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Performance evaluation of a newly in-house developed in-situ soil moisture sensor with standard industrial sensors and gravimetric sampling

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Abstract: The calibration and validation of satellite derived soil moisture products heavily relies upon an accurate source of ground truth data as an accurate in-situ soil moisture information plays an important role in proper error estimation and further improvement in satellite derived soil moisture products. For proper validation of satellite derived soil moisture products at large scale, dense network of in-situ sensor with high accuracy and robustness under adverse conditions are required. In this work, In order to reduce the overall cost of such a dense soil moisture network of sensors, Smart Soil Sensor for Hydrology and land Applications (SHOOL) was designed and developed which is a highly compact and robust sensor, suitable for in-situ measurements of soil properties (dielectric constant, electrical conductivity, soil moisture, soil temperature etc. In-house developed SHOOL was further exclusively tested and validated using commercial probes and gravimetric sampling methods in various crop fields. Performance of in-house developed sensor was also evaluated using performance metrics which includes statistical measures R^2 (coefficient of determination), bias, ubRMSE and RMSE. The SHOOL performed satisfactorily over a large range of soil moisture (from dry to wet) with respect to gravimetric methods and commercial probes. It was observed that SHOOL has shown better performance and in good agreements with commercial probes. Overall, in-house developed sensor (SHOOL) has high potential to be a simpler and economical alternative to the industrial sensors and would be helpful in development of a dense sensor network for validation of satellite derived soil moisture products at various scales.

Keywords: Soil Moisture, Frequency Domain Reflectometry, Gravimetric sampling, Soil salinity.

1. Introduction

Soil moisture is one of the important parameters in the hydrological cycle to drive weather conditions, plant growth, groundwater storage, etc.; thus, it has a role in global climate (Vereecken et al. 2008). Soil moisture consists of only 0.05% of the total water in the global hydrological cycle (Robinson et al., 2008) and 0.001% of the total available freshwater (Drinkwater et al., 2009), but it has been declared as one of the Essential Climate Variable (ECV) due to its important role in the hydrological cycle.

Coarse scale at moderate temporal resolution global surface soil moisture can be obtained by satellite remote sensing, mostly by microwave sensors (Wagner et al., 2013). Currently several satellite missions provide global surface soil moisture products, such as: Soil Moisture Active Passive (SMAP) (Entekhabi et al., 2010) and METOP-A/B Advanced Scatterometer (ASCAT) (Wagner et al., 2013). Recently, Space Applications Centre (SAC), ISRO also adopted a modified version of ASCAT operational algorithm based on change detection (time series methodology) and developed daily operational soil moisture products using SMAP L-band brightness temperature data at 12.5 km grid resolution over India which is available at MOSDAC and VEDAS web portal of SAC (ISRO) (Pandey D. et al., 2016). Development of a time-series based methodology for estimation of large area soil wetness over India using IRS-P4 microwave radiometer data (Thapliyal et al., 2005), these Soil Wetness Index (SWI) and Soil Moisture (SM) data products have wide applications in agriculture productivity assessment, crop-water stress assessment, flood and drought monitoring and meteorological applications etc. Before their applications to solving various scientific or societal problems in different applications, satellite derived soil moisture data products have to be evaluated, and their validity and accuracy have to be assessed by using in-situ or reference data.
As a standard practice for validation of satellite derived soil moisture products, in-situ data are used as a reference, using field portable soil moisture probes or fixed station during field campaign. The validation of large-scale satellite-based soil moisture products from microwave radiometers typically faces the problem of the scale difference with in-situ observations because satellite derived products represents a field mean of large area. So in order to validate satellite derived soil moisture using in-situ data, more number of spatially distributed in-situ soil moisture measurements within satellite footprint are required to represents field mean of soil moisture. This brings us to the immediate need for designing and developing a cost effective soil moisture sensor which could be used to make dense soil moisture networks by installing more number of sensors within satellite footprint at low cost with required measurement accuracy as per the science requirement.

The study aims at the evaluation of newly developed in-house sensor having salient features of low cost, low weight, highly compact, field friendly, which can measure in-situ soil electrical properties, process it and directly transmit the data to the user via smartphone or ftp server. Probes are inserted in soil to provide soil dielectric, conductivity, moisture and temperature measurement with

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a good accuracy. It is fully controlled and operated by android app which user can install and do the field measurements using smart phone. The device is compact and standalone with capability such as wireless interface for app, long lasting battery and robust for field applications. Field calibration and validation campaign was completed to evaluate the performance of the developed sensor for measurement of surface soil moisture.

2. Materials and methods

This study aims at performance evaluation of two industrial sensors; MP306 (ICT International) and Stevens Hydra Probe (Stevens Water) and a newly in-house (SAC-ISRO) developed in-situ soil moisture sensor. Frequency Domain Reflectometry (FDR) based Industrial measures soil dielectric constant and based on dielectric mixing model, calculates soil moisture in volumetric percentage. Inter-comparison and performance evaluation of probes are done through statistical parameters such as: Bias, Root Mean Square Error (RMSE), Unbiased Root Mean Square Error (ubRMSE) and Coefficient of determination (R^2).

2.1 Operating principles of sensors

Indirect measurement of soil moisture is popularized by the principle algorithms that process the raw Analog to digital converter (ADC) values to derived soil moisture equations or dielectric constant and conductivity (Figure 1). A comparative study and their use in standard field validation practices is described here.

2.2 Measurement of soil moisture by standard ICT probe

The MP306 moisture probe is used for measuring the moisture of soil and also moisture of material used in mining, roadways and buildings. The MP306 ICT Probe takes continuous measurement for a particular range of time using permanent or temporary burial and connection to a soil moisture meter. Soil moisture meter contain high frequency moisture detector which follows the property of standing wave principle that calculates the variation in incident and reflected wave. MP306 has a compact body with data logger for displaying the calculated parameters via the MP306 probe. Needles are arranged in one plane which makes it ideal for use in soil columns. Principally, it detects any change in the volume matrix ratio of water which substantially reflects change in the dielectric constant of the matrix. Change in dielectric constant is indicative of the change in water content of soil sample.

2.3 Measurement of soil moisture by standard Stevens Hydra probe

The Stevens hydra probe is the dielectric constant sensor which provides the simultaneous soil moisture, salinity of the soil, temperature, dielectric permittivity and electrical conductivity of the soil. Marine grade stainless steel tines using high grade epoxy potting makes hydra probe a robust sensor. It has basically three major components: cable, sensor and tines. Hydra probe has a wave guide which sends the electromagnetic waves which is received by the center tine. The body of hydra probe contains microprocessors, circuit boards and all the required electrical components. The four tines in hydra probe are 5cm in length that is suitable for surface measurements and wiring could be extended up to 2 meter based on use.

2.4 Measurement of soil moisture by in-house developed in-situ soil moisture sensor

The in-house developed sensor is an integrated smart soil sensor, which is designed based on modular approach. Voltage signal is sent across the active electrodes and raw ADC values are processed to get dielectric constant and electrical conductivity, which is further utilized in deriving soil moisture. High grade stainless steel probes are penetrated in soil for moisture measurement, multiple probes are multiplexed along a hub to increase the volumetric sample area and via a communication module data is sent to the in-house developed android app. Also the data could be uploaded to cloud servers via smart phone. Standard battery pack of 5V is enough to power the device and lasts a day long and an additional temperature sensor is provided to the device for measurement of soil temperature at the same depth which is used for correction of raw measured Dielectric Constant (DC) and Electrical Conductivity (EC).

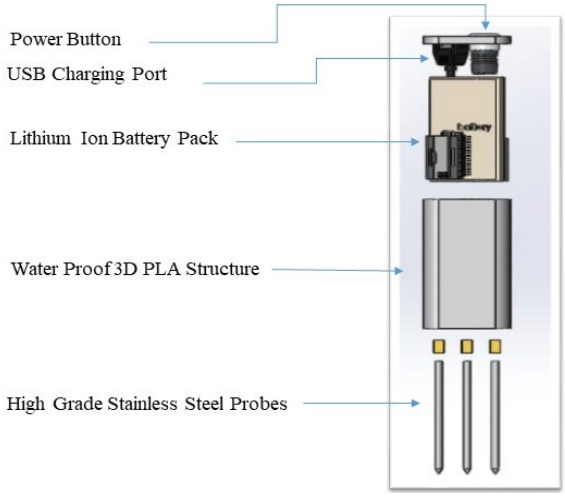

Figure 1: Concept Note

2.5 Data acquisition and processing

2.5.1 HYDRAMON App for Hydra Probe

Hydramon App is particularly used for the data logging of Stevens Hydra Probe which display the sampled readings (data) on the screen for review, received from the processor in Hydra probe. App could be interfaced with the Hydra probe via its Wi-Fi network named "Pogo". This app makes Hydra Probe a modern sensor by eliminating the need of data logger as the data is logged in the smartphone itself. The Hydramon app has a front display screen that shows different parameters of the soil: raw ADC reading with derived pore water electrical conductivity, raw real dielectric permittivity, raw imaginary dielectric permittivity, soil temperature in Fahrenheit or Celsius, soil moisture percentage and bulk electrical conductivity. The soil measurement is stored in .csv format and can easily be emailed for further analysis.

2.5.2 ICT probe Data Logging:

MP306 has hand held meter for receiving the output which is connected through a cable length of 4.5 meter (can be extended by using suitable cable) shows the volumetric water content present in the soil (VSW%). The meter provides power to the MP306 ICT for the reading, storage and to display the values. MP306 is connected to a set of chrome extension rods which have T handle on the end with connect the hand held meter when being used. Input voltage required for enabling the probe is 7-18 V DC unregulated.

2.5.3 Android App for in-house developed Sensor

In order to make the in-house sensor field friendly an app interface was developed to visualize the data (Figure 2). For field purposes the stop-&-go functionality is very important and the app designed aims to fulfil that. To sample a large area of field within a short duration, sampling time has to be reduced; therefore, digital data logging has an important role to play. For post processing purpose is logged in a tabular file format that could easily be taken up on laptop/PC for data analysis. Note-taking and field photograph capability is also embedded in the app as it is important to understand the field condition like soil properties, crop type, field undulations, rainfall, etc.

2.5.4 Features of the developed app

a) Bluetooth interface
b) Date & time of observation
c) Latitude and longitude of position
d) Dielectric permittivity (temperature corrected)
e) Soil moisture (in %)
f) Electrical conductivity (ds/m)
g) Soil temperature
h) Report field condition as notes
i) Data logging capability as .csv format
j) Data visualization through in-built viewer
k) Data sharing through Gmail, WhatsApp, Bluetooth etc.
l) Field photographs

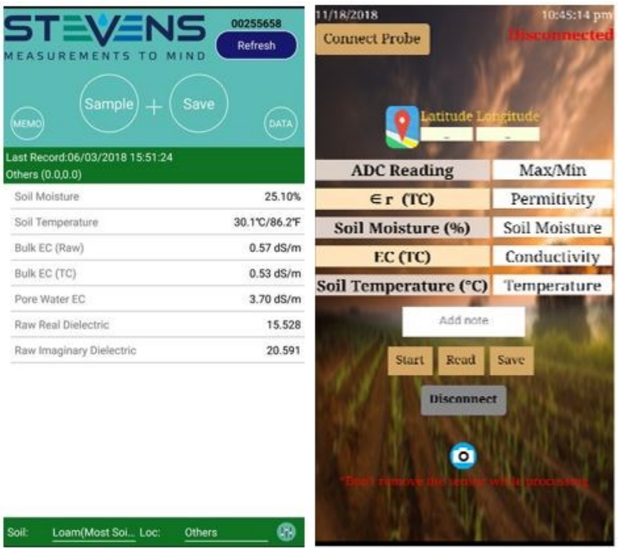

Figure 2: (a) Hydramon App; (b) Android app for in-house sensor

2.6 Measurement of soil moisture content by gravimetric method

Soil moisture measurement through gravimetric method represents the ratio of the mass of water content present in the soil sample to the dry weight (drying in the oven) of the soil sample or also it is defined as the ratio of volume of water to the total volume of soil sample. This can be achieved by calculating weight of the wet soil sample and second sampling after drying in the oven for at least 24 hours at 100°C to 110°C temperature. Difference between both the weights gives water mass. Temperature 100-110°C shows the boiling point of the water and it does not consider the physical and chemical property of the soil. For calculating soil moisture by gravimetric method some precision value of ±0.001 g is added to balance out the variations.

2.6.1 Material

1. Oven dry operating at 100-110°C
2. Tool to collect soil sample
3. Aluminum cans

2.6.2 Procedure

Weight of the can is calculated before taking the soil sample and recorded for further calculation. Soil sample is taken according to the size of can and weight is measured on a calibrated weighing scale. Can containing the sample is placed in the oven at the temperature of 100-110°C. After 48 hours (According to AAU observatory) sample is taken out and weight value is recorded (dry soil + can). Soil moisture is then calculated according by standard formula and procedure repeated for different soil samples.

$$Ratio = \frac{(Wet\ wt. - Can\ Wt.) - (Dry\ wt. - Can\ Wt.)}{(Dry\ wt. - Can\ wt.)}$$

$$\%SM = Wt.ratio * Bulk\ Density * 100$$

3. Validation

For absolute validation through gravimetric analysis, ground truth was carried out in and around Anand Agricultural University (AAU), Anand District, Gujarat (India). Anand Agricultural University has diverse field conditions and therefore it is suitable for validation. Most fields were harvested or being ploughed. Sandy-loamy soil is present with some amount of clayey soil. Gravimetric sampling facility available in observatory building was utilized for sampling and procedures. Sample collected from field was oven dried at 105°C for 48 hours. Soil moisture within Anand Agriculture University (AAU) varied from 10 to 35 volumetric percentage. Sensor Soil moisture measurement are plotted on single graph to create a comparative study. All the sensors follow similar pattern of variations which represents either field variability or some error in measurement when they are located within a 5 cm radii as shown in figure 3. Following graph is linear representation of measured soil moistures by various probes. Surface soil moisture measured using in-house developed sensor and commercial sensor was compared with gravimetric sampling techniques (Figure 4).

Figure 3: (a) Soil sampling at 5 cm, (b) Placement of sensors around sampling site and (c) Oven drying samples

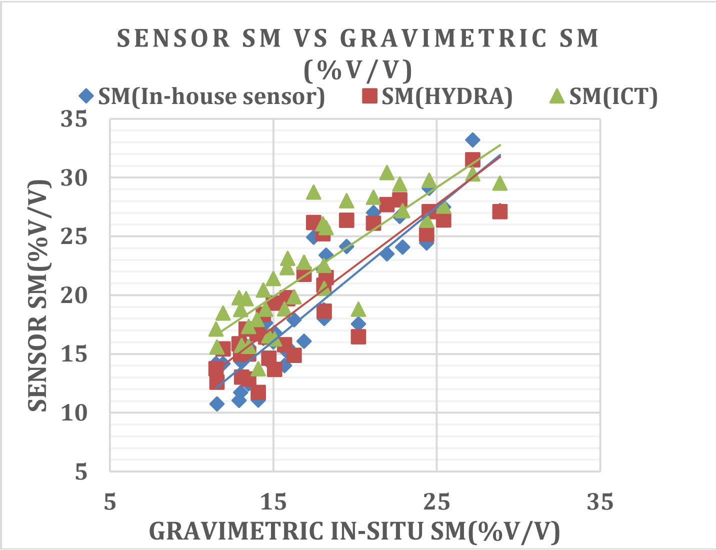

Figure 4: Graphical representation of Sensor measured SM Vs. Gravimetric measured SM

4. Statistical analysis

Performance matrix was generated to determine field capabilities of the sensors being tested. Comparatively in-house sensor showed least bias among the three sensors owing to its higher degree of calibration before field use and RMSE was found to be 2.94 which falls below prescribed accuracy standards of industrial SM measurement (Table 1).

Table 1: Performance Metrics for field validation of sensors

Comparison of in-house sensor & Commercial probes with Gravimetric samples			
Parameters	IN-HOUSE SENSOR	HYDRA	ICT
Bias(%)	1.45	1.68	4.7
RMSE	2.94	5.21	5.42
ubRMSE(%)	2.56	4.93	2.7
R^2	0.82	0.74	0.72

Unbiased RMSE (Instrument Prediction Error) is also found to be close to the other two sensors which validates the capability of in-house sensor to measure field soil moisture accurately. Results shows that based on the four parameters, sensor with extensive field calibration are able to perform estimation with better accuracy and capture field variation across various soil types. Therefore, it is suggested to calibrate the industrial sensor before approaching for in-situ accurate soil moisture measurement.

5. Results and discussion

Surface soil moisture measured using commercial and in-house developed sensor was evaluated across different fields by gravimetric sampling techniques (Figure 4). Results obtained were analyzed using performance metrics which includes statistical measures R^2 (coefficient of determination), bias, ubRMSE and RMSE (Table 1). The sensors performed satisfactorily over a large range of soil moisture with respect to gravimetric methods and in-house sensor has shown better performance and good agreement (Figure 5) with industrial requirements of soil moisture probes. This in-house developed sensor has high potential to be a simpler and economical alternative to the industrial sensors and would be helpful in development of a dense sensor network for validation of satellite derived soil moisture products at various scales.

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