Soil moisture from space: Where are we?

Yann H. Kerr

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Introduction

Soil moisture is certainly an important life sustaining entity. The first "use" of soil moisture is to enable vegetation growth. Actually, water stored in the soil has many other roles. It controls the partitioning of rainfall into runoff and infiltration, and efficient infiltration usually means replenishment of the aquifer, while runoff may mean both exportation of valuable water to other areas and degradation of top soil through leaching and erosion. Also, when saturated, soil may transform heavy rainfall into floods. Consequently, soil moisture is a key variable for improving the forecasting features of run-off models which assess flood risk and aid water-resources management.

Surface soil moisture is also important as it impacts on soil evaporation and transpiration and thus the heat and mass transfers between the Earth and the atmosphere. It is consequently very useful in weather forecast models via global circulation models. Finally, continuous monitoring of soil moisture on a large scale, and over long periods of time, gives a significant insight into climate changes.

However, soil moisture is a very vague term and it is important to define it. The most common understanding of the term is the total amount of water in the unsaturated zone. For practical reasons, it is often separated into two components, surface soil moisture corresponding to the first centimetres (5 cm in general), and the root zone soil moisture or second reservoir. Soil moisture is usually expressed in gravimetric units (g/cm^3) or volumetric units (m^3/m^3). Sometimes it is expressed as a function of the wilting point and the field capacity, both of which are soil type dependent.

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Y. H. Kerr (✉)
CESBIO,
18 Ave E. Belin,
31401, Toulouse CEDEX 9, France
e-mail: yann.kerr@cesbio.cnes.fr

What exists

To achieve the risk-management goals mentioned above, it is necessary to have access to soil moisture estimates. At the local scale and at a given moment, this is relatively easy with gravimetric sampling. However, to have measurements representative of a large area (such as a field), the procedure is already somewhat complex as it involves a dedicated sampling strategy. Moreover, as these measurements are time-consuming, regional and, even more so, global coverage is out of question. Provided one uses automatic probes (resistivity or capacitance measurements, time domain reflectometry, etc.), it is possible to achieve larger coverages and continuous measurements; however, these approaches can only be confined to well equipped and manned sites, as they require care and maintenance. Finally these systems carry their own problems and inaccuracies. So global monitoring of soil moisture can only rely on approaches that use remote sensing from space.

Remotely sensed soil moisture, the main approaches

A large number of remote sensing approaches have been tested. For surface soil moisture, the first ones were based on short-wave measurements and on the fact that soils get darker when wet. Obviously, due to atmospheric effects and potential cloud cover, as well as vegetation cover masking-effects, this approach is bound to fail in most cases. A more promising approach is linked to latent heat effects. Wet soils have a higher thermal inertia and are "cooler" than dry soils. These properties have led to various trials (thermal inertia monitoring, rate of heating in the morning, surface temperature amplitude, etc.) to assess soil moisture indirectly. All these approaches proved to be somewhat disappointing due to factors inherent in optical remote sensing (atmospheric effects, cloud masking, vegetation cover opacity) as well as the fact that (1) thermal infrared probes only the skin of soils and (2) soil skin effects are dominated by exchanges with the atmosphere. Consequently, to infer soil moisture from such measurements one needs to know the forcings exactly (for instance, wind will drastically change the apparent temperature of a wet soil).

As microwave systems measure the dielectric constant of soils, which is directly related to the water content, research has quickly focussed on assessing soil moisture with radar, scatterometers or radiometers. These systems offer, when operated at low frequency, the added

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advantage of being operational in all weather conditions (measurements are not much affected by the atmosphere and clouds) and able to penetrate vegetation, as well as being capable of operating at night.

Finally, in an attempt to be exhaustive, a new approach, relying on measurements of the gravity field from space, is said to indicate changes in the total column of water with a spatial resolution of 500 km or more. When applied, this method shows that the gravity field evolves in several areas, but its relationship with water storage has yet to be demonstrated explicitly and validated (Han et al. 2005).

Microwave as a tool for soil moisture monitoring: current status

The most popular approach relies on the use of synthetic aperture radar (SAR) systems. These systems offer all weather measurements with a fine spatial resolution (tens of metres). However, they are constrained, as with most high-resolution systems, by the requirement to operate at a rather low temporal frequency (i.e., 35 days for the European Remote Sensing satellite, ERS-1, launched in 1991), which is not really compatible with hydrologic requirements or weather forecast models. The most adverse characteristic of SAR is linked to the coherent nature of the signal due to the system design itself. Consequently, SAR images are subject to high and quick variations of the reflected signal leading to the “speckle” effect and to high sensitivity to geometrical distribution of scatterers (leaves, trunks, soil surface, etc.) at the surface. The scattering can be due to the vegetation cover (distribution of water in the canopy) or the soil’s surface (surface scattering when wet, and volume scattering when dry as the wave penetrates inside the medium and is scattered to a much greater depth). The direct consequence of these perturbations is a signal at least as much sensitive to surface roughness as it is to moisture itself (see also Wigneron et al. 1999), not mentioning vegetation. These effects are also frequency dependent. All these inherent difficulties might explain how, although several SAR flights have been undertaken since 1977, they have been neither used in a standard and routine fashion, nor have they resulted in any useful maps of absolute soil moisture. To avoid the roughness and vegetation perturbations, an approach relying on change detection, hence relative, has been used with relative success (Moran et al. 2002). However, temporal coverage is still often an issue. The use of scatterometers offers an interesting trade off. The spatial resolution is much coarser (tens of kilometres) but with a much wider swath allowing reasonably frequent coverage (every 4–6 days on average). It offers the added advantage of being much less subject to speckle (averaging). Consequently, several authors routinely produce soil wetness maps of many areas of the world with scatterometers. The effect of vegetation is, however, still significant and corresponds to most of the signal at C band (ERS-1), which is, incidentally, the lowest frequency currently available for spaceborne scatterometers. So the most interesting results have been obtained over arid and semi-arid regions where vegetation and soil moisture are very highly correlated anyway. The influence of surface roughness is also significant and it is best dealt with by using change detection.

The last possibility in the microwave domain is to use radiometers. The technique is old and well mastered as many sensors and notably sounders rely on passive microwaves. To infer soil moisture, these systems are bound to offer the best compromise if used at low frequency, as demonstrated in the early 1970s with the very short SKYLAB Mission.

However, to be efficient, one needs to work in a protected frequency band to avoid unwanted man-made emissions and radio frequency interferences (RFI) and to be sensitive to soil moisture, while the atmosphere is transparent and vegetation plays a limited role. At L band, the emissivity may vary from almost 0.5 for a very wet soil to almost 1 for a very dry, which corresponds to a range of 80–100 K in terms of brightness temperature. As a typical instrument, sensitivity is usually of the order of 1 K, it gives an equivalent of 80–100 discernible soil moisture levels. As the emitted temperature is not coherently measured, surface roughness and vegetation structure play a reduced role when compared to an active system. So, one may wonder why L-band radiometry was not use extensively before when it had been proved to be most efficient during ground and airborne measurements (Schmugge et al. 1988). The reason relates to an inherent limitation: the spatial resolution is proportional to the antenna diameter and inversely proportional to the wavelength. At wavelength 21 cm, to achieve a 40-km resolution from an altitude of 750 km requires an antenna of about 8 m in diameter, which is a very significant technical challenge. So the research was performed with higher frequency systems as available on the Scanning Multichannel Microwave Radiometer (SMMR, operated between 1978 and 1987, 6.6 GHz; Kerr and Njoku 1990), the Special Sensor Microwave Imager (SSM/I, a series of satellites starting in 1987, 19 GHz) and now the Advanced Microwave Scanning Radiometer (AMSR, operated routinely since 2002, 6.8 GHz; Njoku and Li 1999). Even though the frequency was not adapted, good results were obtained with SMMR and AMSR-E (Njoku and Li 1999). The limitations are mainly linked to the fact that the vegetation becomes rapidly opaque at these and higher frequencies, meaning that the soil signal (i.e., soil moisture) is no more discernable. Moreover, the frequency is not protected and thus is bound to be polluted by RFIs, and the single angular measurement makes it difficult, in several cases, to separate vegetation and soil contributions to the signal.

The step forward

Considering the necessity to make L band measurements, several approaches have been tested to overcome the antenna-size issue. The first was initiated in the early 1990s with the idea of applying radio astronomy techniques (very large arrays and very large baseline interferometers) to Earth remote sensing. The one-dimensional concept,

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electronically scanned thinned array radiometer (ESTAR) was implemented as an aircraft version and proved to fulfil the requirements (Le Vine et al. 1994). It is a system, deployable in space as a set of long, parallel sticks and offering an acceptable spatial resolution, but at the cost of reduced sensitivity. In parallel, another approach, using inflatable antenna (or umbrella-like deploying technology) was studied at the Jet Propulsion Laboratory (JPL) in the USA. Both concepts were proposed on several occasions to space agencies without success. The concepts appeared to be complicated to deploy and to run, or to offer too limited a range of measurements (single angle and frequency). By 1991, a small group of scientists and antenna experts started to work for the European Space Agency (ESA) on the development of a similar instrument, but one working in two dimensions (Goutoule et al. 1996). The concept was named microwave imaging radiometer with aperture synthesis (MIRAS) and an airborne prototype was made and operated (Bayle et al. 2002). From then on, the concept evolved into a more tailored instrument which was proposed to the ESA (Kerr 1998) in the framework of the Earth Explorer Opportunity Mission under the name of the Soil Moisture and Ocean Salinity (SMOS) Mission. The mission was selected and is now underway. It is an ESA lead project with contributions from France and Spain. SMOS is scheduled for a launch in 2008, in the very near future (Kerr et al. 2001). Similarly, a mission proposal was submitted to the US's National Aeronautics and Space Administration (NASA) Hydrospheric Mission (Hydros; Entekhabi et al. 2004). This mission relied on a deployable and rotating antenna related to both a radiometer and a scatterometer. SMOS is a Y-shaped instrument consisting of 69 elementary antennas regularly spaced along the arms providing, at each integration step, a full image (about 1,000×1,200 km) at either 2 polarisations or full polarisation of the Earth's surface (Kerr et al. 2001). The average ground resolution is 43 km and the globe is fully imaged twice (ascending and descending orbits) every 3 days at 6 am and 6 pm local solar time. As the satellite travels in orbit, any point of the surface is imaged at several angles, giving the angular signature of the pixel. The beauty of the concept is thus that a reasonable spatial resolution is obtained; however, this is done at the cost of a reduced sensitivity. Moreover, the pixels are viewed frequently at different angles and polarisations. The angular information is then used to separate the different contributions (soil-vegetation) to the signal (Wigneron et al. 2000).

Root zone soil moisture

The big caveat of the remotely sensed soil moisture data is that the direct measurement only concerns the surface layer. For instance, at X band a few mm are probed, and at L band 4–5 cm are probed on average (depending on soil characteristics and condition). It is necessary, however, for several applications, to know the total amount of available water in the unsaturated zone. Only one direct approach has been considered, i.e. to use even lower frequencies (wavelengths of several meters) so as to reach deeper layers. This leads to large problems in terms of spatial resolution (few hundred km) and of ionospheric effects. So this option is not feasible now. The indirect approaches could be either to use gravity change approaches (provided the method is properly validated and that very coarse resolutions—hundreds of km—are acceptable), or to rely on assimilation techniques, i.e. using models to infer root zone soil moisture, using regular surface measurements and forcing conditions. The assimilation approach has been validated both using simulations and using field data. The real limitations are linked to the models' abilities and input data quality.

Expression of need

In the quest for detailed information on soil moisture, there are many data requirements that are only partly fulfilled, an example being that the unsaturated zone is only partly probed using the currently available methods. Some needs, notably in hydrology, can only be met by having a better spatial resolution, but still with a high temporal sampling frequency. From space, this is not straightforward, but the most promising is probably to use external information to redistribute the area's average moisture within the pixel: the so-called disaggregation. Several studies recently proved the feasibility of the approach with SMOS data (Pellenq et al. 2003; Merlin et al. 2006) and now the real life validation has only to be performed.

Caveats

It is not the intention to say here that everything is resolved and fine. There are still a number of outstanding issues that will require attention before an accurate and global soil moisture product is routinely delivered. Some, such as RFI can be a general issue, especially if protection is reduced in the future, which is a concern. The specific issues identified are currently being tackled and several references in the literature identify them but, obviously, as long as the actual data (SMOS or any other) are not available, definitive conclusions and/or solutions will not be available and some unexpected problems might arise.

Currently, the following issues are well documented. Firstly, the most stringent limitation is the pixel heterogeneity because components may have very significant differences in behaviour. The surface covered by free water within the pixel, for instance, has to be known (better than 2% accuracy) to reach the overall accuracy of 4% per volume in soil moisture; water bodies can be variable as a function of season or weather. Secondly, vegetation is not totally opaque at L band, and when the integrated water content is above 4–5 kg /m^2, soil moisture data retrievals will be difficult and approximate. Hence, forested canopies will impact the signal. It may be

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noted at this level that recent studies showed that the main contributor at L band for a forest was the tree branches which do not emerge as rapidly as leaves; hence the reduced seasonal effect (Ferrazzoli et al. 2002). Tree litter on the ground may behave as a black body, seriously masking the soil's signal. During rain events, water interception by the canopy might artificially increase the apparent vegetation water content. Thirdly, topography will induce an altered angular behaviour, while fourthly, snow and frozen soils will induce different signals which, if not accounted for, will produce wrong estimates. Fifthly, urban areas, rocks, and other hard surfaces are not fully assessed in terms of emissivity. Finally, and generally speaking, good retrieval of soil moisture data will require some a priori knowledge of the surface cover and state, and the quality of the retrievals will be linked to the quality of the input data (Kerr et al. 2005). It must also be noted that systems like SMOS will bring inherent specificities and complexities such as image reconstruction (Anterrieu 2004), which is still a challenge.

Conclusion and perspective

After many unsuccessful attempts, a space mission that can determine soil moisture is now under way. Until launched and commissioned, the concept has to be proved but the elements now available instil confidence to such an extent that an operational SMOS follow-on is currently being studied. Nevertheless, SMOS, in answering some questions, still does not fulfil all the data needs, and ways forward must be sought. The most important, is probably to improve the spatial resolution and there the SMOS concept is close to an optimum, because increasing the arm's length will improve the spatial resolution but significantly degrade the sensitivity to the point that it would not be useful any more. So other techniques such as disaggregation, will have to be developed. To be more efficient, a SMOS-like instrument might gain from either being multi-frequency or having a coupled active system. It is expected that these solutions will be tested using existing sensors—Advanced SCATterometer (ASCAT) and AMSR-E)—when SMOS is operating. Another approach to improve spatial resolution could be to use even larger antennae, pending the possibility of deploying them effectively in space. In that case, to resolve the ambiguities, it will probably be necessary to improve the system by adding other frequencies while keeping the active source. This might also go some way towards addressing the cryosphere, another key element in the global water and energy budget of the planet.

It was stated in the SMOS proposal that the concept, though challenging, would provide a new type of sensor, opening up a challenging new field in measurement and paving the way for operational monitoring of water in soils, thereby making a long-awaited tool for water resources management and water cycle monitoring a real possibility.

References

Anterrieu E (2004) A resolving matrix approach for synthetic aperture imaging radiometers. IEEE Trans Geosci Remote Sens 42(8):1649–1656

Bayle F, Wigneron J-P, Kerr YH, Waldteufel P, Anterrieu E, Orlhac J-C, Chanzy A, Marloie O, Bernardini M, Sobjaerg S, Calvet J-C, Goutoule J-M, Skou N (2002) Two-dimensional synthetic aperture images over a land surface scene. IEEE Trans Geosci Rem Sens 40(3):710–714

Entekhabi D, Njoku EG, Houser P, Spencer M, Doiron T, Kim Y, Smith J, Girard R, Belair S, Crow W, Jackson TJ, Kerr YH, Kimball JS, Koster R, McDonald KC, O'Neill PE, Pultz T, Running SW, Shi J, Wood E, van Zyl J (2004) The Hydrosphere State (Hydros) Satellite Mission: an earth system pathfinder for global mapping of soil moisture and land freeze/thaw. IEEE Trans Geosc Remote Sens 42(10):2184–2195

Ferrazzoli P, Guerriero L, Wigneron JP (2002) Simulating L-band emission of forests in view of future satellite applications. IEEE Trans Geosci Remote Sens 40(12):2692–2708

Goutoule JM, Anterrieu E, Kerr YH, Lannes A, Skou N (1996) MIRAS microwave radiometry critical technical development. MMS, Toulouse, France

Han S-C, Shum CK, Jekeli C, Alsdorf D (2005) Improved estimation of terrestrial water storage changes from GRACE. Geophys Res Lett 32:L07302. DOI 10.1029/2005GL022382

Kerr YH (1998) The SMOS Mission: MIRAS on RAMSES. CESBIO, Toulouse, France

Kerr YH, Njoku EG (1990) A semiempirical model for interpreting microwave emission from semiarid land surfaces as seen from space. IEEE Trans Geosci Remote Sens 28(3):384–393

Kerr YH, Waldteufel P, Wigneron J-P, Martinuzzi J-M, Font J, Berger M (2001) Soil moisture retrieval from space: the Soil Moisture and Ocean Salinity (SMOS) Mission. IEEE Trans Geosci Rem Sens 39(8):1729–1735

Kerr Y, Waldteufel P, Richaume P, Davenport I, Ferrazzoli P, Wigneron J-P (2005) SMOS level 2 processor soil moisture ATBD. SM-ESL(CBSA), Toulouse, France, p 110

Le Vine DM, Griffis AJ, Swift CT, Jackson TJ (1994) ESTAR: a synthetic aperture microwave radiometer for remote sensing applications. Proc IEEE 82:1787–1801

Merlin O, Chehbouni AG, Kerr YH, Goodrich D (2006) A downscaling method for distributing surface soil moisture within a microwave pixel: application to Monsoon '90 data. Rem Sens Environ 101:379–389

Moran MS, Hymer DC, Qi J, Kerr Y (2002) Comparison of ERS-2 SAR and Landsat TM imagery for monitoring agricultural crop and soil conditions. Rem Sens Environ 79(2–3):243–252

Njoku EG, Li L (1999) Retrieval of land surface parameters using passive microwave measurements at 6–18 GHz. IEEE Trans Geosci Remote Sens 37(1):79–93

Pellenq J, Kalma J, Boulet G, Saulnier G-M, Wooldridge S, Kerr Y, Chehbouni A (2003) A disaggregation scheme for soil moisture based on topography and soil depth. J Hydrol 276(1–4):112–127

Schmugge TJ, Wang JR, Asrar G (1988) Results from the Push Broom Microwave Radiometer flights over the Konza Prairie in 1985. IEEE Trans Geosci Remote Sens 26(5):590–597

Wigneron JP, Ferrazzoli P, Calvet JC, Kerr YH, Bertuzzi P (1999) A parametric study on passive and active microwave observations over a soybean crop. IEEE TGARS 37(6):2728–2733

Wigneron J-P, Waldteufel P, Chanzy A, Calvet JC, Kerr Y (2000) Two-D microwave interferometer retrieval capabilities of over land surfaces (SMOS Mission). Rem Sens Environ 73(3):270–282

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