12. A. L. Cochran, thesis, University of Texas (1982).
13. P. Goldreich and S. Tremaine, *Icarus* **34**, 227 (1978).
14. P. R. Weissman, in *Comets*, L. L. Wilkening, Ed. (Univ. of Arizona Press, Tucson, 1982), pp. 637–658.
15. J. A. Fernandez, *Mon. Not. R. Astron. Soc.* **192**, 481 (1980).
16. F. L. Whipple, *Proc. Natl. Acad. Sci. U.S.A.* **51**, 711 (1964).
17. F. J. Low *et al.*, *Astrophys. J.* **278**, L19 (1984).
18. A. G. W. Cameron, *Icarus* **1**, 13 (1962); in *The Origin of the Solar System*, S. F. Dermott, Ed. (Wiley, New York, 1978), pp. 49–75.
19. M. E. Bailey, *Mon. Not. R. Astron. Soc.* **204**, 603 (1983).
20. S. V. M. Clube and W. M. Napier, *Q. J. R. Astron. Soc.* **23**, 45 (1982).
21. E. M. Shoemaker and R. F. Wolfe, abstract, 15th Lunar and Planetary Science Conference, Houston, Texas, 1984.
22. I thank M. Hanner for discussions on the thermal properties of ice and silicate grains, A. Harris for discussions on collisional processes between planetesimals, and R. Carlson for additional discussions. This work was supported by the NASA Planetary Geophysics and Geochemistry Program and was performed at the Jet Propulsion Laboratory under contract with the National Aeronautics and Space Administration.

13 February 1984; accepted 6 April 1984

Time-Domain Reflectometry: Simultaneous Measurement of Soil Water Content and Electrical Conductivity with a Single Probe

Abstract. *Two parallel metallic rods were used as a wave guide to measure the dielectric constant and electrical conductivity of soils having different electrical conductivities but the same water content. Measurements showed that the two parameters were sufficiently independent to permit simultaneous determinations of water content and bulk electrical conductivity.*

Conventional nondestructive methods for measuring the water content of soil are based on the use of neutron probes and less frequently on the attenuation of gamma rays (*1*). Soil water conductivity is tediously determined by sampling the soil and measuring the electrical conductivity of saturated extracts (*2*). Time-domain reflectometry (TDR) is a relatively new method for measuring the volumetric water content of a porous medium. It was first developed by Fellner-Feldegg (*3*) in an effort to obtain in one measurement the frequency dependence of the dielectric constant of liquids. In addition, molecular relaxation times and electrical conductivities could be measured. Topp *et al.* (*4, 5*) showed the general applicability of the method for measuring the volumetric water content of soils and other porous materials. They found that there is a unique relation between the volumetric water content and the dielectric constant for many different soils. One obtains the dielectric constant of the medium by measuring the transit time of an electromagnetic pulse launched along a pair of metallic, parallel rods of known length embedded in the porous medium (Fig. 1). In a saline soil, however, the electromagnetic pulse is attenuated (*4*). The purpose of this study was to determine if the attenuation of the launched signal in a conductive medium could be used to measure soil salinity. If the measurements of transit time and attenuation are sufficiently independent, then the conductivity and dielectric constant can be determined simultaneously.

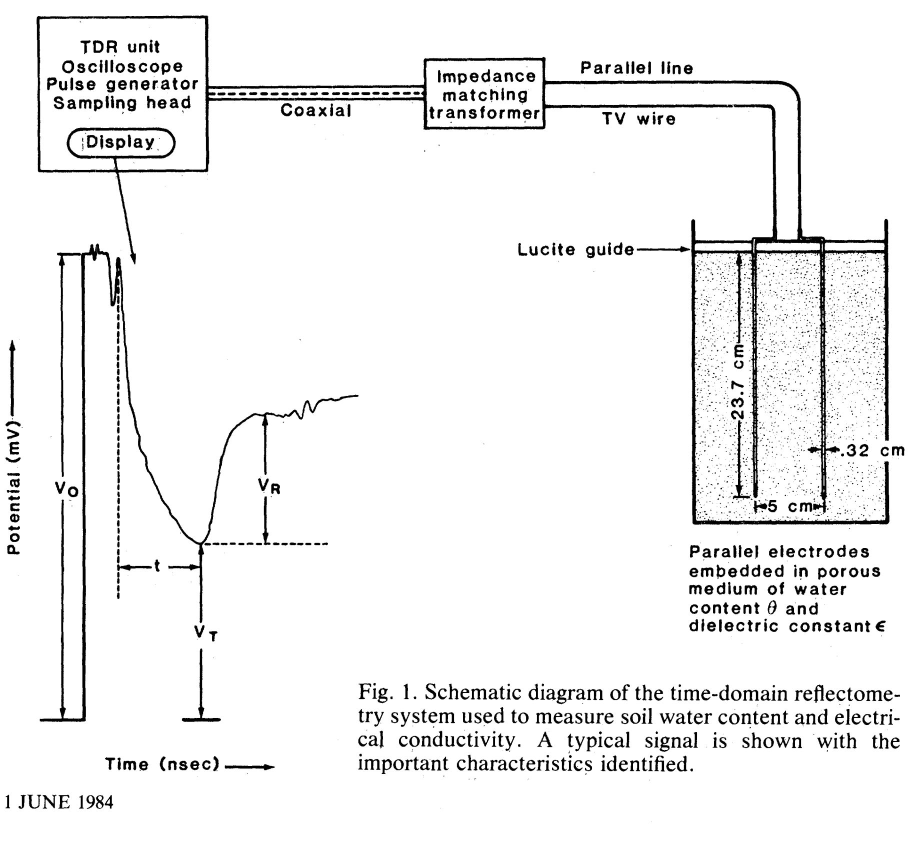

Fig. 1. Schematic diagram of the time-domain reflectometry system used to measure soil water content and electrical conductivity. A typical signal is shown with the important characteristics identified.

At the end of the wave guide, the launched electromagnetic pulse is reflected back to its source. Therefore, the pathlength is twice the length of the wave guide, L (in meters). The measured transit time, t (in seconds), gives the propagation velocity of the pulse (in meters per second):

$$v = \frac{2L}{t} \tag{1}$$

If dispersion is negligible, then v can be given simply in terms of the relative dielectric constant of the medium, ϵ, and the velocity of light in free space, c (3×10^8 m/sec),

$$v = \frac{c}{\epsilon^{1/2}} \tag{2}$$

Therefore, the relative dielectric constant is given by

$$\epsilon = \left(\frac{ct}{2L}\right)^2 \tag{3}$$

Figure 1 shows a schematic of a TDR system used to obtain t; V_0 represents the output of the pulse generator, V_T is the magnitude of the voltage pulse that enters the parallel-rod wave guide, and V_R designates the magnitude of the reflected wave when it has returned to the wave-guide input (*3*). In order to be able to distinguish t, V_R must be greater than zero. In a nonconducting medium, V_R will be equal to V_T and t is easily measured. However, when the medium is conductive, as in a saline soil, the amplitude of V_T will be attenuated in proportion to the conductivity. The attenuation of V_T can be used to measure the electrical conductivity of the medium and therefore the salt content.

According to electromagnetic field theory, the amplitude of a signal traveling a distance $2L$ in an electrically conductive medium with an attenuation coefficient α is diminished exponentially according to

$$V_R = V_T \exp(-2\alpha L) \tag{4}$$

where the attentuation coefficient, α, is approximated by

$$\alpha = \frac{\sigma}{2}\left(\frac{\mu\mu_0}{\epsilon\epsilon_0}\right)^{1/2} \tag{5}$$

In Eq. 5 σ is the electrical conductivity of the medium (in siemens per meter); μ is the medium's relative magnetic permeability; ϵ_0 is the dielectric constant in free space (in farads per meter); and μ_0 is the magnetic permeability in free space (in henrys per meter). For soils low in magnetic material, μ = 1 and Eq. 5 becomes

$$\alpha = \frac{60\ \pi\sigma}{\epsilon^{1/2}} \qquad (6)$$

Combining Eq. 4 and 6 yields the medium electrical conductivity as

$$\sigma = \frac{\epsilon^{1/2}}{120\pi L} \ln \frac{V_T}{V_R} \qquad (7)$$

Under conditions for which t is measurable, ϵ is known by Eq. 3. Equation 7 can then be used to calculate σ by TDR.

The relation between σ and soil water electrical conductivity, σ_w, is given by (*6*)

$$\sigma = \sigma_w \theta T(\theta) + \sigma_s \qquad (8)$$

where θ, $T(\theta)$ and σ_s are, respectively, the soil water content, soil water transmission coefficient, and solid-phase conductivity. Values for these coefficients are available for a fine sandy loam (Indio, coarse-loamy, mixed, thermic haplic durixeralfs), which is similar to the soil used in this investigation (Arlington, coarse-silty, mixed hyperthermic typic torrifluvents), and are given by

$$T = 1.29\theta - 0.116 \qquad (9)$$

and σ_s = 0.25 dS/m.

In order to compare the TDR determinations of the σ values as predicted from Eq. 7 with those described by Eq. 8, we brought ten soil columns to equal water contents, using waters of ten different σ values. Twenty-five days after infiltrating each column with waters of known electrical conductivities, we made TDR measurements of t, V_T, and V_R. Then we determined the average volumetric θ for each column by sampling in 5-cm depth intervals. In order to obtain the average σ_w value we took another set of soil samples and extracted the soil water by centrifuging. We then measured the σ_w values of the extracts by using a standard conductivity bridge.

During the time period allowed for each column to come to an equilibrium distribution of water content, a dissolution of residual salts occurred. This was reflected in a measured increase in the σ_w at the end of the experiment. The value of σ_w ranged from 0.8 to 11.1 dS/m, whereas the average volumetric θ for the ten columns was fairly constant at 0.34 ± 0.01. The average value of ϵ was 19.48 ± 0.53; this value is in good agreement with that determined by Topp *et al.* (*4*), (that is, 19.57), for a number of different soils, all at a θ =0.34. The effect of the large variations in the σ values of the media thus has a negligible effect upon the determinations of θ.

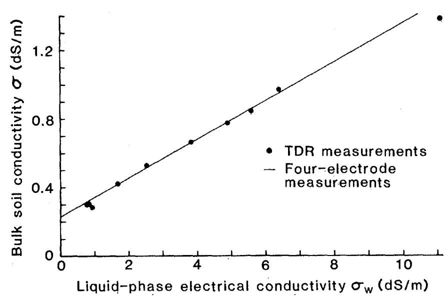

Fig. 2. The relation between bulk soil electrical conductivity and soil water electrical conductivity, as determined by four-electrode measurements (Eq. 8) and TDR measurements (Eq. 7).

Figure 2 compares the two determinations of σ as a function of σ_w. The solid line is a plot of Eq. 8; we calculated the positions of the data points from Eq. 7, using the values measured from the ten soil columns. The close agreement between the two determinations demonstrates that TDR can be used to obtain bulk medium σ and volumetric θ values with a single probe. Since the probe is spatially sensitive to the average ϵ and σ between the rods, water and solute distributions can be monitored if the probes are placed in a horizontal orientation at specified vertical intervals. Alternatively, vertical installations with probes of various lengths can yield average quantities over those lengths insofar as the soil σ does not completely attenuate the signal.

Only recently has bulk medium σ been used to estimate the pore-water σ. Even in the best instances, two separate measurements are necessary in order to determine θ and pore-water σ. Thus, when TDR is used in conjunction with known relations between medium σ and σ_w, it provides a powerful new tool in soil water research because a single measurement can yield both θ and the soil water salinity.

F. N. DALTON
U.S. Salinity Laboratory, Department of Agriculture, 4500 Glenwood Drive, Riverside, California 92501
W. N. HERKELRATH
U.S. Geological Survey, Menlo Park, California 94025
D. S. RAWLINS
J.D. RHOADES
U.S. Salinity Laboratory

References

1. W. H. Gardner, in *Methods of Soil Analysis*, C. A. Black, Ed. (American Society of Agronomy, Madison, Wis., 1965), vol. 1, pp. 82–127.
2. C. A. Bower and L. V. Wilcox, *ibid.*, vol. 2, pp. 933–951.
3. H. Fellner-Feldegg, *J. Phys. Chem.* **73**, 616 (1969).
4. G. C. Topp, J. L. Davis, A. P. Annan, *Water Resour. Res.* **16**, 574 (1980).
5. ——, *Soil Sci. Soc. Am. J.* **46**, 672 (1982).
6. J. D. Rhoades, P. A. C. Raats, R. J. Prather, *ibid.* **40**, 651 (1976).

23 January 1984; accepted 22 February 1984

Nautilus Growth and Longevity: Evidence from Marked and Recaptured Animals

Abstract. *Study of* Nautilus belauensis *in its natural habitat in Palau, West Caroline Islands, shows that growth is slow (0.1 millimeter of shell per day on the average) and decreases as maturity is approached and that individuals may live at least 4 years beyond maturity. Age estimates for seven animals marked and recaptured between 45 and 355 days after release range from 14.5 to 17.2 years. These data indicate that the life-span of* Nautilus *may exceed 20 years and that its life strategy is very different from that of other living cephalopods.*

There has been considerable interest in the growth rate of *Nautilus* as a measure for estimating growth rates, life-span, and timing of ontogenetic events in such fossil groups as the ammonoids and nautiloids. Diverse approaches have been used to estimate *Nautilus* growth rates; Oliver Wendell Holmes, for instance, suggested a rate of one chamber per year (or about 32 years to maturity) (*1*), which may be closer to fact than more recent projections. Other estimates, based on aquarium records of animals maintained in captivity (*2*), chamber partial gas pressures (*3*), shell radionuclide half-lives (*4*), and growth line counts (*5*), have ranged from 13 to 75 days per chamber (about 2 to 6 years to maturity). Longevity has not been the subject of such speculation; most cephalopods die after reproducing, and *Nautilus* has not been assumed to be an exception.

Reliable data on growth of animals in their natural habitat has not been available. The deep habitat of *Nautilus* limit-