SOIL MOISTURE MEASUREMENTS BY SYNTHETIC APERTURE RADAR AND SCATTEROMETERS IN THE ARID AND SEMI-ARID ENVIRONMENT

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ABSTRACT

Water is a scarce commodity in desert regions; yet, most remote sensing experiments of soil moisture have been conducted in temperate areas. The ability to detect and reliably assess soil moisture in the arid environment has important implications both at the micro scale such as the individual farm and at the macro scale for climate modeling.

A series of experiments utilizing an airborne scatterometer operating at P-band were conducted to assess the ability to measure soil moisture over farmlands in the Negev Desert by remote sensing. The soil moisture is determined by measuring the backscattered radar signal at the scatterometer.

Results show that in the arid environment of the Negev scatterometer data correlate well with field measured soil water content. The water content values measured were between 2 and 7% (volumetric). Some extreme values were measured at the Ramat Negev experimental farm. A later visit to the farm confirmed a faucet leak at the location of the extensive values (>20%.) We could also detect an increase in water content adjacent to a sewer reclemation pond at Mashabei Sadeh.

A second series of experiments were conducted with spaceborne synthetic aperture radar using the ERS-2 SAR system. This system is single wavelength operating at C-band HH polarization. We used two images to achieve two incidence angles for the same site. Results show that 90% of the variance in radar backscatter over individual fields can be explained using soil water and surface roughness measurements.

1 INTRODUCTION

Soil water content is an important component that influences a great variety of meso- and micro-scale environmental processes. A multi-channel system has been developed as a remote sensor for mapping soil water content. The system consists of two microwave scatterometers using frequency-modulated continuous radiation centered at 149,6 MHz and 440 MHz respectively, and a sensitive gamma-radiometer. In principle, the frequency and the pulsed methods are similar in information capability. However, the use of the frequency method allows to measure and take into account influence of the height of an aircraft on the incoming signal by simple means simplifying the electrical scheme of the scatterometer and to increase its reliability. Overall, two quantities are recorded by the scatterometer: the amplitude of the incoming signal that provides information on the soil moisture content, and the frequency (phase) providing information on the flight altitude. The system is usually used onboard of an aircraft or helicopter. The transmitting and receiving antennas are similar in their design and characteristics. The antenna represents a horizontal half-wave dipole fixed under the reflecting surface (fuselage paneling of the aircraft) at the distance of a quarter of the average wavelength, parallel to the ground. The antennas are designed with wide diagrams so that ground slopes would not affect the results of the moisture retrieval for surfaces with slopes up to 10. The first Frensel zone defines the radius r of the surface illuminated by the scatterometer: $r = \sqrt{H\lambda}$, where H is the height of the aircraft. For example, with H = 150 m and λ = 0.68 m the illuminated area is r = 10 m.

A second series of experiments used ERS synthetic aperture radar data. To solve for roughness and soil water content, two ERS images with different look directions were acquired providing two different radar signatures. An empirical model was derived to assess water-content conditions explaining ca. 90% of the backscatter variation using water-content, roughness, and incidence angle. Being that it is empirical, the model holds locally and would not be universally true. However, the approach can still be tested elsewhere.

2 FIELD STUDIES

Measurements were conducted in two environments with different implications: (i) in the Chernobyl nuclear disaster area; (ii) in the Negev Desert. For each test site the scatterometers were calibrated by mounting them above a typical soil for the region for several days. The soil below was wetted to field capacity and then left to dry naturally after mounting the scatterometer. Ground measurements were taken periodically as moisture decreases, and these were then compared with concurrent scatterometer measurements providing a calibration curve. For the interpretation of the backscattered information a theoretical model has been developed taking into account the soil texture, water content, and surface roughness [1].

(i) Survey of the Chernobyl area had been conducted during a calm weather period when the anticyclone weather has settled. The scatterometer was flown aboard An-2 aircraft flying at a mean altitude of 150 m above the surface, and at a speed of 160 km/h. Each site was flown several times with 500 m spacing between swaths. To reduce the forest impact to a minimum, the routes passed over cleared strips in the forest. Terrain-reference points were chosen and a navigation complex consisting of GPS-receivers and Trimble Navigation software determined their location. Based on the information regarding trees crown height from the air-teledetection system, correction factors were inserted to compensate for tree moisture. The coefficients were calculated using a radiation transfer model for weakly scattering medium where multiple scattering could be neglected. A gamma-ray radiometer was also flown over the Chernobyl site together with the scatterometer to measure radioactive levels. For determination of the soil moisture content from reflectivity measurements we used curves Fig. 1 obtained from a theoretical model presented in [1].

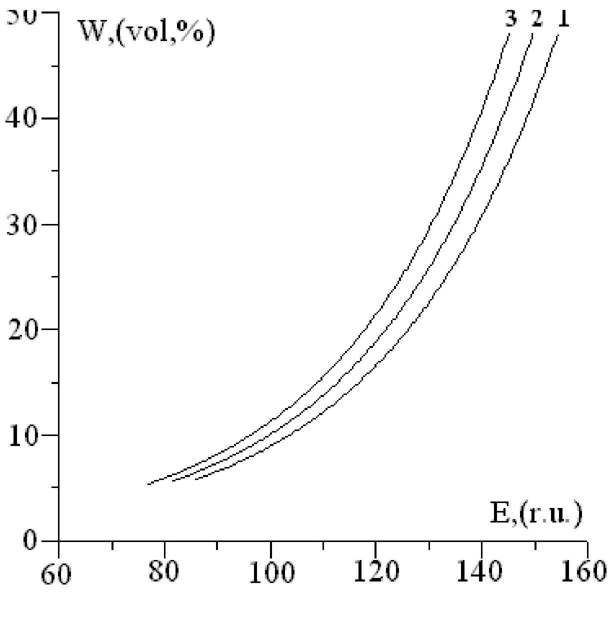


Fig.1 Water content in vol% as a function of the scatterometer intensity E calculated using a priori data on the soil texture of the Chernobyl area. (1) is sandy (2) sandy loam and (3) is loamy soil.

A comparison of the values estimated by the airborne remote sensing systems revealed the highest correlation between the remote sensing estimates and the ground measurements for sandy soils. This is true for both soil moisture and the water table depth. The sandy loam and loamy soils also show high correlation coefficients but slightly lower than sand (87% and 89% respectively for moisture content and 88% and 82% for water depth). This is to be expected because part of the water molecules are bound in the clay and are unable to align with the incident radar energy as does free water particles. The results of measurements from the flights were mapped using contouring software and regions with high water tables and high levels of soil moisture were detected. Such sites are located along the Prypiat, Uzh, and Veresnia valleys and their tributaries. The water table depth varies from 0 to 2 m with some places that have already evolved into swap land due to a combination of relief and soil degradation caused by deforestation related to the Chernobyl NPP accident

2.1 Gamma ray measurements

The gamma-ray spectrometer flown with the scatterometer allowed assessing the distribution of radioisotopes as a function of water table depth and soil moisture. A water table depth of 3-4 m characterizes the inclined part and watershed terrain. At the same time there are a lot of upper marshes that were formed by clay layers. The overall area of the submerged lands has increased to 28% for the studying area, which is an increase of 10% over the pre-accident period. The contaminated part spans 35% of the study area where _-exposures exceed 20 _R/h. In addition to the submerged areas within the contaminated territory (which cover 20.5 % of the area with a H_{wtd} from 0 to 1 m) less than 40% have a water table depth of 1 to 2 m. These sites are periodic flood plains and have a higher probability contamination not only by moving soluble forms of radioisotopes, but also by those that are bound to soil grains and are gravitationally re-distributed.

2.2 Negev measurements

At the Negev Desert a series of experiments were conducted over agricultural sites. The Negev Desert is located in Southern Israel on the margin of the Sinai and Great Deserts. The region is subject inconsistent precipitation with an annual mean of less than 100mm/year. Local communities include townships relying on industry and Kibbuts and Moshav settlements that rely on industry and farming for their livelihood. The local farming uses water pumped from the Lake Galilee in Northern Israel, local underground brackish water, reclaimed water mainly from the metro area of Tel-Aviv in central Israel, and some rainfall.

The experiments included overflying test sites with the scatterometers and consequently generating soil moisture maps and validating the maps with ground-truth measurements. Several test fields were chosen for testing the abilities of scatterometer for airborne soil-moisture retrieval. The test sites were chosen such that they would comply with the following criteria: a) topographically flat, b) sparse vegetation at time of overflight, c) serves local farming communities, c) soil constitutes of mainly sand and silts, d) easily accessible for ground measurements, e) easy to obtain over-flight permits.

The scatterometers were mounted on a “Cessna 174” together with an infrared radiometer. The aircraft flew at a transient altitude of approximately 1 km, and above the target sites at an altitude of 150 m. This provided a ground resolution of ~10 m. Each field was over-flown 2 or 4 times using parallel routes (the number of swaths was determined by the size of the field to provide relatively reliable maps.) We chose to fly with a 100 m spacing between swaths so that it be useful for precision agriculture purposes. In essence, the swath spacing should be based on the potential soil moisture variability within a field and the irrigate technique operating in the field. Concurrent field measurements included measuring soil moisture at 4 depths, every 15-cm, at four locations along the scatterometer footprint. The soil samples were taken using seal proof “Gerber” jars. The soil samples were dried at 105_ for 24 hours and the gravimetric and volumetric water content was determined. Results from the flights were mapped using contouring software.

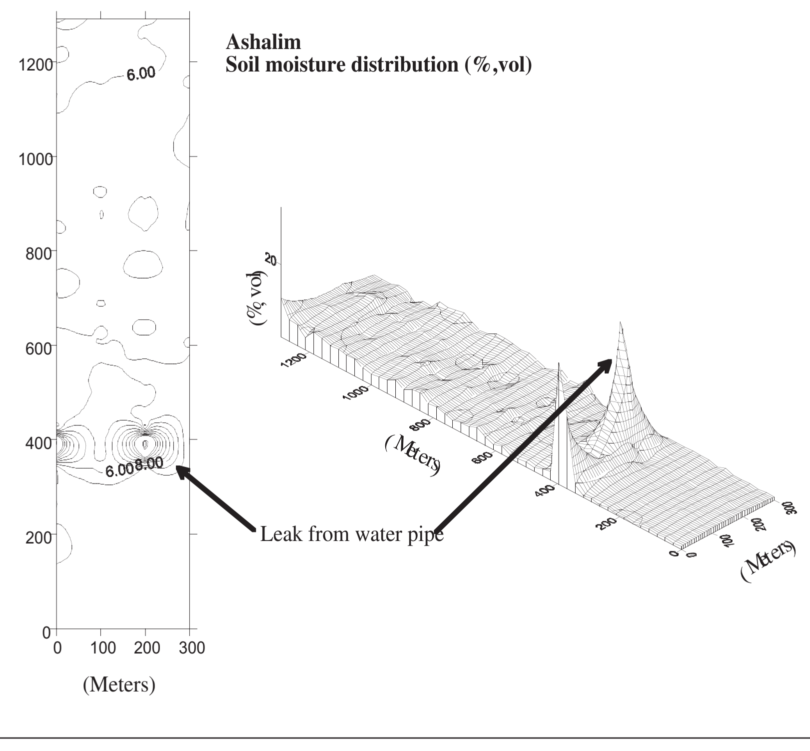
The first calibration flight was over a large water reservoir where the water content was 100%. Interestingly, leakage from a nearby reclamation pond can also be seen in the scatterometer map. This leakage is through the sides of the reclamation pond into the adjacent soils.

The second site was the Ashalim experimental farm. The Ramat Negev regional council operates the experimental farm located near Ashalim. This farm develops new techniques for agriculture harvesting such as developing crops that are not accustomed to the area and acclimating plants to brackish water. A technique for precisely monitoring the soil moisture seemed relevant to the manifest of the farm. A grid of the farm was flown twice from north to south, twice from south to north, once from east to west, and once from west to east. Maps generated from the scatterometer data show similar values to those measured in the field. To demonstrate this, the ground measurements for the Ashalim farm are given within the map (Fig.2). There is a moisture spike with an estimated moisture level of 34%. Post flight evaluation of the site shows a water irrigation leak at this place.

The third site was a field near Kibbutz Urim in the western Negev. This site was very suitable for the test having a high sand component in the soil and being very flat and wide. The field that was chosen is 500 x 500 meters. At this site there is also an increase in the water content near the northwest edge of the field. Overall, the soil moisture content ranges from 3.5% to 8% at the peak.

The last site flown was a Nabatian farm at the Avdat archeological area. The Nabatian community lived in the region from 300B.C. to 106A.C. The Nabatians had extremely efficient water management policies and managed to support a large community on sparse rainfall. In recent years Ben-Gurion University and the Hebrew University of Jerusalem have conducted experiments to reproduce the Nabatian farming methods in the region. Continuous desert heat and shallow soil make it hard to keep moisture in the soil at this site. The values estimated by the scatterometer are for the most part on the order of 3%. Toward the western part of the farm the moisture increases to nearly 10%. This coincides with a topographic low where water does accumulate and the soil is much deeper than the rest of the farm.

Fig. 2 The contour map shows a soil moisture map for the Ashalim experimental farm. There is a good correlation between the values measured in the field and those shown by the scatterometer. The moisture peak (close to 34% moisture content) is attributed to an irrigation hose that was leaking at the time.



3 SAR STUDY

This experiment utilized two images, ascending and descending to achieve two values that could be used for solving roughness and water-content. However, in order to utilize the ascending and descending images in a set of equations to delineate two parameters, it was first verified that for this study area the radar backscatter coefficients (from the two images) are not correlated which was indeed found true. Oriented roughness rather than random roughness can easily explain the lack of correlation by the difference between the roughness in the X and Y directions. Processes that yield roughness in this area (at a scale comparable to the radar wavelength) include human induced roughness, such as plowing, mostly parallel to the length of the field, and windblown processes from the southwest to the northeast. At these sites fluvial processes have very little effects, however, if they would occur, they would also be oriented. Consequently, the ascending and descending see different features and different facets of the roughness elements one from another.

The use of SAR for mapping soil water-content in the arid environment has great potential even though very little research has been conducted in this type of environment. Results from this research show that soil water-content can be mapped for individual fields using SAR data. However, either a priori knowledge is needed regarding the surface roughness, or alternatively a second image with different viewing geometry or polarization is required to solve for water content and roughness. In this project results were shown for two look directions that yield a good prediction of the soil water-content. This correlation function has only been verified and is probably valid only for sandy sites, with a RMS height of up to 25 mm. Despite the high correlation coefficient it is important to note the parameterization is of an empirical nature and therefore requires further studies to verify that the processes can work in other regions. Still, the approach of using two images, ascending and descending is most probably a valid route to take when multi-polarization data are not available.

4 CONCLUSIONS

To conclude, the presented results demonstrate the use of airborne scatterometers flown aboard a light aircraft for environmental monitoring and precision agriculture. A good agreement between values measured in the field and estimated by the scatterometers has been found with some overestimation for the lower moisture sites. Furthermore, for a more temperate site in Ukraine the scatterometer was found to be very useful also in estimating the depth of the ground water table. Alongside the scatterometer a gamma-ray radiometer was flown at the Chernobyl nuclear power plant disaster site. The ability to map soil moisture and water table depth in conjunction with gamma-ray radiometry is extremely useful in monitoring the after affects and the rehabilitation of the Chernobyl NPP disaster area. Due to deforestation caused by the Chernobyl disaster high levels of soil moisture can be hazardous in creating swampland. This phenomenon can be monitored and mapped by airborne scatterometers.

The use of SAR data with multiple look directions yielded extremely good results for the sand sites. However, this technique is empirical in nature and cannot be considered universal.

5 REFERENCES

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