Description of Soil Moisture Retrieval Algorithm for ADEOS II AMSR

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1. ALGORITHM DESCRIPTION

To a large degree, the research in microwave remote sensing of soil moisture has focused on the forward modeling problem. This is the process of predicting the brightness temperature from soil properties using radiative transfer theory. When measuring soil moisture we must be concerned with inversion of this model. This is more difficult than forward modeling. There are five steps involved in extracting soil moisture using passive microwave remote sensing. These are; normalizing brightness temperature to emissivity, removing the effects of vegetation, accounting for the effects of soil surface roughness, relating the emissivity measurement to soil dielectric properties, and finally relating the dielectric properties to soil moisture.

In our approach, soil moisture retrieval is based upon an algorithm developed by Jackson (1993). Brightness temperature for a single AMSR channel (6.9 GHz H) is converted to emissivity using a surrogate for the physical temperature of the emitting layer. This emissivity is corrected for vegetation and surface roughness to obtain the soil emissivity. The Fresnel equation is then used to determine the dielectric constant. Finally, a dielectric mixing model is used to obtain the soil moisture. The theory describing this follows.

Fundamental basis for a smooth bare soil. The measurement provided is the brightness temperature, T_B, that includes contributions from the atmosphere, reflected sky radiation, and the land surface. Atmospheric contributions are negligible at frequencies <6 GHz. Galactic and cosmic radiation contribute to sky radiation and have a known value that varies very little in the frequency range used for soil water content observations (T_{sky} ~4 K). The brightness temperature of a surface is equal to its emissivity (e) multiplied by its physical temperature (T).

Based upon the above, the equation for T_B is

$$T_B = eT + [1 - e]T_{sky} \qquad (1)$$

The second term of equation 1 will be on the order of 2 K and will be dropped for computational purposes. For inversion equation 1 is rearranged as follows

$$e = \frac{T_B}{T} \qquad (2)$$

If the physical temperature is estimated independently, emissivity can be determined. This can be done using surrogates based on satellite surface temperature, air temperature observations, or forecast model predictions.

There are two important relationships that must be utilized to relate the sensor measurement to soil water content. In the first it is necessary to link the sensor measurement to a basic property of the soil that changes with water content. By assuming that the target being observed is a plane surface with surface geometric variations and volume discontinuities much less than the frequency, only refraction and absorption of the media need to be considered at low frequencies such as L band (at higher frequencies scattering must be included). This permits the use of the Fresnel reflection equations (Ulaby et al., 1986). These equations predict the surface microwave reflectivity as a function of dielectric constant (relative permittivity) of the target (ε_r) and the viewing angle (Θ) based on the polarization of the sensor, horizontal (H) or vertical (V). At these frequencies the reflectivity is equal to 1 minus the emissivity. The Fresnel equations can be simplified by including only the real part of the complex dielectric constant (the imaginary part of the complex dielectric constant is relatively small and often ignored). This simplification makes it possible to invert the Fresnel equations to solve for ε_r' given the measured emissivity.

$$e_H(\Theta) = 1 - \left| \frac{\cos\Theta - \sqrt{\varepsilon_r - \sin^2\Theta}}{\cos\Theta + \sqrt{\varepsilon_r - \sin^2\Theta}} \right|^2 \quad (3)$$

$$e_V(\Theta) = 1 - \left| \frac{\varepsilon_r \cos\Theta - \sqrt{\varepsilon_r - \sin^2\Theta}}{\varepsilon_r \cos\Theta + \sqrt{\varepsilon_r - \sin^2\Theta}} \right|^2 \quad (4)$$

For a bare soil surface, the target consists of an interface of air and soil plus a shallow contributing layer at the top of the soil column. Since the dielectric constant of air is a known value (~1), the reflectivity provides a measurement of the dielectric constant of the soil. The Fresnel equations apply when the two media at the interface each have uniform dielectric properties within the contributing depth. Although this is certainly valid for air, however, for a soil surface this is not always a valid assumption. It should also be noted that the basic formulations in equations 3 and 4 result in a larger dynamic range or sensitivity of emissivity to changes in the dielectric constant for H polarization. It is possible to invert equation 3 to solve for the dielectric constant given the measured emissivity.

The next critical relationship involves relating this derived dielectric constant to volumetric soil water content. The dielectric constant of soil is a composite of the values of its components: air, soil and water. Although the dielectric constant is a complex number, for soil mixtures the real part is much more important and variable. Values of the real part of the dielectric constant for air and soil particles are approximately 1 and 5, respectively. For water the value of the dielectric constant varies with frequency and is about 80 at the lower frequencies considered here (<6 GHz) (Ulaby et al., 1986).

The basic reason microwave remote sensing is capable of providing soil water content information is this large dielectric difference between water and the other soil components. Since the dielectric constant is a volume property, the volumetric fraction of each component must be considered. The computation of the mixture dielectric constant (soil, air and water) has been the subject of several studies and there are different theories as to the exact form of the mixing equation (Schmugge, 1980 and Dobson et al., 1985). A simple linear weighting function is typically used.

The dielectric constant of water referred to above is that of free water in which the molecules are free to rotate and align with an electrical field. It has been recognized for some time that not all the water in soil satisfies this condition. Schmugge (1980) suggested that some water in the soil had different properties. He proposed that for a given soil this could be estimated using soil texture in much the same way that pedo-transfer functions are used to estimate 15 bar and 1/3 bar water contents based on texture (Rawls et al., 1993). He proposed that the initial water added to dry soil below a "transition" water content were held more tightly by the soil particles and had the dielectric properties of frozen water (~3).

Vegetation and Surface Roughness. For natural conditions, varying degrees of vegetation will be encountered. The presence of vegetation will have a major impact on the microwave measurement. Vegetation reduces the sensitivity of the retrieval algorithm to soil water content changes by attenuating the soil signal and by adding a microwave emission of its own to the microwave measurement. The attenuation increases as frequency increases. This is an important reason for using lower frequencies. As described in Jackson and Schmugge (1991), at lower frequencies it is possible to correct for vegetation using a vegetation water content-related parameter.

When there is vegetation, the observed emissivity is a composite of the soil and vegetation. To retrieve soil water content it is necessary to isolate the soil surface emissivity (e^{surf}). Following Jackson and Schmugge (1991), the equation describing this is

$$e_p = [1 - \alpha_{p,f,v}][1 - \gamma_{p,f,v}][1 + [1 - e_p^{surf}]\gamma_{p,f,v}] + e_p^{surf}\gamma_{p,f,v} \quad (5)$$

Both the single scattering albedo (α) and the one-way transmissivity of the canopy (γ) are dependent upon the vegetation structure (v), polarization (p) and frequency (f).

The transmissivity is a function of the optical depth (τ) as described by the following equation

$$g_{p,f,v} = \exp[-t_{p,f,v} \sec\Theta] \tag{6}$$

At low frequencies the single scattering albedo can be assumed to be negligible, then substituting equation 6 into equation 5 and rearranging yields

$$e_p^{surf} = 1 + [e_p - 1]\exp[-2t_{p,f,v} \sec\Theta] \tag{7}$$

The vegetation optical depth is also dependent upon water content (W). In studies reported in Jackson et al. (1982) and Jackson and Schmugge (1991), it was found that the following functional relationship between the optical depth and vegetation water content could be applied

$$t_{p,f,v} = b_{p,f,v} W \tag{8}$$

There is a limited database of values of b available. The vegetation water content can be estimated using a variety of ancillary data sources. One approach is to establish a relationship between w and a satellite based vegetation index such as the Normalized Difference Vegetation Index (NDVI) as described in Jackson et al. (1999).

The emissivity that results from the vegetation correction is that of the soil surface. This includes the effects of surface roughness. These effects must be removed in order to determine the soil emissivity (e^{soil}) which is required for the Fresnel equation inversion. One approach to removing this effect is a model described in Choudhury et al. (1979) that yields the bare smooth soil emissivity

$$e_p^{soil} = 1 - [1 - e_p^{surf}]\exp[-h_{p,f,g}\cos^2\Theta] \tag{9}$$

The parameter h is dependent upon the polarization, frequency and geometric properties (g) of the soil surface. Typically, values are assigned based upon land use and tillage (Choudhury et al., 1979 and Jackson et al., 1999).

2. OPERATIONAL IMPLEMENTATIONN

For each AMSR pixel, the latitude and longitude (from the input file) are used to cross reference to the land cover and NDVI ancillary data files. The third set of ancillary data files representing soil texture and porosity, is not mapped to any projection and the resolution is 0.083 degrees. The AMSR footprint is readily located in the soil texture file and its latitude and longitude are retrieved from the input file.

Land cover is first used to screen the data for the selected number of categories that can be inverted for soil moisture. This also removes water pixels. The next step is another screening to check for anomalous T_B values. Following this, an index developed by Ferraro et al. (1994) is used to screen out pixels with active rainfall. The final screening is a check of the surface air temperature from the AMSR files versus T_B.

Having passed all of the tests above, the footprint data is used to compute soil moisture. T_B is divided by an adjusted surface air temperature to estimate emissivity.

Vegetation correction is performed using the pixel NDVI to compute the vegetation water content. Surface roughness effects are removed utilizing a single roughness parameter, fixed at 0.1 at this time.

The net result of these corrections is the soil emissivity. From this the dielectric constant of the soil is computed. The value of the dielectric constant is then used with the dielectric mixing model and the soil texture and porosity to compute the volumetric soil moisture.

3. ANCILLARY DATA SOURCES

Land Cover

The University of Maryland Geography Department produced a global land cover data base at a resolution of 8 km which is available at http://glcf.umiacs.umd.edu/. The codes for the land covers are as follows;

1	Evergreen Needleleaf Forests
2	Evergreen Broadleaf Forests
3	Deciduous Needleleaf Forests
4	Deciduous Broadleaf Forests
5	Mixed Forests
6	Woodlands
7	Wooded Grasslands/Shrubs
8	Closed Bushlands or Shrublands
9	Open Shrublands
10	Grasses
11	Croplands
12	Bare
13	Mosses and Lichens

AMSR data over areas covered by cover types 1 – 6 cannot be used for retrieving soil moisture due to the effects of forests. Data over cover types 7 – 10 and 12 – 13 can be used for retrieval. Croplands are considered for soil moisture retrieval if the NDVI is less than 0.5. Thus, the new land cover types are:

0	ocean and inland water – more than 20% of footprint covered by ocean or by inland water
1	good for retrieval – more than 60% of footprint covered by wooded grasslands/shrubs, closed bushlands or shrublands, open shrublands, grasses, bare, mosses and lichens
2	reasonable for retrieval – categories listed in 1. occupied more than 30% of footprint and croplands less than 30%
3	conditional for retrieval – categories listed in 1. occupied less than 30% of footprint and croplands over 30%
4	limited for retrieval – more than 60% of footprint covered by croplands
5	unable for retrieval – more than 30% of footprint covered by evergreen needleleaf, evergreen broadleaf, deciduous needleleaf, deciduous broadleaf, and mixed forests and woodlands

NDVI

The technique used to incorporate vegetation effects requires NDVI information. These products are available from various sources and can be acquired and updated to reflect current conditions. The GLI team may generate data products that can be used for this purpose. However, since this is a research algorithm and arrangements to import ancillary data sets such as NDVI are not in our control, we are providing an alternative that should be adequate for most conditions in soil moisture retrieval.

We are providing a series of NDVI data sets that represent the historical averages for each 10 day period throughout the year. The algorithm will retrieve the NDVI data set that is closest in time (day of the year) to the observation date for the AMSR data. This NDVI data set then represents the average condition expected for this date. The quality of the estimate will depend upon how the current year deviates from the average. It might be possible in the future to adjust these values for the current conditions by tracking climatological information and comparing this to the year to year conditions in the records.

To develop the historical averages we used the Pathfinder AVHRR Land data sets. These are global, land surface data derived from the Advanced Very High Resolution Radiometers (AVHRR) on the NOAA/TIROS operational meteorological satellites (NOAA-7, -9, and –11) that have provided continuous daily and composite data set from July 1981 through the present. The daily and composite products include 12 data layers, (NDVI, CLAVR flag, QC flag, Scan Angle, Solar Zenith Angle, Relative Azimuth Angle, Ch 1 Reflectance, Ch 2 Reflectance, Ch 3 Brightness Temperatures, Ch 4 Brightness Temperatures, Ch 5 Brightness Temperatures, and Day of Year). The composite is generated by comparing the NDVI values for each 8 km bin from 10 consecutive Daily Data Sets. Because data at the edge of a scan may contain distortion and bi-directional effect biases, only data within 42 degrees of nadir are used in the composite. For each 8 km pixel, the day with the highest NDVI during a 10 day period is chosen as the date for inclusion in the composite, and all 12 data layers are updated with data from that date. This composite process is effective for removing most of the clouds and atmospheric contaminants, thus providing as close to a cloud free field in each of the data layers as is possible (Holben, 1986). There are three composites per month. The first composite of each month is for days 1 to 10, the second composite is for days 11 to 20, and the third composite is for the remaining days.

The NOAA/NASA Pathfinder Land data team has completed their software development and data reprocessing. Their data are distributed by the Goddard Distributed Active Archive Center (DAAC) (ftp://daac.gsfc.nasa.gov/data/avhrr/global_8km). Data are available from July 13, 1981 to the present. For this analysis, we only used data from 1982 to 1999. The NDVI composite is mapped in a global 8 km equal area grid using the Goode Interrupted Homolosine projection. There are (36*18) data sets. The original AVHRR Pathfinder NDVI 8 km 10-day composite data from 1982 to 1999 that were used in our processing are on CDROMs (18 of them).

For each pixel in a 10-day composite data set which is not ocean, inland water or filler, all data points that fall in a 7x7 box centered at that pixel were averaged. In the averaging process, if there were any ocean, inland water or filler pixels in the 7x7 box, these were not included in the average computation. After this process was completed for each individual NDVI data set, the values for each 10 day interval were averaged over the 18 year record to produce the average annual time series 10-day composite.

Soil Texture

The soil texture and porosity data sets are a result of a study to estimate global soil water-holding capacities by linking the Food and Agriculture Organization (FAO) soil map of the world with global pedon databases and continuous pedotransfer functions (PTF) (Reynolds et al., 2000). The FAO-UNESCO Soil Map of the World (SMW) at 1:5,000,000 is the most comprehensive soil map with global coverage. Great efforts have been made to relate the FAO soil units to physical soil characteristics by statistically analyzing global pedon databases to estimate soil texture, bulk density and organic matter content. The data set images produced by Reynolds et al. (2000) have a 5-min spatial resolution to preserve the spatial integrity of the SMW, which is equivalent to a 9 km x 9 km cell size at equator. Soil properties were estimated at two depths, i.e., 0-30 cm and 30-100 cm. Only the 0-30 cm depth is needed here. Three of these soil properties were placed in the ancillary directory; clay content, sand content and porosity.

4. REFERENCES

Choudhury, B. J., Schmugge, T. J., Chang, A. T. C., and Newton, R. W. 1979. Effect of surface roughness on the microwave emission of soils. J. Geophysical Research, 84:5699-5705.

Dobson, M. C., Ulaby, F. T., Hallikainen, M. T., and El-Rayes, M. A. 1985. Microwave dielectric behavior of wet soil, II, Dielectric mixing models. IEEE Trans. Geoscience and Remote Sensing, GE-23:35-46.

Ferraro, R. R., Grody, N. C., and Marks, G. F. 1994. Effects of surface conditions on rain identification using the DMSP-SSM/I. Remote Sensing Reviews, 11:195-209.

Holben, B. N. 1986. Characteristics of maximum-value composite images from temporal AVHRR data. International Journal of Remote Sensing, 7:1417-1434.

Jackson, T. J. 1993. Measuring surface soil moisture using passive microwave remote sensing. Hydrological Processes, 7:139-152.

Jackson, T. J. and Schmugge, T. J. 1991. Vegetation effects on the microwave emission from soils. Remote Sensing of Environ., 36:203-212.

Jackson, T. J., Schmugge, T. J., and Wang, J. R. 1982. Passive microwave remote sensing of soil moisture under vegetation canopies. Water Resources Research, 18:1137-1142.

Jackson, T. J., Le Vine, D. M., Hsu, A. Y., Oldak, A., Starks, P. J., Swift, C. T., Isham, J. and Haken, M. 1999. Soil moisture mapping at regional scales using microwave radiometry: the Southern Great Plains hydrology

experiment. IEEE Trans. On Geoscience and Remote Sensing, 37: 2136-2151.
fRawls, W. J., Gish, T. J., and Brakensiek, D. L. 1993. Estimating soil water retention from soil physical properties and characteristics. Advances in Soil Sciences, 16:213-234.
Reynolds, C. A., Jackson, T. J., and Rawls, W. J. 2000. Estimating soil water-holding capacities by linking the Food and Agriculture Organization soil map of the world with global pedon databases and continuous pedotransfer functions. Water Resources Research, 36:3653-3662.
Schmugge, T. J. 1980. Effect of texture on microwave emission from soils. IEEE Trans. on Geoscience and Remote Sensing GE-18:353-361.
Ulaby, F. T., Moore, R. K., and Fung, A. K. 1986. Microwave remote sensing: active and passive, Vol. III, from theory to application. Artech House, Dedham, MA.