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Evaluating Surface-Soil Water Content by Measuring Reflectance¹

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ABSTRACT

Water's property to absorb certain wavelengths in the near infrared was the basis for developing a reflectometer to measure reflectance of near-infrared radiation from a soil surface. The reflectometer's essential elements include: source of infrared radiation, optical system, integrating sphere, detector, light chopper, amplifier, and meter system. The radiation from an incandescent lamp was filtered with narrow-band pass filter, chopped and allowed to strike the test surface, where it was either absorbed or reflected onto the surface of the integrating sphere. The intensity of the reflected radiation was measured with a lead sulfide detector and appropriate amplifier and meter. The reflectance as a function of water content was measured for filter paper and several soils at 1.30, 1.45, 1.65, and 1.95 μm . Although at low water contents soil properties (other than water content) strongly influenced soil reflectance, at 1.95- μm wavelength—the most prominent absorption band of liquid water—the reflectance–water content relationship tended to be log-linear.

Additional Index Words: reflectometer, soil erosion, integrating sphere, light chopper, infrared detectors.

GENERALLY, agriculturalists evaluate soil water to determine how its content and activity change in time and space in the soil's root zone volume. Of the many methods used, none accurately indicates water status at the most transient position, the surface, where water content may change rapidly because of precipitation, irrigation, or evaporation. Even though water status of the thin surface layer may be inconsequential when considering total-volume change of water in the entire soil volume or the number of roots occupying the surface volume of soil, it should be considered carefully. Its assessment is required in many soil-plant atmosphere simulation models; furthermore, the water status greatly influences a soil's wind erodibility. Chepil (6) showed that the resistance of the uppermost soil particles against wind erosion was, on the average, proportional to the equivalent moisture squared, when equivalent moisture was defined as the ratio of the amount of water held in the soil to the amount held by the same soil at 15 atm percentage. This was the basis for developing a climatic factor (7) in the wind erosion equation (24) used to predict the amount of soil that will erode from a given agricultural field and to determine the conditions necessary to reduce potential erosion to a tolerable amount.

Surface soil water must also be assessed to determine the time required for the soil to dry to wind-erodible dryness for various climatic and soil conditions.

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Water's property to absorb certain wavelengths in the near-infrared electromagnetic spectrum suggests that an instrument might be developed to measure surface soil water. Curcio and Petty (10) found five prominent absorption bands of liquid water in the spectral range 0.70 to 2.50 μm . Absorption coefficient was the highest for 1.94- μm wavelength, which has been used in absorption techniques to measure moisture in liquids, solids, and methanol extracts of seeds (13, 19, 20). Although such a technique would not be feasible for soil *in situ*, one minus absorption or reflection (assuming no transmission) apparently would be feasible (2, 3, 4, 22). Bowers and Hanks (3) demonstrated the potential of using reflectance measurements to determine soil water content by showing that a 1.9- μm wavelength, for a Newtonia silt loam, reflectance decreased as water increased.

Since we were convinced that a method to evaluate soil water at the surface was needed and knew that water can absorb certain radiation wavelengths, we developed and evaluated an instrument to indicate water content at the soil atmosphere interface by measuring reflectance.

THE INSTRUMENT DESCRIBED

A device to measure surface soil water content by infrared reflectance has these essential elements: source of infrared radiation, optical system, light chopper, integrating sphere, detector, and amplifier meter system. These elements, their relationship to each other, and radiation path from source to test surface are shown in Fig. 1. Figure 2 is a photograph of soil reflectometer and readout instrument.

Radiation Sources—Many infrared sources consist of tungsten filament incandescent lamps that operate at temperatures of 2,400 to 2,900 K (2, 4, 5, 20). We used a tungsten filament lamp rated at 6.3 V but operated at 12.0 V. Just below the radiation source is an iris diaphragm used to control the diameter of the radiation beam at the sample port.

Optical System—The optical system (with associated lenses and filters) is used to transmit the desired radiation band from source to test surface, where a portion of the radiation is reflected back into an integrating sphere and onto the IR detector. The holder beneath the diaphragm contains three compartments for 2.5-cm diameter filters; thus, simply by repositioning the holder, a different filter can be placed in the path of the radiation beam.

Figure 3 shows transmission characteristics of the filters we used; each produced a different wavelength band. The 1.95- μm and 1.45- μm bands coincided with absorption bands of liquid water. The filtered radiation passed through two equiconvex lenses, mounted so that the lamp filament was at one focal point and the light chopper tines at the other.

The chopped radiation passed through a small port on the top of the integrating sphere immediately below the light chopper, then to the sample port.

Light Chopper—Using interrupted radiation with AC amplification was considered an important advance (12, 16). Until recently, a synchronously driven rotating sector was used (17, 18) to produce an alternating signal from the detector. We now use tuning fork choppers (11, 15) which offer many advantages over the synchronous motor and rotating sector. We chopped the radiation beam with a Bulova³ tuning fork light chopper at a frequency and tine amplitude of 400 Hz and 2.5 mm, respectively. Although 400 Hz is less than the optimum frequency, it

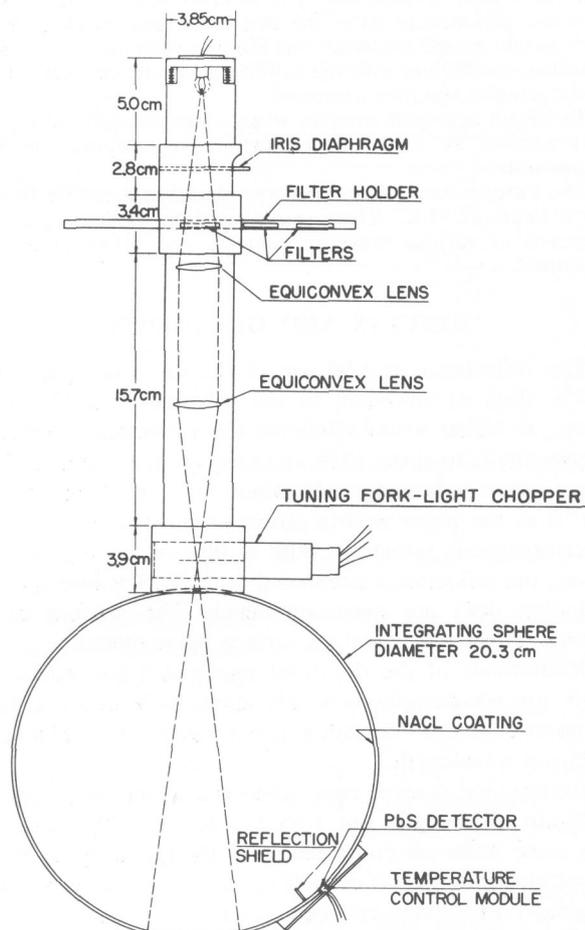


Fig. 1—Diagram of reflectometer.

is on the edge of the plateau and a desirable frequency to use with lead sulfide (PbS) detectors (9, 14, 15).

Integrating Sphere—Integrating spheres are generally prepared by applying a highly reflective coating, such as MgO, to the inside of a hollow sphere. The coating diffuses the radiation to insure uniform irradiance of any part of the sphere (4, 23). We made our sphere from two Pasco Scientific 20-cm aluminum hemispheres coated internally with NaCl, which has several advantages over commonly used MgO coatings. (Personal communication with John W. Stuart, NASA, Goddard Space Flight Center.)

The NaCl coating solution was prepared by ball milling NaCl in ethyl alcohol and then adding propylene glycol and xylene to the mixture. The coating was applied by the conventional wet-spraying technique: alternately spraying and drying.

The diameters of the sample port and radiation entry were 5 and 1 cm, respectively.

Detector—Infrared detectors are conveniently classified as either thermal or photoconductive (21). Thermal detectors have a broader spectral response, but the sensitivity of the best photoconductive detectors is better than that of the best thermal. The most useful photoconductive detector for wavelengths in the vicinity of $2 \mu\text{m}$ is the PbS, developed in World War II (14, 21). The PbS cell responds best in the 2- to $2.5\text{-}\mu\text{m}$ region, which is near a very strong absorption band of water, $1.94 \mu\text{m}$.

PbS is current noise limited, which follows an inverse frequency dependence for frequencies $< 1 \text{ kHz}$; the optimum chopping frequency is 640 Hz (9, 14, 15).

³ Trade names and company names, included for the benefit of the reader, do not imply endorsement or preferential treatment of the product listed by the US Department of Agriculture.

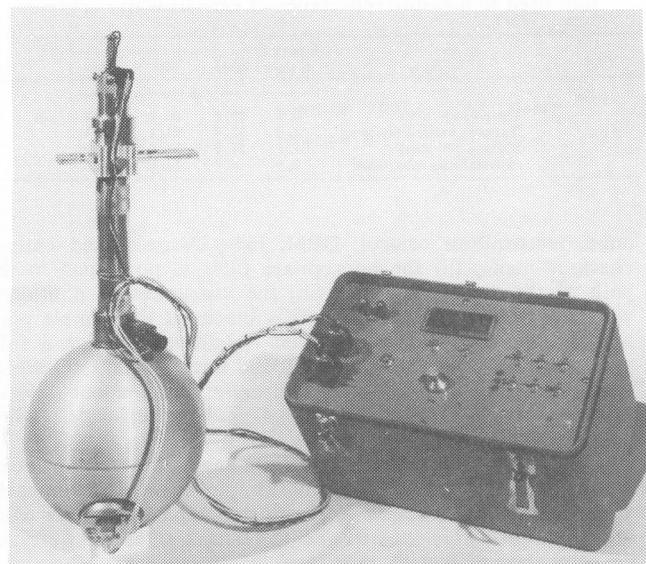


Fig. 2—Portable reflectometer and readout instrument for determining surface soil water content by measuring reflectance from soils in the near infrared.

A lead sulfide detector T1-SA17, Infrared Industries, was mounted with thermal conductive epoxy on thermoelectric module 2AD-FP, Nuclear Systems, Inc. A VECO 41AZ 2T5 thermistor was also attached to the thermoelectric module and PbS detector; it was installed midway on the lower hemisphere.

The thermoelectric module is operated to control the detector's temperature at $25.00 \pm 0.05\text{C}$. After the temperature control unit is turned on, about 10 sec is required to obtain set temperature.

By using the selective switch, the temperature of the PbS detector can be read on the same digital panel meter used for reading output of the detector. A linearizing bridge circuit was added to the temperature-sensing thermistor so that 1 V of output equaled 10C with a null at 25C .

Full-wave rectifier, amplifier, and power-supply circuits were designed and built so that a small AC signal from the PbS detector could be read by using a suitable digital panel meter (DPM). We used Analogic Model AN2535 $3\frac{1}{2}$ digit with a full-scale range $\pm 199.9 \text{ mv}$. Panel meters with lower power requirements are now available.

The entire instrument assemblage ready for use is shown in Fig. 2.

Operation—To obtain readings and determine reflectance of a surface: (i) the instrument is turned on (power, amplifier,

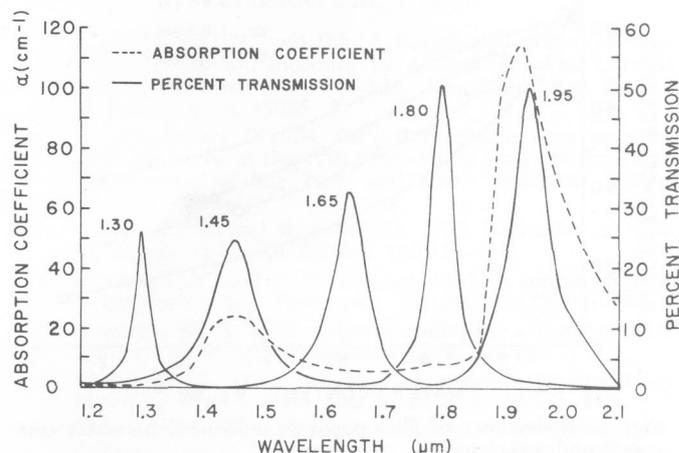


Fig. 3—Transmission characteristics of various filters and absorption coefficients of liquid water.

Table 1—Organic matter content and mechanical analysis of soils used to measure reflectance at various water contents

Soil	Organic matter	Sand	Silt	Clay
Carr sandy loam	0.7	69.5	23.7	6.8
Farnum sandy clay loam	1.8	57.3	21.4	21.3
Eudora silt loam	1.7	26.2	51.9	21.9
Smolan silty clay loam	2.9	6.7	54.8	38.5

lamp, temperature control, DPM, light chopper) and battery check is made; (ii) the appropriate filter is positioned in the path of the radiation beam; (iii) the instrument is positioned with a reference surface—a $MgCO_3$ block—at the sample port; and (iv) the gain of the amplifier is adjusted to give a full-scale reading on the DPM. Background error on the test surface (with the diaphragm closed), is usually small—about 1% of full scale—when amplifier gain is adjusted for full-scale reading using the 1.95- μm filter.

After background and reference readings are obtained, measurements are made on the desired sample surfaces. After background readings are subtracted from sample and reference readings, the ratio is obtained to give the sample-surface reflectance (as percentage of $MgCO_3$ reference).

EXPERIMENTAL METHODS

Distilled water was added to filter paper until it was nearly saturated (12 mg water/cm² of filter paper). Then, reflectance of the wet filter paper was measured at 1.95 μm . After a slight amount of water had evaporated, reflectance was measured again. This process was repeated until most of the water had evaporated from the filter paper. Reflectance of the oven-dry filter paper was measured also. The process was repeated for 1.65-, 1.45-, and 1.30- μm radiation bands.

Four soils varying widely in texture (Table 1) were wetted with water to various contents by mist spraying the soil while it was being mixed in a small homemade mixer, similar to a commercial concrete mixer. Then, the soils were placed in sealed containers and allowed to equilibrate for several days before reflectance was measured and moisture content determined.

Because clayey soils became sticky when moisture content was high, we saturated these soil samples by capillary absorption, then extracted some of the water, using moisture-extraction equipment commonly used to determine soil-moisture characteristic curves.

Aggregate size fractions of the Eudora silt loam of < 0.42 mm, 0.42 to 0.84 mm, 0.84 to 2.0 mm, and 2.0 to 6.35 mm were obtained by sieving. Samples of each aggregate size were placed in desiccators containing sulfuric acid solutions of 4, 7,

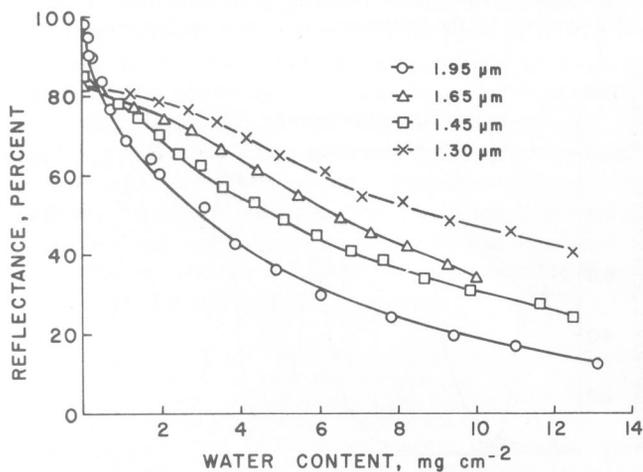


Fig. 4—Reflectance of filter paper as influenced by water content and wavelength.

16, 28, and 45%, yielding water potentials of 10, 30, 100, 300, and 1,000 bars, respectively. The samples and containers were removed periodically from the desiccator and weighed. When their weight ceased to change, the samples were assumed to be in moisture equilibrium with the sulfuric acid solution. Reflectance of the samples was then measured.

To obtain aggregate samples when water contents were > 10 bars suction, we used moisture-extraction equipment as with clayey soils.

The Farnum sandy loam soil was placed in a muffle furnace for 2 hours at 730C. Then, samples of the oxidized soil were prepared at various moisture contents and reflectances were measured.

RESULTS AND DISCUSSION

The reflectance at 1.95 μm of the dry filter paper was 100% (Fig. 4), or equal to the reference $MgCO_3$ block. Then, at higher water contents, the reflectance decreased exponentially to about 15% at 13 mg water per cm² of filter paper, thus indicating that water 10 μm thick (10 mg cm⁻²) in the paper matrix absorbed most of the 1.95- μm electromagnetic radiation. With as little as 1.0 mg cm⁻² of water, the reflectance attenuated > 25%. Because infrared radiation does not penetrate deeply, the amount of IR energy reflected is mainly a surface phenomenon.

Reflectance of the dry filter paper at 1.30-, 1.45-, and 1.65- μm wavelengths was only about 80% and decreased as water content increased, but to a lesser extent than at the 1.95- μm wavelength.

Reflectance changed most when water content changed at 1.95- μm wavelength; but 1.45 > 1.65 > 1.30, which was the same order as coincidence of filter transmission and water absorption coefficient (Fig. 3). We had hoped to find a greater difference between absorption bands (1.95 and 1.45) and nonabsorption bands (1.65 and 1.30).

As with filter paper, a well-defined relationship exists at 1.95 μm between reflectance and water content of the Farnum sandy clay loam soil (Fig. 5).

Reflectance of the Farnum sandy clay loam increased from 43 to 80% (1.95 μm) when the organic matter was removed by dry combustion. Initially this soil was 10YR

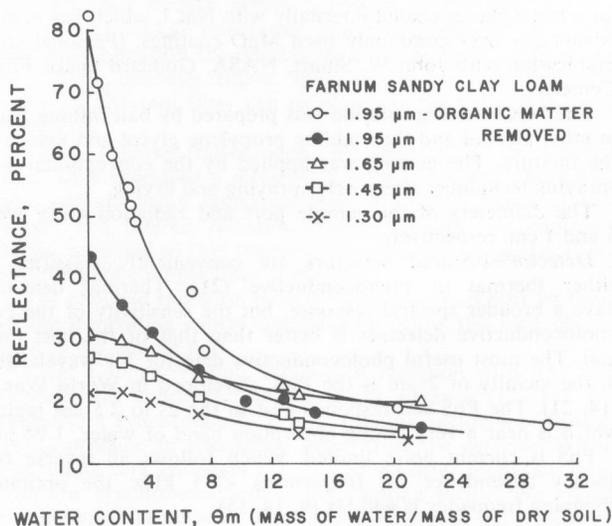


Fig. 5—Reflectance of Farnum sandy clay loam at indicated wavelengths.

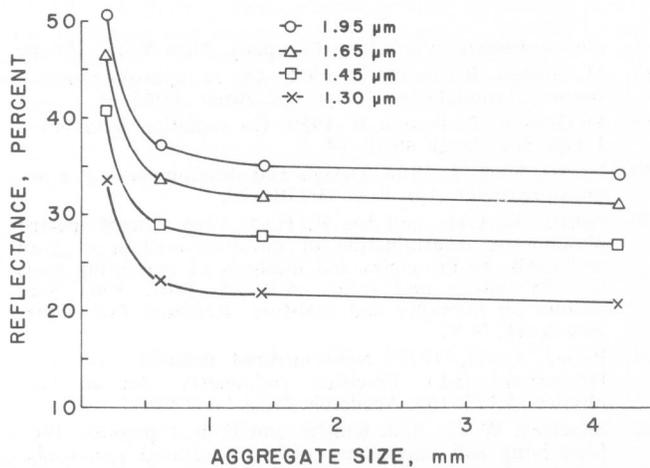


Fig. 6—Reflectance of Eudora silt loam (with water suction of 5 bars) at indicated wavelengths and aggregate sizes.

3/2, very dark-greyish brown; after oxidation it was 2.5YR 5/6, red.

As with the filter paper, soil reflectance was much more sensitive to water content at the 1.95- μm wavelength than at the other wavelengths.

Aggregate size only slightly influenced reflectance at all four wavelengths for aggregates larger than about 1.0 mm (Fig. 6). The data show that reflectance from a smooth surface composed of Eudora silt loam aggregates < 0.42 mm was much greater than reflectance from 0.42- to 0.84-mm aggregates.

These results agree with work by Bowers and Hanks (3) and Shockley et al. (22). Bowers and Hanks (3) found that reflectance decreased rapidly exponentially as particle sizes of bentonite and kaolinite increased; the most noticeable decreases occurred at sizes < 0.4 mm, and influence was not great for particles greater than about 1.5 mm. Shockley et al. (22) found that for grain sizes of slag > 1.5 mm, the reflectance remains relatively constant. They also reported that beyond 1.5 mm, reflectance values seemed to result from surface characteristics of the grain particles and not grain size.

Though cloddiness (under natural field conditions) may negligibly influence soil reflectance, other soil properties do have significant influence (Fig. 7). A large difference in reflectance exists from soil, especially when dry.

The oven-dry Carr sandy loam (Fig. 7) reflected almost 80% of the radiation energy passing the 1.95- μm filter, whereas the oven-dry Farnum sandy clay loam reflected only about 43%. To the human eye, those two soils are light and dark, respectively.

Condit (8) obtained spectral reflections extending from 320 to 1,000 nm for 160 soil samples by measuring both wet and dry samples. They classified their 160 sets of curves into three general types according to shape. For the wet and dry curves at 1,000 nm, one soil had < 2% difference in reflectance; another of the same type had 25% difference. When soils are wet, reflectance is dominated by water absorbing the radiation, and differences between soils become small. The reflectance vs. water content curves at 1.95

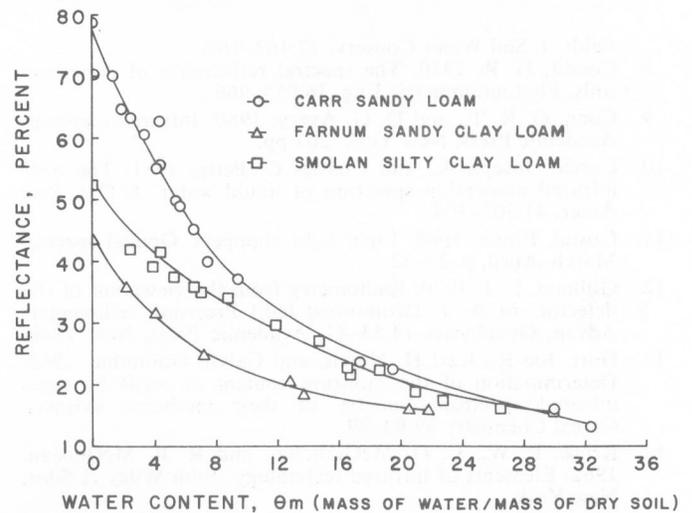


Fig. 7—Reflectance at 1.95 μm of three soils as influenced by water content.

μm (Fig. 7) essentially coincide when water contents by weight are > 26%.

For fine sandy loam soil at 580 nm, Allen and Sewell (1) found very little sensitivity of reflectance when water content by weight was > 10%. Shockley et al. (22) stated that the reflectance vs. water content curve decreased sharply as water content increased until nearly all soil particles were coated and nearly all interstices filled with water; then, an inflection point was reached and added water produced only small changes in reflectance.

The shape of the reflectance vs. water content curve closely resembles a log-linear relationship for soil water contents between oven-dry and the point of small change in reflectance as water content is increased. We calculated the least squares fit for a log-linear relationship for the soils in Fig. 7 for water contents between oven-dry and 0.3 bar tension and also the filter paper (Fig. 4). The R^2 values were 0.99, 0.99, 0.96, and 0.99 for filter paper, Carr sandy loam, Farnum sandy clay loam, and Smolan silty clay loam, respectively. Although this shows promise for two-point calibration of reflectance vs. water content relationship for many soils, further testing is needed.

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