ASTERRA
Technology by Utilis

# Using L-Band Synthetic Aperture Radar to Map Soil Moisture Content

ASTERRA EarthWorks Technology

A White Paper

## Introduction

ASTERRA uses satellite data from L-Band synthetic aperture radar (SAR) instruments to detect underground soil moisture. They have been doing this successfully for over five years, detecting water leaking from potable water pipe systems, with multiple patents secured. ASTERRA has branched out to detect soil moisture from multiple water sources and for industries spanning the full infrastructure market (water, wastewater, pavement, rail, road, dams, and mining activity). The later set of markets (outside of water and wastewater) are being employed in their product line called EarthWorks. This paper outlines the steps that ASTERRA has taken to validate the EarthWorks technology.

## Summary

A recent study measured soil moisture data using traditional methods, in this case, lab-testing field-collected soil samples for gravimetric water content (GWC) and used this data to calibrate data provided by ASTERRA EarthWorks, which uses algorithms to interpret SAR images taken by satellite. The study also examined whether the additional data layer provided by ASTERRA could help identify at-risk infrastructure due to soil moisture so that damage, danger to the public, and cost can be contained with a proactive response.

The experiment demonstrated that ASTERRA EarthWorks, which provides soil moisture mapping to identify at-risk infrastructure, does indeed provide a useful and valuable new data set. This new data can locate areas of subsurface moisture that translates into drainage problems or geotechnical instabilities near critical infrastructure; individual locations can then be prioritized for investigation, inspection, and mitigation.

## Background

There are several methods currently in wide use to determine soil moisture content.

- One, the laboratory method, physically determines the gravimetric water content (GWC) through laboratory testing of soil samples. This is a labor-intensive process in which soil samples are collected by field technicians and then brought to a lab where they are weighed, heated in an oven, and then re-weighed.
- The direct field test method is another, in which a field technician uses a time-domain reflectometry (TDR) meter. A probe attached to the meter is inserted into the soil and quickly provides the volumetric water content (VWC).

Both methods have limitations, specifically when measuring at depths (Zhang et al. 2020; Koyama 2017; Hajj et al. 2018). In addition, both methods can only examine the moisture from the precise depth a sample is taken, or at the entry point of each probe. They do not allow for the assessment of a wide area. Both require the extensive use of ground crews. The field test method, TDR, has a restricted data range compared to the laboratory test method.

ASTERRA has commercialized a method to measure soil moisture remotely. This involves using synthetic aperture radar (SAR) data acquired from satellites. This is an established technology that uses microwaves and was first introduced in the 1980s. SAR uses a band of the microwave spectrum known as the L-band, which operates on a frequency of 1–2 GHz and a wavelength of 15–30 cm. The long L-band wavelength can penetrate the soil to various depths, depending on soil conditions.

In addition, because satellite-based SAR is being used, ASTERRA can use it to examine a much wider area, with single satellite passes measuring up to 3,500 sq km (1,359 sq miles). This is not practical or even possible using field technicians and ground crews. SAR also penetrates clouds and dust, plus vegetation and pavement, giving it access to areas where field crews could not easily reach or collect samples.

In this study, ASTERRA gathered data derived from satellite-based instruments using SAR L-band. In-situ data was also collected and measured within the laboratory, individually measuring the gravimetric water content of hundreds of field soil samples collected from topsoil layers, from two different regions: the M1 J18 Crick interchange in England; and the Fort William-Mallaig railway in Scotland. Samples were collected at different times, then transferred to a laboratory for gravimetric moisture testing.

The in-situ data were collected in the field at or around the time that the satellite passed over the area so that the datasets would be measuring in the same environmental conditions. This is important when using the in-situ data to calibrate the EarthWorks satellite-derived data.

# The Study

## Study Sites

Two different regions were selected for this study:

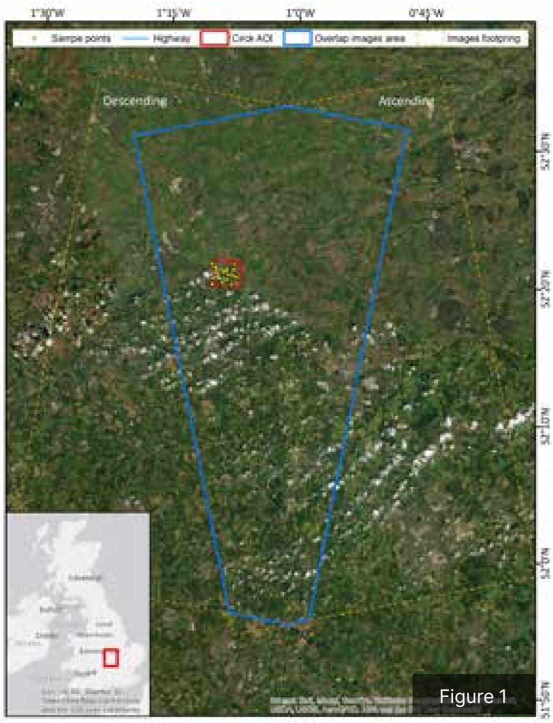



**Figure 1**. Crick Interchange Site: Rectangles outlined in blue and dashed blue lines in figure 1 describe descending and ascending view angles of an 11.7 sq km (4.5 sq miles) site located near the M1 J18 Crick interchange at Northampton, UK.

**Figure 2**. Scotland rail line site: the blue rectangle represents the SAR image footprint. Transecting the image is a 66-km (41-mile) section of rail line (red) known as the Mallaig-Fort William line in northwest Scotland.

## Acquisition of Soil Samples and SAR Images

The chart below outlines the timing and location information of the sampling and ALOS-2 SAR images.

| Study Site | Sampling Day | Satellite Direction | SAR Image Taken, BST | Sampling Period | Sample Quantity |
|---|---|---|---|---|---|
| Crick | 1 | Descending | May 3rd., 2018 **13:22** | 9:30 am – 4:30 pm BST | 60 |
| Crick | 2 | Ascending | May 4th – 5th, 2018 **00:44** | 21:00(4th) – 2:00(5th) BST | 60 |
| Scotland | 1 | Ascending | October 23rd, 2021 **23:53** | 22:00(23rd) – 2:30(24th) BST | 120 |
| Scotland | 2 | Ascending | June 2nd – 3rd, 2021 **00:44** | 22:00(2nd) – 2:30(3rd) BST | 120 |

# Study Parameters

### Weather

Crick Site: May 3, 2018, was 6-10 C°, clear sky, no rain; clouds but no rain appeared around 15:00 BST. During the nighttime acquisition on May 5, 2018, heavy dew was noted.

Scotland Site: Rain on October 23-24, 2020, averaged about 30mm, with heavy rain reported during the sampling. June 2-3 was reported clear and cold.

### Sample Collection Process

1. The upper organic soil layer was excavated by hand shovel and sampled. Leaves, branches, flora, etc., were removed. (**Figures 3-4**).
2. Sampling points were numbered, with field conditions described for each point.
3. Each sample was sealed in air-tight glass (Crick) or white plastic (Scotland) containers and marked for identification with sample number and collection day.
4. Precise coordinates of each location were taken using a Trimble RTK GPS (only Crick).
5. The water content was estimated using a soil moisture meter probe (TDR).
6. Each sample was described in a field notebook that included sample name, surrounding description, time of sampling, sample depth, soil type, soil description, and water content estimation.
7. Samples were delivered for laboratory for analysis the following morning:
   - Crick: The first day's samples were delivered to the laboratory with the sampling team on May 4th, 8:30 BST. The second day's samples were picked up by a courier early morning on May 5th and then delivered to the laboratory.
   - Scotland: The samples were delivered to the laboratory the morning after sampling.

**Figure 3.** Crick: top left to right - excavating topsoil, taking coordinates with Trimble RTK. Bottom left to right – measuring water content with soil moisture probe, sampling soil.

**Figure 4.** Scotland: top left to right - excavating topsoil, an example of the soil hole. Bottom left to right – gathering sample to a container, example of peat soil sample.

### Laboratory Water Testing

This laboratory process was applied to each of the 360 samples taken from both sites (**Figure 5**):

### Sample Collection Process

- Samples were logged.
- A tray of established weight was weighed with the soil.
- Each sample was described.
- The soil trays were placed in a drying oven for several days at temperatures of 50°c, 105°c, and 110°c for various sample sets.
- Drying tray was re-weighed after a few days of oven drying.
- Trays were placed back in the oven for one hour and weighed again. If there was more than a 10% difference between measurements, the tray was placed in the oven for an extra 16 hours.
- This step was repeated until the weight difference was <10%.
- Water content was calculated.

**Figure 5.** Top left to right – weighing trays and describing samples, laboratory report. Bottom left to right – trays with soil samples ready for oven drying, trays in the oven.

## Correlation Results

Soil moisture algorithm development is correlated based on pixel neighborhoods. This is done for a number of reasons, namely the difference in pixel scales. The samples were measured with high-accuracy GPS. The satellite data does not give pinpointed data with the same accuracy as the GPS, but rather pixel data. To match scales, the soil moisture algorithm development is correlated in pixel neighborhoods and not for exact pixels. The accuracy of the algorithm is then checked based on two windows: a 5×5 pixel window (2 pixels in each direction from the center pixel) and a 3×3 pixel window (1 pixel in each direction from the center pixel).

The following tables and graphs show the number of windows with predicted soil moisture values within a certain range from the measured pixel. The table shows the total predicted pixel values within a 10%, 7%, 5%, 3%, and 1% absolute difference from the measured central pixel. For example, in a 3×3 window, 73 out of 120 windows (61% of the windows) have at least one correlated predicted pixel value within 7% of the measured value.

| Absolute SM value difference (measured vs predicted) | Total field samples within difference range from predicted | Percent field samples within difference range from predicted |
|---|---|---|
| Diff<12% | 101 | 84% |
| Diff<10% | 96 | 80% |
| Diff<7% | 87 | 73% |
| Diff<5% | 77 | 64% |
| Diff<3% | 62 | 52% |
| Diff≤1% | 39 | 33% |
| Total field samples | 120 | **5×5 window** |

**Figure 6**

| Absolute SM value difference (measured vs predicted) | Total field samples within difference range from predicted | Percent field samples within difference range from predicted |
|---|---|---|
| Diff<10% | 92 | 77% |
| Diff<7% | 73 | 61% |
| Diff<5% | 54 | 45% |
| Diff<3% | 41 | 34% |
| Diff ≤1% | 24 | 20% |
| Total field samples | 120 | **3×3 window** |

**Figure 7**

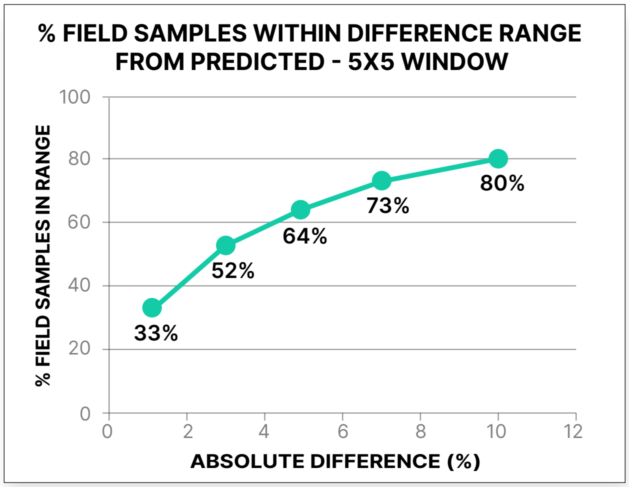


**Figure 8**

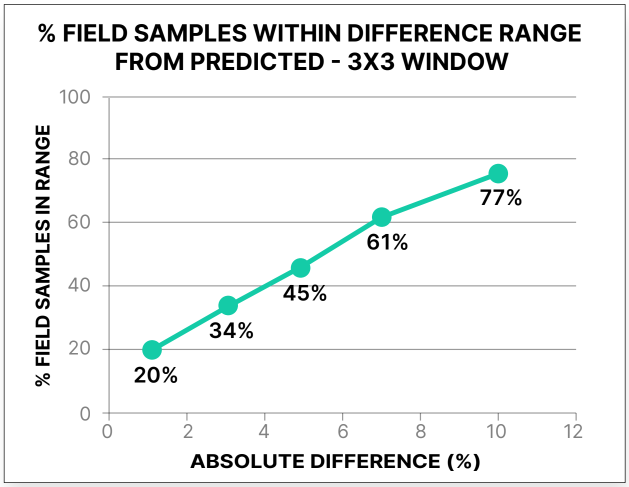


**Figure 9**

## Saturated Ground Mapping

The SAR satellite images were processed using a model created from the correlation with the soil water content laboratory test results and mapped to indicate soil water content.

For Crick, the mapping was provided over the STA (strategic testing area) with a 100m buffer to adjacent property on either side of highway infrastructure, and a 500m buffer for railway infrastructure. The data has been provided in various data layer formats.

**Figure 10** provides an example of the data in the area over a Junction at Crick. The drainage network data layer has been overlaid onto the mapping data (purple lines).

For Scotland, two separate algorithms, and therefore two separate maps, were conducted for each image:

- For the October 2020 image, only the results from the samples gathered in October 2020 are shown (**Figure 11**).
- For the June 2021 image, both the October 2020 and June 2021 results are shown (**Figures 12-13**).

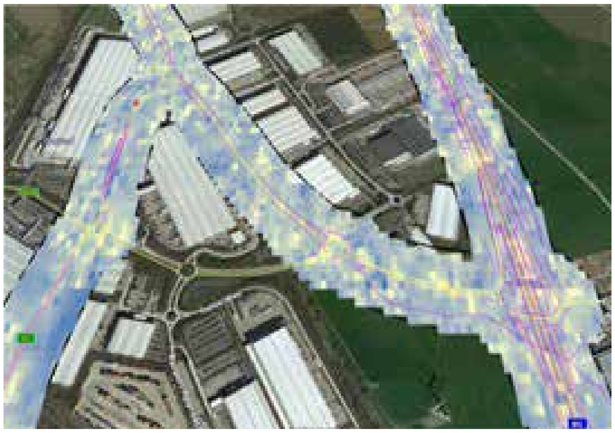

**Figure 10.** Example of the soil moisture mapping data around junction.

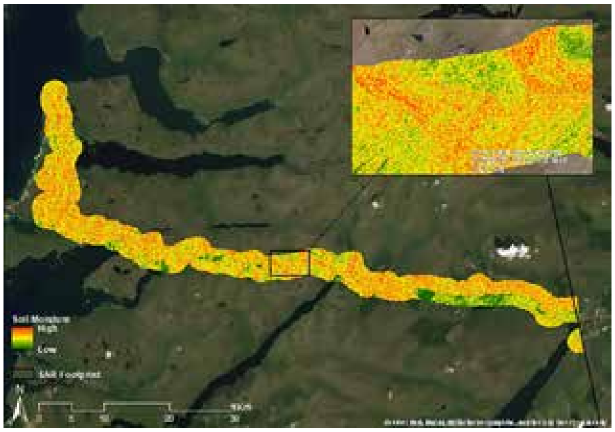

**Figure 11.** Soil moisture map based on October image and October 2020 model. A zoomed-in section shows the moisture data in greater detail.

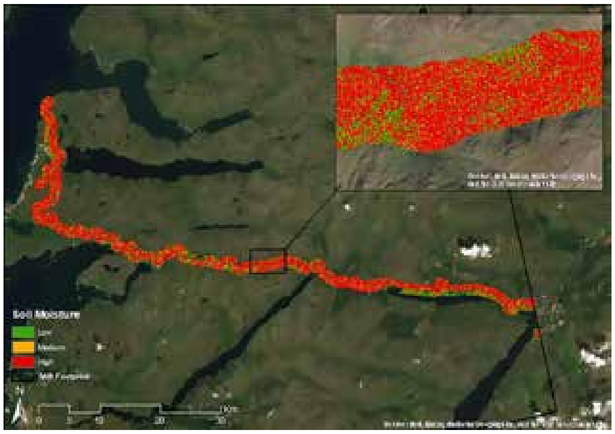

**Figure 12.** Soil moisture map based on October image and June 2021 model.

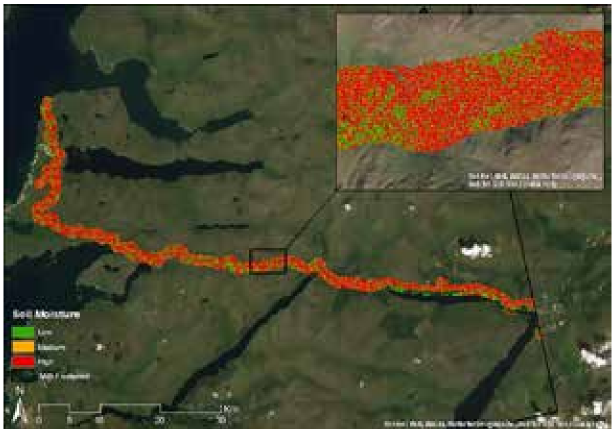

**Figure 13.** Soil moisture map based on June image and June 2021 model.

## Conclusions

The high degree of correlation between the soil moisture content data provided by laboratory testing with the data provided by ASTERRA demonstrates conclusively that the concept of applying algorithmic processing to satellite-based L-band SAR images is a viable method of evaluating and mapping soil moisture that is far less labor-intensive than gathering and testing individual soil samples, particularly over a large area.

In addition, the test demonstrated the value of soil moisture mapping, in conjunction with topographical, drainage, and geotechnical information as an important additional data layer within infrastructure assessment tools. The data set it provides to investigators will help them identify specific infrastructure risks to guide further inspection and investigations and limit their eventual damage and costs.

## References


Behari, J. (2005). Microwave Dielectric Behavior of Wet Soils. New Delhi: Springer.

Dall, J. (2007). InSAR elevation bias caused by penetration into uniform volumes. *IEEE Transactions on Geoscience and remote sensing*, 45(7), 2319-2324.

Koyama, C. N., Liu, H., Takahashi, K., Shimada, M., Watanabe, M., Khuut, T., & Sato, M. (2017). In-situ measurement of soil permittivity at various depths for the calibration and validation of low-frequency SAR soil moisture models by using GPR. *Remote Sensing*, 9(6), 580.

Ponganan, N., Praseartkul, P., Pipatsitee, P., Taota, K., Kongpugdee, S., Sakulleerungroj, K., & Eiumnoh, A. (2016). The determination of soil water content in various depth levels in cassava fields using ALOS-2 PALSAR Imageries. Asian Association on Remote Sensing 2016 Conference proceedings.

Singh, A., Meena, G. K., Kumar, S., & Gaurav, K. (2018). Analysis of the effect of incidence angle and moisture content on the penetration depth of l-and S-band SAR signals into the ground surface. *ISPRS Annals of Photogrammetry, Remote Sensing & Spatial Information Sciences*, 4(5).

Ulaby, F. T., Long, D. G., Blackwell, W. J., Elachi, C., Fung, A. K., Ruf, C., ... & Van Zyl, J. (2014). *Microwave radar and radiometric remote sensing* (Vol. 4, No. 5, p. 6). Ann Arbor: University of Michigan Press.

Zhang, L., Li, H., & Xue, Z. (2020). Calibrated Integral Equation Model for Bare Soil Moisture Retrieval of Synthetic Aperture Radar: A Case Study in Linze County. *Applied Sciences*, 10(21), 7921.