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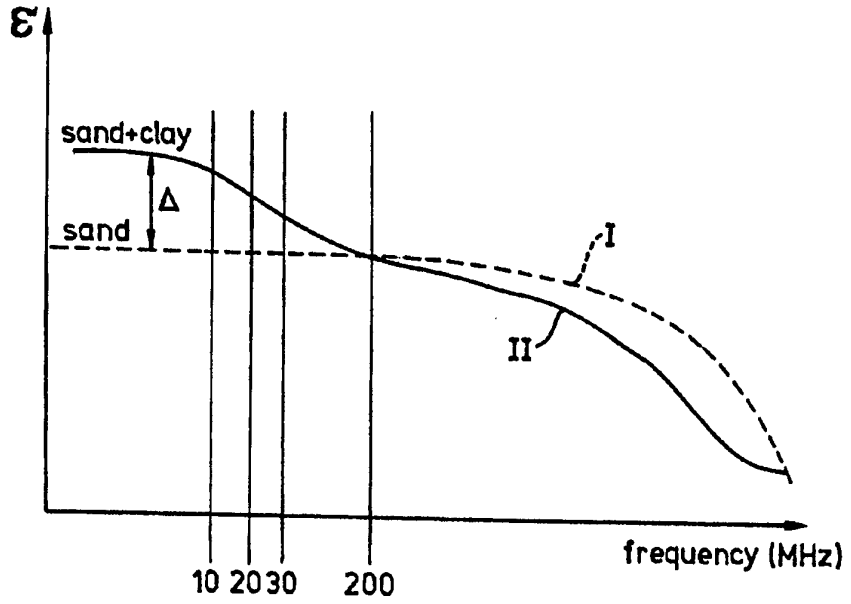
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(54) Title: METHOD FOR MEASURING THE WATER CONTENT OF GROWING SUBSTRATES



(57) Abstract

The invention relates to a method for measuring the water content of growing substrates such as sand, clay, earth, glass wool or rock wool. To this end, the impedance of the growing substrate is measured and the real part ϵ' of the complex permittivity ϵ'-jϵ'' is determined for at least two frequencies. From these two permittivities the real part ϵ' of the complex permittivity is extrapolated to a frequency between 100 and 200 MHz. At these values it was found that the permittivity of the growing substrate is equal to that of sand having a similar water content. From the variation of the permittivity of sand or a similar-type granular material with the water content it is possible to determine the water content of the growing substrate, without prior calibration measurements.

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METHOD FOR MEASURING THE WATER CONTENT OF GROWING SUBSTRATES

The invention relates to a method for measuring the water content of growing substrates. It is known from WO 86/05278 that the impedance of the soil can be measured by a probe being positioned therein which has two or more electric contacts. From this impedance the electric permittivity of the soil can be determined. The electric permittivity, or the dielectric constant, is largely determined by the water content of the soil. For most minerals the dielectric constant is in the order of 4-6, whereas for water it has an order of magnitude of 80. It is noted, in Figure 7 of WO 86/05278, that for granular materials the conductivity and dielectric constant are independent of the frequency. In Figure 8 of WO 86/05278 it is shown that the dielectric constant and the conductivity for a coherent system such as clay vary as a function of the frequency. According to the known method it is possible to determine, by measuring the dielectric constant of a soil type and comparison with a number of calibration curves, the composition of the soil and the water content. By determining the dispersion of the dielectric constant (the difference between the maximum and minimum value of the dielectric constant within a specific frequency range) the composition of the soil can be determined.

It is an object of the present invention to provide a method where the water content of soil samples, in particular of growing substrates, can be determined in situ in an accurate and simple manner, without the need for carrying out a calibration for the material in which the water content is being measured. Such calibration measurements are often time-consuming and constitute a serious problem when dielectric sensors are used. If, for example, soils are to be decontaminated, laboratory calibrations are often not possible.

To this end the method according to the invention is characterized in that it comprises the following steps:

a) determining the value of the real part of the complex permittivity at at least two frequencies within a first predetermined frequency band,

b) determining by interpolation, on the basis of the values found at a), of the value of the real part of the complex permittivity at a reference frequency within a second frequency band, at least most of which is situated above the first frequency band,

c) comparing the values determined at b) with values which,

depending on the moisture content, hold good at the reference frequency for a reference material, and determining therefrom the moisture content of the soil sample in question.

The invention is based on the insight that for many types of soil, in particular for growing substrates such as, for example, rock wool, glass wool, granular clay, compressed organic material or potting soil, the real part ϵ' of the complex electric permittivity varies with the frequency. For frequencies around 100-200 MHz, however, the real part ϵ' of the electric permittivity of these growing substrates depends on the water content, θ, in the same manner as the permittivity ϵ' of sand, or granular materials having a similar dielectric behaviour as sand. For sand and granular materials the real part of the electric permittivity does not, up to a frequency of 17 GHz, vary with the frequency. By means of a calculation, from the two or more measured values for the real part ϵ' of the complex permittivity, of the complex permittivity ϵ' at a frequency between 100 and 200 MHz, a permittivity is found which is equal to the permittivity of sand having a water content equal to that of the growing substrate. From the known relationship between the water content θ and the variation of the permittivity ϵ' of sand or of a similar granular material it is then possible to determine the water content θ from $\epsilon'(\omega_0)$. By virtue of using the method according to the invention it is no longer necessary to carry out a calibration measurement for a particular growing substrate.

The dielectric behaviour of a material such as a growing substrate can be described by the complex dielectric constant, sometimes known as the complex electric permittivity. The complex permittivity ϵ can be written as:

$$\epsilon = \epsilon' - j\,\epsilon''.$$

Here the real part of the permittivity, ϵ', is a measure for the polarizability of different material components, including the water which may or may not be bound. The imaginary part of the permittivity, ϵ'', is a measure for the absorption of energy. The ionic conductivity contributes to ϵ''. The two components ϵ' and ϵ'' of the permittivity can be measured as the capacitance, C (in farad) and the conductivity G (in Sm^{-1}), respectively, of a capacitor with the growing substrate as the dielectric between the electrodes.

The reorientation of a polarizable particle such as water in an alternating electric field requires some time. With increasing frequency the particles or molecules become too sluggish to be able to follow the

rapidly alternating field. This inertia is affected, inter alia, by the degree to which the particle or the molecule is bound to its environment. With higher frequencies ϵ' then decreases. At higher frequencies the supplied energy is absorbed, as a result of which the dielectric losses, for which ϵ'' is a measure, will increase. For frequencies lower than those where the most important absorptions take place, ϵ'' is dominated by the ionic conductivity.

The real part ϵ' of the electric permittivity of wet soil is dominated by the volumetric water content θ, i.e. $\epsilon' = f(\theta)$. Two electrodes with the growing substrate in between them as a dielectric can be represented, in electronic network theory, by the complex impedance Z^* which is formed by a connection in parallel of a capacitor having a capacitance in F and a resistor having a conductivity G in S/m. The complex impedance $Z^* = 1/(G+j\omega C)=1/j\omega\epsilon\epsilon_0 k$. It follows from this that the real part ϵ' of the electric permittivity can be found by measuring the capacitance via $C=k\epsilon'\epsilon_0$ where k is a geometry factor and ϵ_0 is the permittivity of free space.

Preferably, the extrapolation of the real part ϵ' of the electric permittivity to $\epsilon'(\omega_0)$ is carried out at ω_0 between 100 and 200 MHz on the basis of measurement at frequencies of approximately 10 MHz, approximately 20 MHz and approximately 30 MHz. Measuring at these relatively low frequencies results in considerable simplification of the measuring apparatus. The behaviour of the electric permittivity of a growing substrate can further be described as a relationship with three unknowns, which can be solved by determining the three values for ϵ'. ϵ' can be expressed, for a growing substrate, as:

$$\epsilon' = \frac{\Delta}{1+\omega\tau} + \epsilon_\infty$$

Here, Δ is the difference between the electric permittivity of the growing substrate and that of pure sand at a predetermined angular frequency ω. τ is a constant, and ϵ_∞ is the permittivity at an infinitely high frequency.

An apparatus for implementing the method comprises:
- two electrodes which can be positioned in or near a growing substrate,
- an alternating-current source for supplying an alternating current to the electrodes with at least two different frequencies,
- a measuring device for determining the voltage difference generated by the alternating current between the electrodes, and

- an arithmetic unit for determining, from the voltage measured, the real part ϵ' of the complex electric permittivity at the at least two frequencies, for determining $\epsilon'(\omega_0)$ and for determining the water content θ from $\epsilon'(\omega_0)$.

Preferably, the alternating-current source comprises three stable oscillators working at frequencies which have a mutually integer ratio. Preferably, three frequencies are used in a ratio of 1:2:3, for example 10, 20 and 30 MHz. Such oscillators are relatively simple and inexpensive and take up little space.

An embodiment of the method and the apparatus according to the present invention will be explained in more detail with reference to the appended drawing.

In the drawing:

Figure 1 shows the behaviour of the real part ϵ' of the complex electric permittivity for a mixture of sand and clay and for pure sand having the same water content,

Figure 2 schematically shows the circuit for carrying out dielectric measurements according to the invention,

Figure 3 shows an apparatus for measuring the impedance of a growing substrate, where the electrodes are located in the growing substrate, and

Figure 4 shows an apparatus for measuring the impedance of a growing substrate, where four electrodes are situated at a distance from the growing substrate.

In Figure 1, curve I shows the behaviour of the real part ϵ' of the electric permittivity for sand. Here it was found that ϵ' for sand is virtually constant up to a frequency of 17 GHz. Sand generally refers to granular particles without cohesion.

For a particular mixture of sand and clay, the electric permittivity ϵ varies with frequency according to curve II in Figure 1. At 200 MHz curve II intersects with curve I, and the permittivity of the sand-clay mixture having a particular water content θ is equal to the permittivity of pure sand having the same water content θ.

As a result of three permittivities $\epsilon 1$, $\epsilon 2$ and $\epsilon 3$ of the sand-clay mixture being measured at three frequencies having a mutual ratio of 1:2:3, for example at the frequencies 10 MHz, 20 MHz and 30 MHz, the formulae to be used are simplified, and the shape of the sand-clay curve can be determined relatively easily, and ϵ' at 200 MHz can be calculated. In so doing, ϵ' for a growing substrate can be represented by:

$$\epsilon' = \frac{\Delta}{1+\omega\tau} + \epsilon_\infty$$

Here τ is a constant which is found from the three measured permittivity values $\epsilon 1$, $\epsilon 2$ and $\epsilon 3$ via the relationship

$$\tau = \left[\frac{-(-\epsilon 1 + 2\epsilon 2 - \epsilon 3)}{(-\epsilon 1 + 4.\epsilon 2 - 3.\epsilon 3)} \right]$$

The value Δ which is formed by the difference between the measured permittivity for the growing substrate and the permittivity of pure sand having an equal water content is found from the relationship:

$$\Delta = \frac{-(\epsilon 2 - \epsilon 1)}{\tau} (1 + \tau).(1 + 2.\tau)$$

From the values thus found for τ and Δ the permittivity $\epsilon'(\omega_0)$ is found at ω_0 = 200 Hz.

$$\epsilon'(\omega_-) = \epsilon 1 - \frac{\Delta}{1+\tau}$$

Then, with the aid of the values $\epsilon'(\omega_0)$ found, the water content θ of the growing substrate can be determined, since the variation of the permittivity of sand with the water content θ is known, and by solving the equation:

$\epsilon'(\omega_0) = 3.03 + 9.3\ \theta + 146.\theta^2 - 76.\theta^3$

Figure 2 schematically shows the measurement set-up for determining the real part $\epsilon'(t)$ and the imaginary part $\epsilon''(t)$ of the complex permittivity ϵ of a growing substrate. The electrode configuration with in between, as the dielectric, the hardenable material is represented as a complex impedance Z^*. Via a feeder line 1 an alternating current is fed, via a switch 3, to an input terminal 5 of the impedance Z^*. The alternating-current source 7 is formed by three crystal oscillators which generate a sinusoidal current with an oscillator frequency of, for example, 10 MHz, 20 MHz and 30 MHz. Via a shunt line 9, the output signal of the oscillator 7 is fed to a switch 11. The switch 11 can be selectively connected to a phase-shifting element such as a capacitor 13 or a constant-phase element such as a resistor 15. The input terminal 5 of the electrode configuration and the input terminal of the capacitor 13 or the resistor 15 are connected to a multiplier 17, the voltages formed over the electrode configuration Z^* and the element 13 or 15, u_z and u_{shift}, respectively, being multiplied with one another. The

product $u_z \cdot u_{shift}$ is fed to a low-pass filter 19. The signal of the output of the low-pass filter 19 is converted in an analog-digital converter 21 whose output is connected to the input of an arithmetic unit 23. In the arithmetic unit 23 the real part $\epsilon'(t)$ of the complex permittivity is determined. Then, in the arithmetic unit 23, the permittivity $\epsilon'(\omega_0)$ at 200 MHz is calculated in the above-specified manner, and from $\epsilon'(\omega_0)$ the water content θ is determined. Via a time control unit 25, the switches 3, 11, the analog-digital converter 21 and the arithmetic unit 23 can be triggered to take a measurement at predetermined time intervals, for example every hour. The time control unit 25, the switches 3, 11 and the phase-shifting element 13 could be omitted.

The manner shown here of measuring the impedance Z^* of the electrode configuration is based on synchronous detection. The sinusoidal voltage frequencies ω, which may be chosen between 1 MHz and 100 MHz, are fed to the multiplier 17. The phase of the current fed to the multiplier 17 via the shunt line 9, can be phase-shifted by 0° or 90° by positioning the switch 11. The voltage u_z generated on the input terminal of the phase-shifting element 13 or the constant-phase element 15 is fed to the other input terminal of the multiplier 17. The output voltage of the multiplier $u=u_z u_{shift}$ has a frequency component with frequency 2 ω and a d.c. voltage component. The low-pass filter 19 removes the a.c. voltage component having frequency 2 ω. If the switch 11 is connected to the resistor 9, no phase shift takes place, and the d.c. voltage is a measure for the capacitance of the impedance Z^*. In case the switch 11 is connected to the capacitor 13, the voltage on the output terminal thereof has been shifted by 90°. This voltage is a measure for the conductivity G of the impedor Z^*. As it is the case that $Z^*=1/(G+j\ \omega\ C) = 1/j\ \omega\ (\epsilon' - j\ \epsilon'')\ \epsilon_0\ k)$, it is possible for ϵ' and ϵ'' to be calculated therefrom in the arithmetic unit 23.

The measurements are repeated for a reference impedance Z_{ref}, in order to calibrate the sensor automatically. Preferably, the circuit in Figure 2 is constructed as an integrated circuit in the form of an ASIC.

Figure 3 schematically shows an electrode configuration where two electrodes 30,31 are disposed in a growing substrate 33. The electrodes are connected to an alternating-current source 35. The current paths between the electrodes 30, 31 are schematically indicated by 37. The voltage across the input terminals of these electrodes, which is generated by the current flowing between the electrodes 30, 31, is measured with the aid of a voltmeter 39. The output signal of the

voltmeter 39 is fed to a signal processing unit 40 which comprises, for example, a multiplier 17, a low-pass filter 19, an analog-digital converter 21, an arithmetic unit 23 and a time control unit 25, as shown in Figure 3.

Figure 4 shows an alternative set-up, where four electrodes 41, 43, 45 and 47 are situated at a distance above the subsoil 49. The current paths are indicated by 51, and the equipotential lines by 53. With the aid of a current source 55, a current is passed along current paths 51 through the material 49 from an electrode 41 to an electrode 47. With the aid of the electrodes 43, 45 the potential formed in the material 49 is measured. The output of the voltmeter 59 is connected to a signal processing unit 61 which may comprise the same components as the signal processing unit 40 of Figure 3. The advantage of the set-up according to Figure 4 is that it is not necessary for electrodes to be positioned in the growing substrate 49 and that the water content thereof can be sensed remotely.

CLAIMS

1. Method for determining the moisture content of soil samples, in particular of growing substrates, comprising the following steps:

a) determining the value of the real part of the complex permittivity at at least two frequencies within a first predetermined frequency band,

b) determining by interpolation, on the basis of the values found at a), of the value of the real part of the complex permittivity at a reference frequency within a second frequency band, at least most of which is situated above the first frequency band,

c) comparing the values determined at b) with values which, depending on the moisture content, hold good at the reference frequency for a reference material, and determining therefrom the moisture content of the soil sample in question.

2. Method according to Claim 1, characterized in that in step a) use is preferably made of three or more frequencies.

3. Method according to Claim 2, characterized in that the values of the frequencies used have a mutually integer ratio.

4. Method according to Claim 3, characterized in that three frequencies are used whose values have a mutual ratio of 1:2:3.

5. Method according to any one of the preceding claims, characterized in that the reference material is a granular material, whose conductivity and dielectric constant are independent, at least within the first and second frequency band, of the frequency.

6. Method according to Claim 5, characterized in that the moisture content of the reference material is determined, at least in a good approximation, by the Topp calibration curve, known per se.

7. Method according to Claim 5 or 6, characterized in that the reference material consists of sand.

8. Method according to any one of the preceding claims, characterized in that the first frequency band is situated within the range between 100 MHz and 200 MHz.

9. Method according to any one of the preceding claims, characterized in that the second frequency band is situated within the range between 100 MHz and 200 MHz.

10. Method for measuring the water content of growing substrates such as sand, clay, earth, glass wool or rock wool, comprising the steps of:

a- measuring the impedance of the growing substrate and the determination therefrom of the real part ϵ' of the complex permittivity $\epsilon'-j\epsilon''$ at at least two frequencies,

b- the determination of the real part $\epsilon'(\omega_0)$ of the complex permittivity from the at least two measured values at a reference frequency ω_0, ω_0 being between 50 and 350 MHz, preferably between 100 and 200 MHz, and

c- the determination of the water content θ from the variation of ϵ' with θ for sand or from the variation of ϵ' with θ of a granular material whose variation of ϵ' with θ is similar to that of sand and which has a constant real part ϵ' of the permittivity in the frequency range between 0 and 17 GHz.

11. Method according to Claim 10, wherein in step a the real part ϵ' of the complex permittivity is determined by positioning at least two electrodes in or near the growing substrate, applying an alternating current across the electrodes, measuring the a.c. voltage across the electrodes, the determination of the complex impedance $Z^* = 1/(G+j\omega C)$, where G is the conductivity in S/m and C is the capacitance in F, and the determination of ϵ' via the relationship: $C=k\epsilon'\epsilon_0$, where k is a constant.

12. Method according to Claim 10 or 11, wherein in step c the variation of ϵ' with the water content θ is given by $\epsilon'(\omega_0) = 3.03 + 9.3\ \theta + 146\ \omega 2 - 76\ \theta^3$.

13. Method according to Claim 10, 11 or 12, characterized in that in step a the real part ϵ' of the permittivity is measured at three frequencies between 5 and 50 MHz, preferably at approximately 10 MHz, approximately 20 MHz and approximately 30 MHz.

14. Apparatus for implementing the method according to any one of Claims 10 to 13 inclusive, comprising:

- at least two electrodes which can be positioned in or near a growing substrate,
- an alternating-current source for supplying an alternating current to the electrodes with at least two different frequencies,
- a measuring device for determining the voltage difference generated by the alternating current between the electrodes, and
- an arithmetic unit for determining, from the voltage measured, the real part ϵ' of the complex electric permittivity at the at least two frequencies, for determining $\epsilon'(\omega_0)$ and for determining the water content θ from $\epsilon'(\omega_0)$ according to Claim 1.

15. Apparatus according to Claim 14, characterized in that in the

arithmetic unit the water content θ is determined from $\epsilon'(\omega_0)$ by solving the equation $\epsilon'(\omega_0) = 3.03 + 9.3\,\theta + 146\,\theta^2 - 76\,\theta^3$.

16. Apparatus according to Claim 14 or 15, characterized in that the apparatus comprises:

- a shunt line between the alternating-current source and an input terminal of a constant-phase element,
- a multiplier whose input is connected to an input terminal of the electrodes and with a constant-phase element,
- a low-pass filter which is connected, by its input, to the output of the multiplier and by its output, via an analog-digital converter, to the arithmetic unit.

Fig - 1

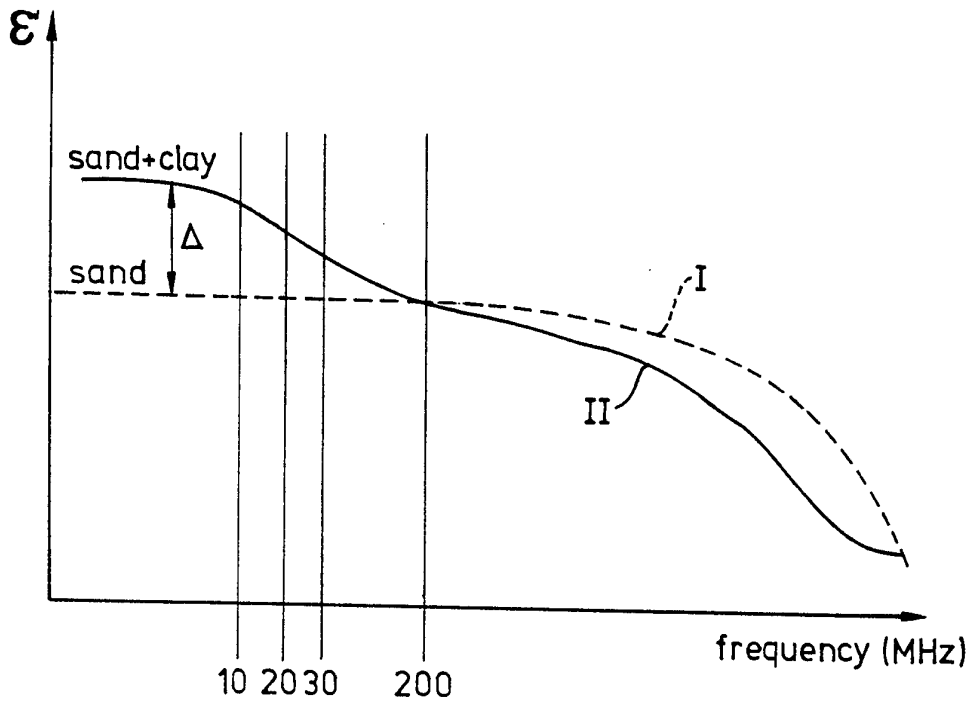


Fig-2

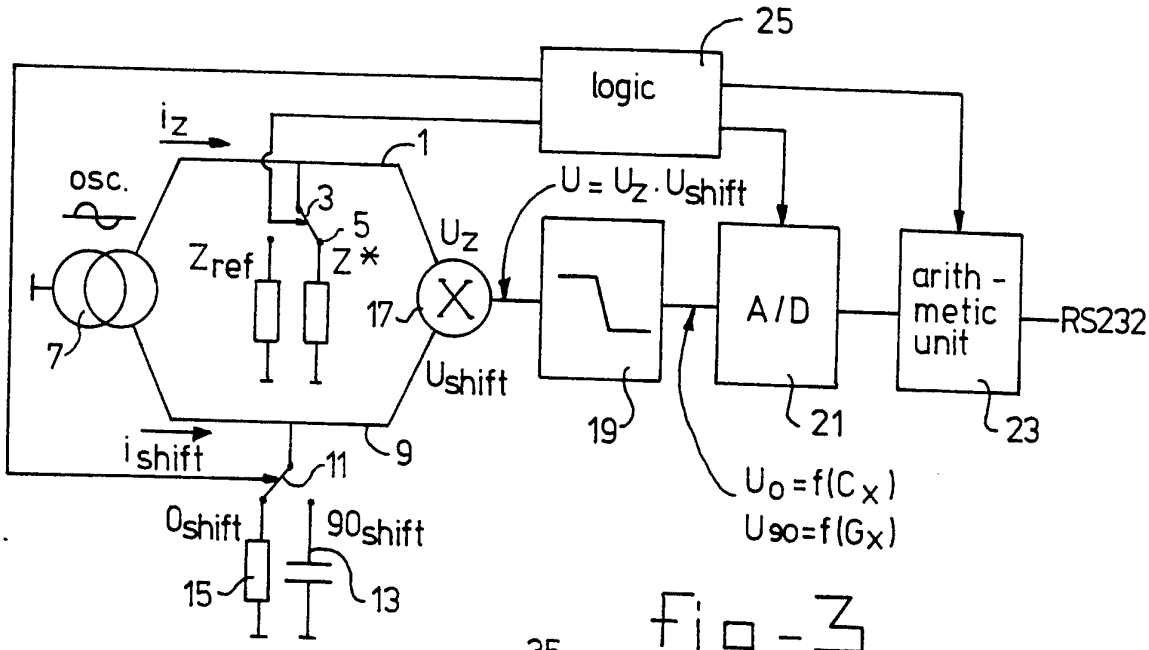


Fig-3

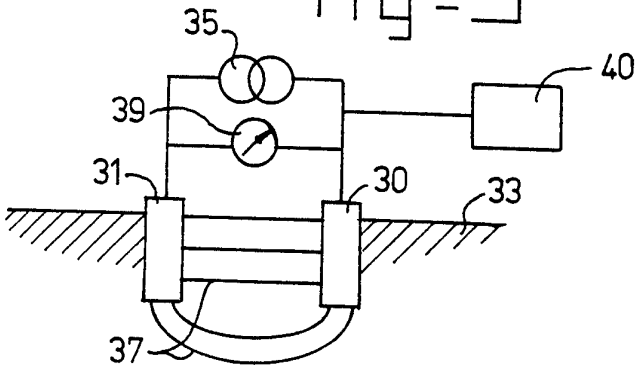
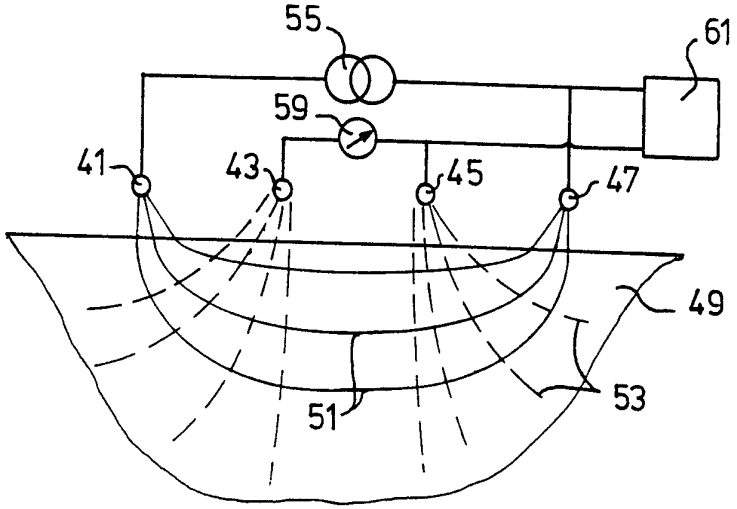


Fig-4



INTERNATIONAL SEARCH REPORT

In. ational Application No
PCT/NL 96/00251

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01N27/22 G01V3/12 G01N22/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO,A,86 05278 (UNIVERSITY OF CALIFORNIA) 12 September 1986 cited in the application see page 1, line 10 - line 26 see page 9, line 21 - page 10, line 32	1,2,10
A	see page 16, line 12 - line 16 see page 22, line 29 - line 33 see claim 6 ---	13
X	US,A,4 727 311 (WALKER) 23 February 1988 see abstract see column 2, line 30 - line 58 see column 3, line 23 - line 32 see column 3, line 42 - column 4, line 2 see column 4, line 44 - line 52 see column 8, paragraph 3; figure 2 ---	1,10
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[X] Further documents are listed in the continuation of box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
1 October 1996	04.10.96

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax (+31-70) 340-3016	Thomas, R.M.

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INTERNATIONAL SEARCH REPORT

International Application No
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP,A,0 159 270 (SCHLUMBERGER) 23 October 1985 see abstract see page 8, line 1 - page 10, line 17 see page 15, line 13 - page 16, line 11 see claim 6; figures 1,5	1,10
A	FR,A,2 347 694 (SCHLUMBERGER) 4 November 1977 see page 1, paragraph 1 see page 1, line 30 - page 2, line 6 see page 3, line 35 - page 4, line 32 see page 10, line 22 - line 24 see page 10, line 33 - line 36 see page 13, line 5 - line 6 see figure 1	1,10

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Information on patent family members

Ir. ational Application No
PCT/NL 96/00251

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