 0.

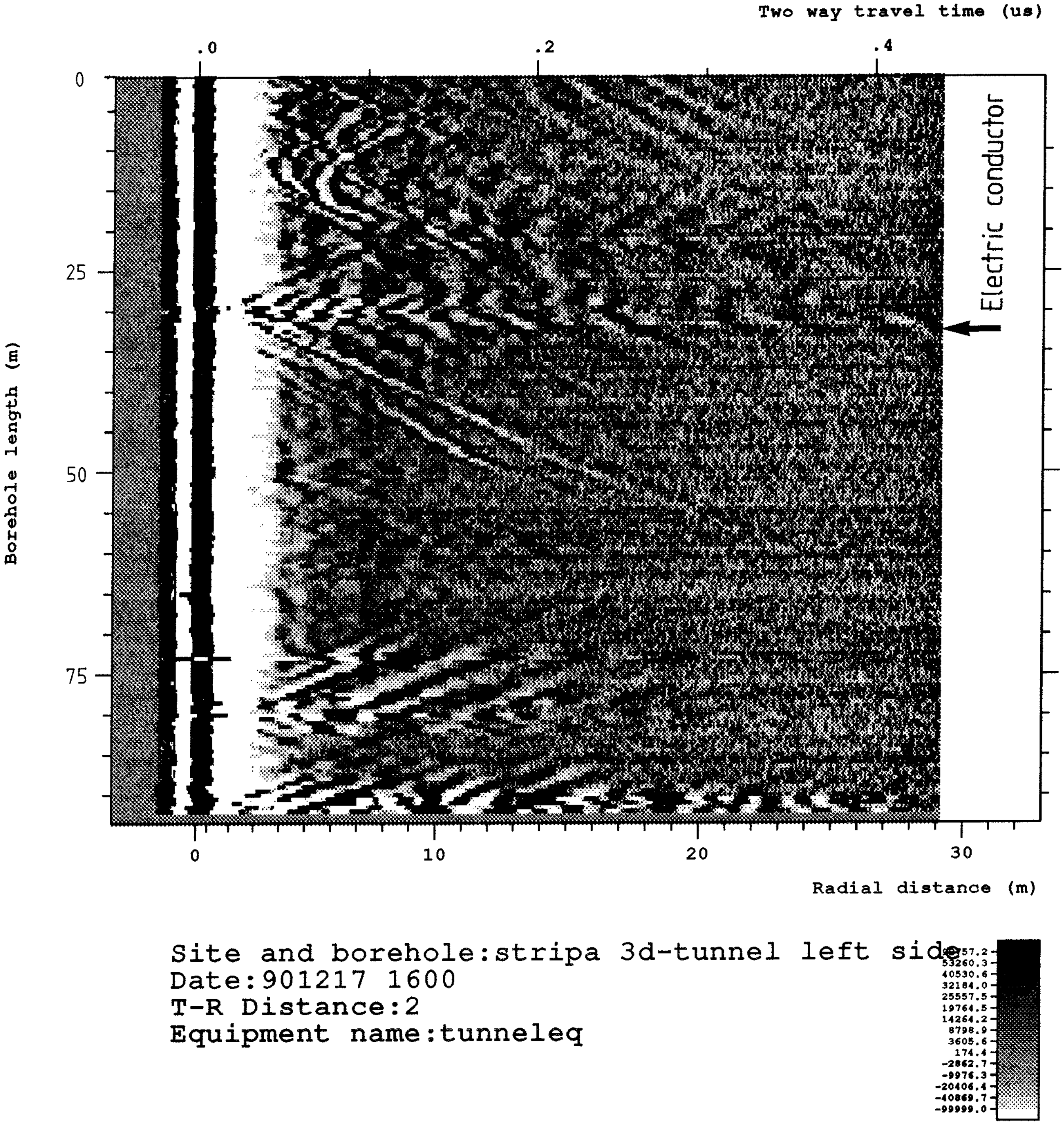


Figure 5.8 Left side of 3D-tunnel. 60 MHz tunnel antennas held vertically against the wall. Start at point 0.

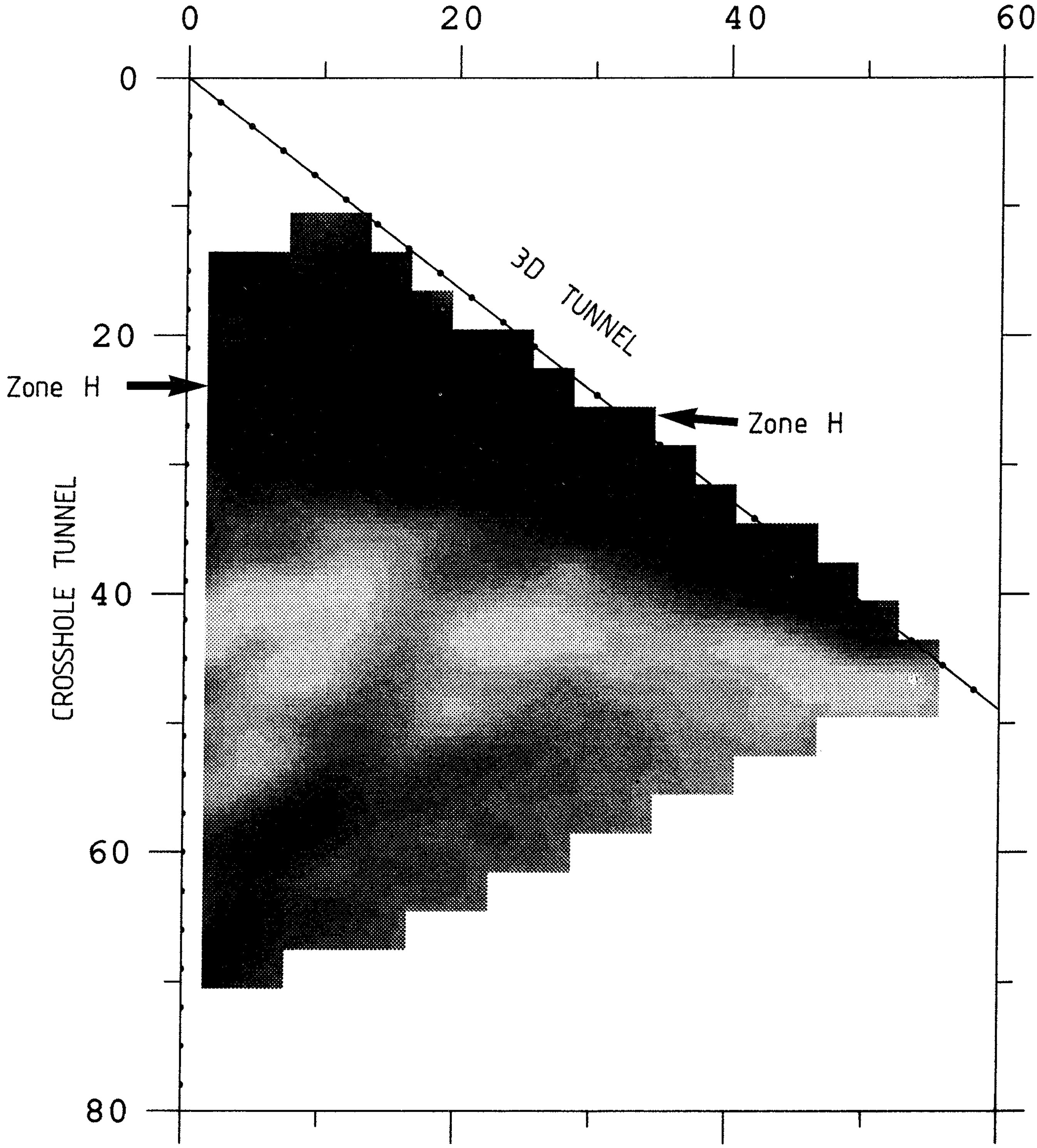


Figure 5.9 Tomogram measured between the 3D-tunnel and the Crosshole tunnel showing slowness (inverse velocity). 60 MHz tunnel antennas.

6. RECOMMENDATIONS

Many questions concerning tunnel antennas remain to be answered and in spite of the successful tests the antenna units can be improved, e g by reducing their size and weight. Experiments which provide important knowledge about the antennas can often be performed in a matter of hours in the course of other measurements. Some experiments of this type are listed below to ensure that they are performed during future tunnel measurements. Most of them have already been discussed.

1. The effect of tunnel size and shape on the signal should be investigated as well as the effect of metal obstacles, particularly long cables.

2. The radiation lobes can be investigated by very simple means if there is a nearby tunnel or some other well-defined reflector: by successively moving the two antennas around the tunnel periphery and observing the reflected signal one can deduce the radiation pattern. The width of the antenna lobe depends on the dielectric permittivity of the rock, but presumably also on the diameter of the tunnel as long as the diameter is comparable with the wavelength.

3. If tunnel antennas are constructed for other frequencies the distance dependence from the wall should be tested in the same way as described in section 4.

4. The pulse emitted by the transmitter electronics should be measured directly on the coaxial line and its frequency content matched to the antenna.

5. The antennas have been constructed for tunnels but their performance on ground is important in many applications and should be investigated under various conditions.

7. CONCLUSIONS

Antennas suitable for tunnel radar measurements in the frequency range 50-100 MHz have been constructed and tested. A series of experiments have demonstrated the importance of isolating the electronics from interference by the antenna radiation field. For this purpose the antenna units, including the batteries and the transmitter and receiver electronics, were rebuilt and placed in screened boxes at the center of the dipole antennas. Experiments performed in Stripa mine demonstrated the correctness of this concept. The range of the radar was about half that observed in borehole experiments and the ringing was small. The experiments showed that the tunnel antennas must be easy to maneuvere, because in many cases the outcome of an experiment depends on the antenna orientation. The antenna radiation is focused into the rock by the difference in dielectric permittivity. The radar can provide information both about the range and the direction to a target if it is applied to different sides of the tunnel. In this respect the tunnel radar is different from a borehole where a directional antenna must be used to obtain the corresponding information.

8. ACKNOWLEDGEMENTS

The tunnel radar project would have been impossible without the generous support of SKB and PNC. We are indebted to Koji Tsubota and Hideki Sakuma at PNC and Karl-Erik Almén at SKB for their continuous interest in the project. It is our sincere belief that the tunnel antennas developed during the project can produce detailed and reliable information about sites investigated with radar.

The radar equipment was designed by Olof Forslund and constructed by him and Bernth Johansson in Malå. Important contributions to the final construction were made by Lars Lundmark.

The antenna experiments were performed by Lars Falk, Olof Forslund, Bernth Johansson and Eric Sandberg in the laboratory in Malå and later in Stripa mine in central Sweden. Stripa has proved an invaluable facility for radar resesarch and we are grateful to its personnel for support during many years. The measurements and interpretation were greatly facilitated by the RAMAC software written by Bo Hesselström. The numerical antenna calculations were performed in collaboration with Agneta Vogel at the National Defence Research Laboratory. Annika Wettervik expertly drew the figures.

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[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
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[1]Vattenfall HydroPower AB
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