Soil Moisture Estimation Using Radar Images (SMAP)

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ABSTRACT

Soil moisture can be estimated using microwave techniques (active and passive) which involves measurement of natural emissions from soil (passive) and radar backscattering (active),meanwhile taking care of soil roughness, vegetation cover, frequencies required, incident angle, polarization effects, and other parameters. Each of these techniques has their individual specialties and flaws. Therefore, to retrieve volumetric soil moisture within negligible error limits, NASA launched their SMAP mission on January 31st, 2015 which is basically a combined technique of Active and Passive methods. In this paper we will study active and passive models step by step along with their drawbacks and discuss about SMAP, its key features and its current goals.

1. INTRODUCTION

Soil moisture estimation is an important task that has been carrying on from the last several decades. The sole need of this comes because of its effect plant growth, ability to bind the soil and resist erosion, and its interaction with the global climate system. The information of soil moisture has proven useful in the times of floods and droughts. It is also been used for irrigation and management of diseases and pests. But a lack of real-time soil moisture data is a major problem in an effective management of water during irrigation. This over-irrigation not only cost the farmer money, it is also a cause of plant stress which reduces crop yield and profit. Therefore, soil moisture is estimation is important for applications varying from agriculture sector to understanding the land-atmosphere interaction to determine vehicle mobility.

Since decades, many methods have been invented for estimating soil moisture but very few became successful. Conventional methods for estimating soil moisture included gravimetric, capacitive sensors and neutron scattering were not able to provide large-scale, rapid data collection. Recent growth in remote sensing technology made possible the estimation of soil moisture using various parts of Electromagnetic spectrum. Such microwave techniques include both active and passive approaches, each of which having distinct advantages. Out of all previous space borne L-band synthetic aperture radar systems, which include SeaSat (1978), SIR-A (1981), SIR-B (1984), SIR-C (1994), JERS-1 (1992-98), and PALSAR (2006-2011), only SIR-C and PALSAR have multi-polarization capabilities. Some success in retrieving soil moisture has been achieved with these instruments (with bare soil) but none of them were specifically designed for soil moisture estimation purposes. In spite of this, the revisits provided by SAR method were actually after thirty or more days because of relatively small swath sizes which limits the hydrologic applications and the potential advantages of any time series retrieval approach. Due to all these problems, from more than 40 years, the absolute retrieval is soil moisture from radar observations is still a dream.

2. PASSIVE MICROWAVE SENSING

Passive method of estimating soil moisture exploits the large differences between the dielectric constant of dry soil (about 3 to 5) and wet soil (about 80). It incorporates measurement of intensity of natural emissions from the soil surface, which relates to the water content of soil, using a radiometer. The intensity measured, usually known as Brightness Temperature (T_B), is proportional to the product of emissivity and temperature of the surface. For a space orbiting radiometer, observed T_B will be the collective emission from the soil as attenuated by overlying foliage, vegetation cover, atmosphere and cosmic background. But for a simpler model, considering bare surface and emissions other than from soil surface to be negligible, it is seen that

$$T_B = eT_{soil}$$

where T_{soil} is the soil temperature and e is the soil emissivity, which depends on the dielectric constant of the surface. In spite of a linear relationship between Emissivity (e) and soil temperature (T_B), soil moisture shows a non-linear relationship with Emissivity (e) due to polarization of light and nonlinear dependence of emissivity on dielectric constant. Thus, soil moisture and soil temperature (T_B) share a relationship which is highly dependent on ground parameters like the surface roughness, soil composition, dielectric constant and vegetation biomass. Also, the adequacy of the measurement relies on the frequency band used (Njoku and Entekhabi 1996).

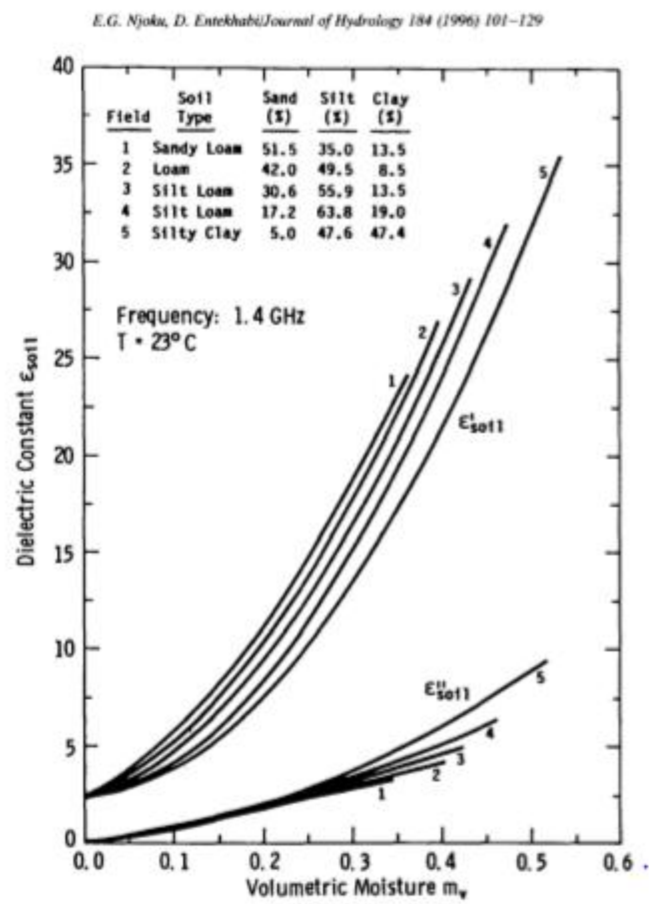

FIG: Dielectric constant vs Soil Moisture for different types of soil

3. ACTIVE MICROWAVE SENSING

Active microwave approach involves establishing a calibrated relationship between soil water content and radar backscatter. The backscatter (σ^0) is measured using a space based radar which is directly related to the soil moisture and other parameters of the ground. Empirically, a linear relationship has been found between soil moisture and backscatter values obtained over bare soil, ignoring the soil roughness (Dobson & Ulaby 1986, Holah et. al 2005).

$$\sigma^0_{db} = aM_v + b$$

The coefficients a and b were observed to be dependent on the incidence angle, frequency, polarization of light and ground parameters (Holah et. al 2005). For example, b is found to be greater for HH polarization, lower incidence angles and rough surfaces (N. Baghdadi 2006). Moreover, the efficacy of results improve with lower incidence angles as radar signal is much more sensitive to ground parameters at high incidence angles (N. Baghdadi 2006). Also, this primitive backscatter model fails to comply when the soil roughness and vegetation biomass is taken into account. Therefore, as in passive approach, the relationship between soil moisture and backscatter value require knowledge of ground parameters.

4. FREQUENCY SELECTION

The active and passive measurement of soil moisture can be done using all microwave frequencies but low microwave frequencies (at L-Band) provide greater advantages over higher ones like minimizing solar illumination effects on measurements allowing day and night experiment. L-Band frequencies are emitted from deeper in the soil at about 5cm or so, whereas C-Band (6 GHz) and X-Band (10 GHz) are emitted from 1cm deep or less of the soil. Also, low frequencies can penetrate through foliage up to a greater extent as compared to higher frequencies. However, at very low frequencies, manmade and galactic noise degrade the radiometric and radar measurements. Thus, L-Band (1.400-1.427 GHz) is preferred exclusively for active and passive technique for estimating soil surface moisture.

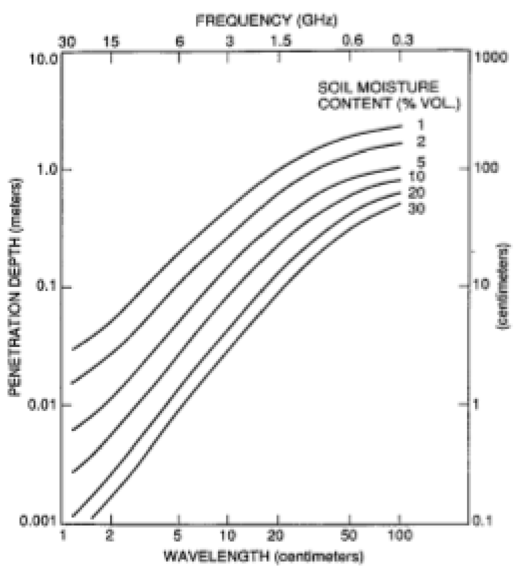

FIG: Variation of Penetration Depth with Wavelength for different soil moisture content (E.G. Njuko 1996)

5. SOIL TEXTURE

The soil composition or texture affects the microwave estimation of soil moisture in the way as different components of soil have different tendencies to hold water particles, thus changing dielectric constant from soil to soil. However, this effect is comparatively small to alter the observations drastically (Wang and Schmugge 1980).

6. SOIL ROUGHNESS

Under passive approach, soil moisture depends upon the reflectivity (1-e) of the surface. Reflectivity can be calculated easily for smooth surfaces using Fresnel equations but for rough surfaces, it becomes a tedious task. Surface roughness increases the emissivity of the surface which in turn decreases the soil moisture sensitivity (Newton and Rouse, 1980). For a rough surface, reflectivity can be stated as

$$r' = r \exp(-h\cos^2\alpha),$$

where r is the reflectivity of smooth surface, α is the incidence angle and h is the roughness parameter. It is found that reflectivity is very sensitive to soil roughness (Edwin T. Engman 1995).

However, roughness is not a major concern in case of passive use as compared to active use. Soil roughness affects the backscatter value as much as soil moisture. If we account for both, the soil moisture and the surface roughness, the radar signal in decibels can be stated as a combination of the linear function describing the dependence on the soil moisture, and the exponential (or logarithmic) function in terms of the roughness (N. Baghdadi 2006).

$$\sigma^0_{dB} = aM_v + £\exp(-k*rms) + \mu$$

where k is the wave number, £ and μ are coefficients depending on the surface reflectivity (or emissivity) and RMS is the root mean square surface height. As the rms surface height appears in the exponential, roughness sometimes outnumbers the effect of soil moisture on radar backscatter. To understand this problem, researchers have proposed many models. Oh et. al (1992) proposed an empirical model based on RMS roughness height, wave number and relative dielectric constant using multi-polarized lights and low incidence angles. This model worked well and adheres to the roughness domain. The more adaptive model to surface roughness is proposed by NASA in their SMAP program launched in the year 2014 (Level 2&3 Soil Moisture (Active-Passive)). Based on NASA's algorithm, a more empirical model can be stated taking a generalized function f(roughness) which will assume all the surface roughness characteristics, therefore,

$$\sigma_s = f(\text{roughness}) * \text{reflectivity of surface}$$

7. VEGETATION COVER

Biomass vegetation over the surface affect the radar measurements as vegetation adds to the total emission with its own and also attenuates the radiation flux coming from the soil surface. It also sets up the internal scattering between the foliage. This effect primarily depends upon the frequency, angle of incidence and the mass of vegetation. At low frequencies, these scatterings are very small and can, therefore, be neglected. The total radar backscatter from a vegetated surface is composed of three contributions:

$$\sigma = \tau^2\sigma_s + \sigma_{dv} + \sigma_{int}$$

where σ is the backscatter from the bare soil surface, τ is the two-way attenuation of the crown layer and is basically the vegetation opacity divided by cosine of incidence angle, σ_{dv} represents the direct backscatter from the vegetation layer, and σ_{int} is multiple scattering among the vegetation and the ground surface (Ulaby et al., 1996).Using generalized functions as in NASA's roughness model f, g and h assuming all roughness and vegetation characteristics, the above expression can be stated as

$$\sigma = f(\text{roughness}) * \text{reflectivity} + g(\text{vegetation}) + h(\text{vegetation, roughness}) * \text{reflectivity}$$

In case of passive method also, the vegetation attenuates, absorbs and emit the radiation emitted by soil before it reaches to radiometer. For simplicity, such vegetation layer can be taken as a homogeneous layer between air and soil. According to Njoku and Entekhabi, 1996 and Level 2&3 Soil Moisture (Passive), the brightness temperature can be formulated as

$$T_{Br} = e_p\, T_e \exp(-\tau) + T_c[1 - \exp(-\tau)][1 + r_p \exp(-\tau)](1-\omega)$$

where T_{Br} is the revised brightness temperature, T_c is the vegetation effective temperature, T_e is the soil temperature, ω is the vegetation single scattering albedo and e_p and r_p are the emissivity and reflectivity, respectively, of the underlying soil surface.

The magnitude of τ varies with the vegetation type like the geometrical structure of woody and leafy components, the moisture of the foliage which affects its dielectric properties, and the frequency.

These models become more and more unreliable with the increase in the moisture of the vegetation and their density.

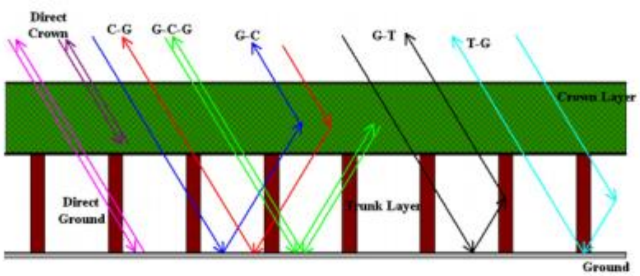

FIG: Effect of vegetation layer on microwave emissions

8. LIMITATIONS OF ACTIVE AND PASSIVE METHODS

Active and passive techniques, till far, are the most successful techniques but they also have various drawbacks. Most radars and radiometer use the idealistic property, the land being "bare" (without or very little vegetation) which is true for only 14% of the time but not always. Most of the existing algorithms and functions are designed for bare soil, like the Empirical or semi-empirical, Integral Equation Model and the numerical inversion of the IEM were all successful for bare soils. Based on the above discussion, it is crucial that the primitive models for active and passive approaches need to be modified considering vegetation, soil roughness, texture and other parameters. But, in spite of building compatible models, there still exist reliability issues with these models as the uncertainties in the result can increase anytime depending on the environmental factors.

As said above, vegetation, roughness and soil moisture all affect radar measurements, it is not possible to retrieve absolute soil moisture from a single radar observation. It becomes more feasible with multiple observations having multi polarizations and varying incidence angles. Passive method of soil estimating does not meet the requirements for measuring soil water content in watershed areas but active method does in such areas (M. Susan Moran 2004). However, passive method provides better spatial resolution and frequent revisits as compared to active method. Hence, each of these has distinct advantages and disadvantages over each other. This has lead to the evolution of a new approach which is a combination of active and passive.

9. SMAP – SOIL MOISTURE ACTIVE PASSIVE

NASA developed a new active-passive algorithm that draws all the key features as stated above in the active and passive models, under special conditions concerning vegetation and roughness, with the objective to determine soil moisture at a initial spatial resolution of 40km within an error limit of $0.04 m^3 m^{-3}$ in the top 5 cm of the soil for vegetation water content less than 5Kg m^{-2} and an average 3-day revisit intervals over the global land area.

The L2_SM_AP algorithm merges the active passive measurements to produce soil moisture retrieval with intermediate resolutions to meet the LEVEL 1 demands. This algorithm is focused on the brightness temperature (T_b) using backscattering patterns inferred from the radar measurements. To mitigate the variations due to the variability in vegetation mass, the radar observations within radiometer impression are scaled via parameters that are derived from the temporal fluctuations in the radar and radiometer measurements.

The SMAP L-band radiometer reads the natural thermal emission as the brightness temperature (T_B) of the soil surface, while the L-band radar observes the backscattered energy (σ) from soil after transmission of an electromagnetic pulse. The two readings are combined together in accordance with the above equations and (e= 1-r), a linear relationship is obtained between T_B and σ.

$$T_B = \alpha + \beta.\sigma$$

The constants and are dominantly dependent on the vegetation and roughness profiles and can be calculated using the above equations. This relation is further improved to obtain a greater spatial resolution of 9 km.

KEY FEATURES:

1. Large Antenna - Radar and radiometer share the same large antenna which collects all the radio waves and focuses them into the feed horn. These echoes are further sent for processing. The antenna reflector is a mesh antenna 6 meters (about 20 feet) in diameter. It is not due to such antenna size SMAP has reached the goal of 40Km effective ground resolutions

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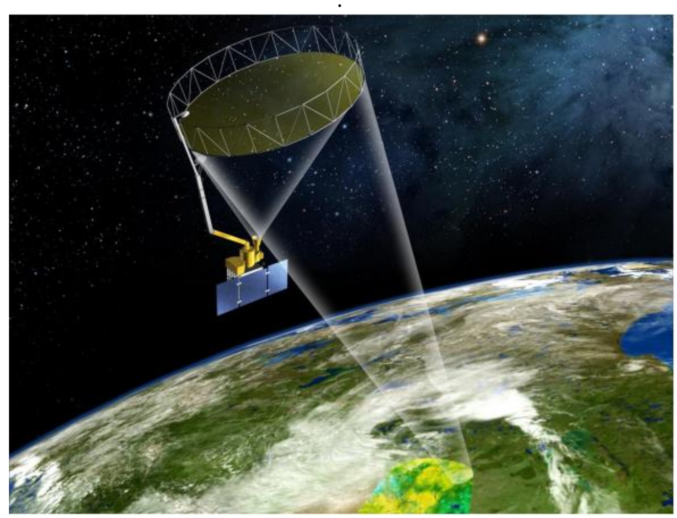
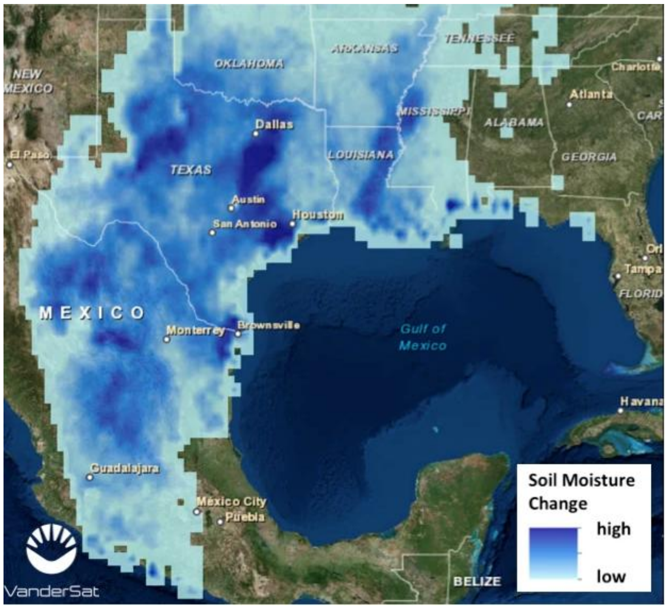


2. Use of the 6:00 AM Descending Node Orbit for the Primary Mission Product - The vertical profiles of soil temperature and dielectric properties are more uniform at 6:00 am than rest of the day. This will minimize the difference between canopy and soil temperatures and thermal differences between land covers within a pixel and help to minimize errors in the soil moisture calculations.

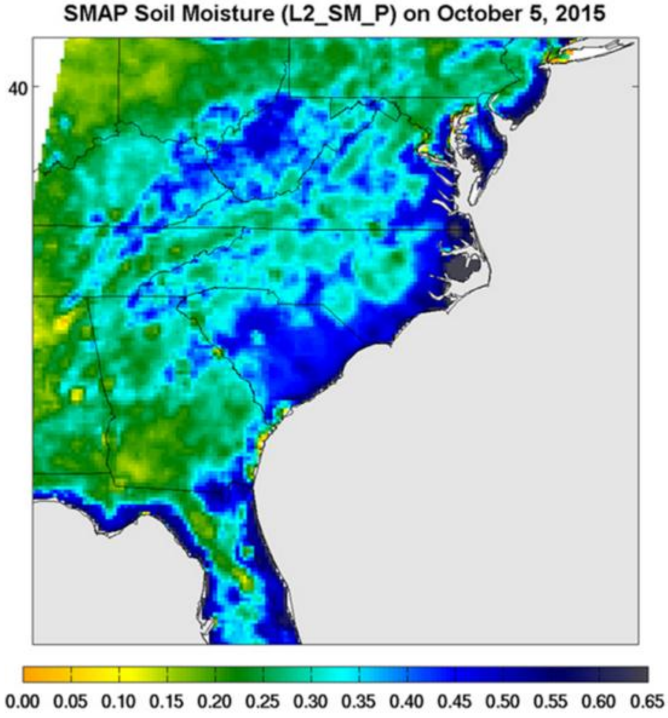
10. RESULTS OF SMAP

SMAP has been successful with great results. Some of its great achievements are as follows. With the help of data from SMAP, researchers were able to imagine Hurricane Patricia's coarse. The figure below shows the intensity map of the soil moisture change (i.e. light blue shows a small increase, dark blue shows strong increase in soil moisture) right after Hurricane Patricia passed the continent as seen by NASA's mission SMAP.



Also, SMAP data show that many parts of Southeastern Carolina appear blue, indicating heavy impacts of rains and flooding on Oct 5, 2015 as shown below.

SMAP Soil Moisture (L2_SM_P) on October 5, 2015



11. PRESENT SCENARIO

After successfully accomplishing its level 2 & 3 objectives, SMAP is currently working on its Level 4 plans to measure root zone soil moisture till the depth of 1m below the soil with a spatial resolution of 9 km downscaled from 40 km and more frequent revisits. SMAP has released its Level 4 beta (i.e. calibrated) product and is planning to release the validated product in mid 2016. Also, SMAP need to mitigate more reliably with the contamination produced by Radio Frequency Interference in the radiometer and radar measurements. They should use selective filters and carrier frequency stabilizers to set to already known RFI-free portions of L-Band while on orbit. They can also use Doppler discrimination and kurtosis detection to survive this problem.

SMAP was launched with a view of 3 year functioning but seeing its current state, it can be extended for more duration.

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