DRAFT REPORT

Refinement of MudMaster Antenna prototype

Contents

Background and Project Aims

The recent failures of tailings storage facilities (TSF) have once again revealed their structural weaknesses and technical insufficiencies, and the threats that are posed by these unique structures to life and limb, our environment and the economy. Statistics have proven that TSFs fail more frequently than similar structures used as water storage facilities. The main reason for the higher probability of failure of TSFs is the lack in sufficient compaction of the tailings material during deposition and the subsequent consolidation. The threats posed by TSFs could be significantly reduced if the tailings material could be more effectively compacted already during deposition.

One possibility to improve compaction of tailings is mud farming using amphirols. These amphibious vehicles move using two Archimedean spirals. The vehicle can float in pure water and operates for very thin suspensions like a motorboat. With increasing compaction when soil properties start to influence the performance of the amphirol, the operation becomes similar to a tracked vehicle. Early operation of the amphirol allows the tailings material to reach higher compactions due to:

- Drainage of water to the surface, from where it can flow due to gravity to a drainage channel,
- overcoming of hindered sedimentation, which prevents further consolidation due to self-weight only, and
- increased evaporation as the surface is kept water saturated and thus evaporation at its maximum.

Operation of the amphirol starts ideally with the deposition of the tailings material. At this stage, the suspension is rather thin and behaves viscous. With ongoing operation, the solid concentration in the suspension increases and the suspension is reaching a soil-like state, where friction starts to dominate the overall material behaviour. Also controlling and operation of the amphirol changes and requires more skilful operators. With increasing suspension density, the draught of the amphirol decreases until the efficiency of additional overruns is significantly reduced. Operation of the amphirol is stopped at this stage, or when a sufficient shear strength of the soil is reached.

The most important parameter for quality control during amphirol operation is the density of the tailings material. So far, there is no indirect and non-invasive method available that allows the measurement of the tailings density. Density measurements using samples is laborious and not representative if only few samples are taken. Therefore, to date substitute parameters have been observed that are linked to the density, such as torque and fuel consumption. However, these are insufficient parameters to quantify the density of tailings materials during operation of an amphirol.

To fill this gap, Phibion Pty Ltd and researchers from the University of Queensland (UQ) from the Schools of Electrical Engineering and Civil Engineering have been founded by Innovation Connection (IC - Development of Dielectric Sensor System on Intelligent Amphirols for Mud Farming Tailings Facilities) to develop a novel electromagnetic measurement monitoring method based on the antenna technology. Investigations at UQ on various soils, dredged material and tailings materials have shown that electromagnetic methods can be used to quantify the water content from the dielectric permittivity with sufficient accuracy. The free water in a soil/water mixture dominates the dielectric permittivity in the radio to microwave frequency range. Based on laboratory investigations, calibration functions can be developed for determining the water content from the dielectric permittivity. Since tailings material is fully water saturated throughout the operation of the amphirol, the water content can directly be back calculated into the density when the specific gravity (the dry unit weight of only the solid phase divided by the unit weight of water) is known. Within this first project funded by Innovation Connection, the concept of measuring dielectric permittivity non-invasively from a MudMaster was proven. In this connection, an HF antenna for contactless dielectric measurements

has been developed and tested. Based on numerical simulations with variation of the surface topology and permittivity a calibration procedure for the antenna was developed and a dataset produced based on computational simulations that was used to train a Neural Network for analysing measurements with the antenna. For completing the proof-of-concept, the antenna and the analysis system were tested during a large-scale test at the premises of Phibion Pty Ltd. Water content and density of the material under test (soil from the Port of Brisbane) could be quantified during the test.

Based on the outcomes of the first IC project in form of the antenna and the analysis procedure using the Neural Network, the aim of the second project is to further develop this antenna concept to an operational prototype and to bring it into operation on a selected mine site in Queensland. For this purpose, the proposed contactless dielectric measurement system will be integrated on Phibion's Mud-master vehicle for the purpose of evaluating the density and water saturated condition of tailings. The focus of the second IC project is to further develop the established concept of a non-invasive measuring system to an operational prototype and to perform a field test.

To achieve this goal the following work packages have been defined:

- WP1: Merging of antenna and VNA, and assembly of the system on the MudMaster
- WP2: On-site calibration procedure for antenna
- WP3: Library of calibration functions for tailings materials
- WP4: Field test with data analysis

Each work package will be described in the following part of the report.

WP1: Merging of antenna and VNA, and assembly of the system on the MudMaster

Introduction

The work package 1 was focused on the design of a mounting system for the antenna system on the MudMaster. The design has several constraints:

- Need to merge antenna and vectorial network analyser (VNA) and manufacturing of a housing to hold both items in a vibration proof way.
- Need of the design to be in a ready to operate condition.
- Mounting of the antenna system on the MudMaster including wiring and integration of the antenna system into the measuring system existing for the MudMaster.

The mounting system was realized at UQ workshop and delivered to Phibion. To test the design, it was installed on a MudMaster at Phibion's workshop. The complete industrial drawing for the mounting system has been delivered to Phibion and is added as appendix to this report.

WP2: On-site calibration procedure for antenna

Introduction

The work package 2 was focused on the development of calibration procedure and a control software based on Python for continuous measurements using the antenna system. Both steps were merged in a control software. The software has been delivered to Phibion.

The following of this section presents the different part of software and can be considered as a user guide.

System Overview

The user interface can be accessed using a web browser and navigating to `localhost:8080`. This will take you to the main menu.

User Interface

Status Bar

The status bar is shown in the top right corner of the application. This has three indicators:

1. Error,
2. VNA connection,
3. Mounting system controller connection.

The status indicators are shown in Figure 1.
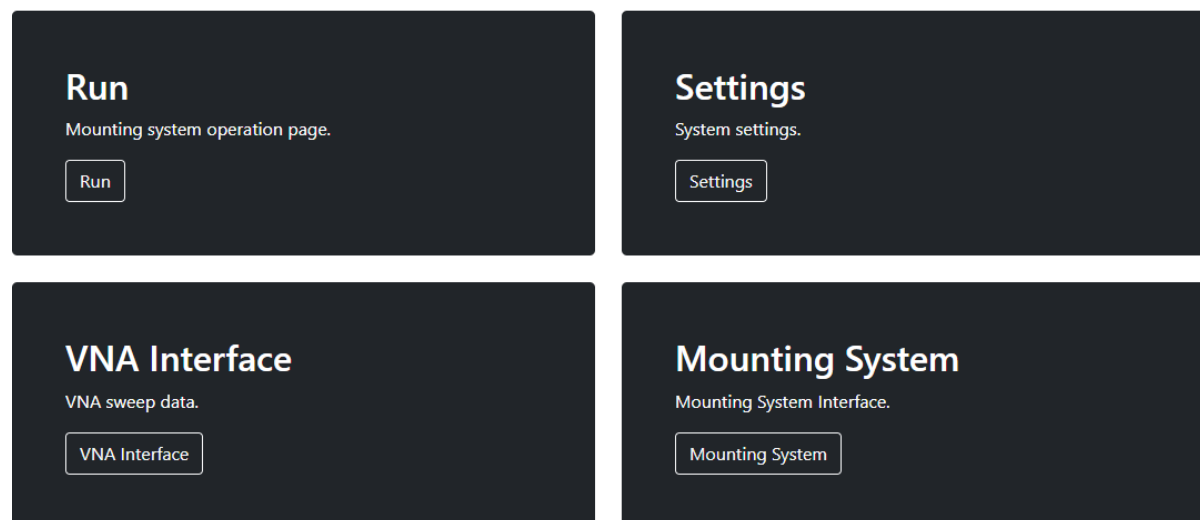

Figure 1: Status indicators.

Main Menu

Figure 2: Main menu, with buttons for the system run, settings, VNA interface testing, and mounting system control.
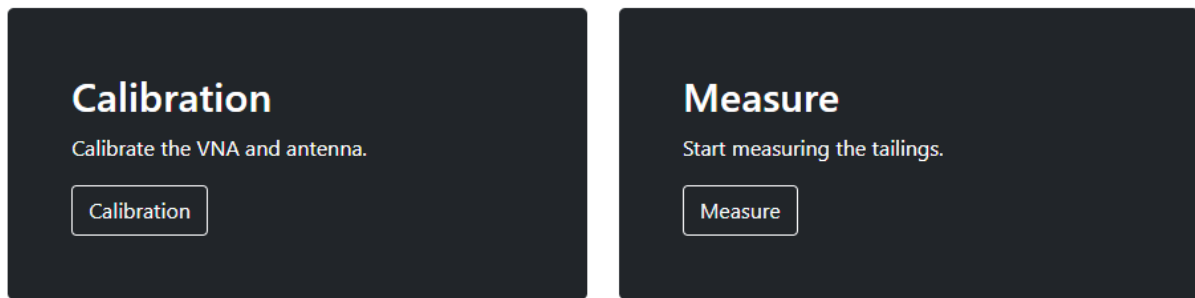
Figure 3: Run menu.

The Run Menu provides access to the calibration and measurement screens. Pressing 'Calibrate' will take you to the Calibration screen. Here, you can instruct the machine to perform the calibration. This is an automated process, only requiring the operator to place the absorbers on the ground in front of the antenna.
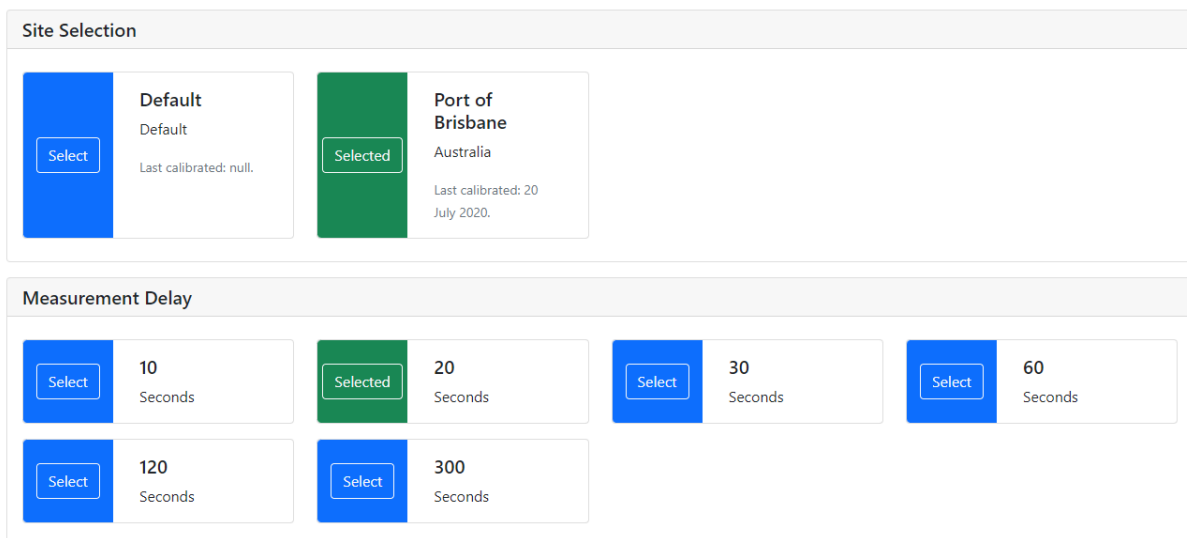
Pressing 'Measure' will take you to the measurement screen. This is the screen that shows the calculated measurements from the antenna. This includes the water content, density and permittivity.

Settings

The settings page is used to set runtime configurable options for the device. This includes the current site and the VNA data logging interval. The settings page is shown in Figure 4.

The current site options are filled from the config_site.py file. If no site has been selected yet, the system will use the 'Default' site.

The measurement delay, which sets the time between VNA measurements can be controlled from this screen. This allows the user to set the measurement delay to times between 10 seconds to 5 minutes.

Figure 4: Settings page. Allows the user to set the current site and VNA measurement interval. The currently selected option has a green bar on the left, unselected options have blue bars.

Site Selection

The site selection panel is used to select the mine site that the machine is operating at. This will configure the information used for the water content and tailings density calculations.

The site selection options are filled using the information in the config_site.py file. If no site has been selected yet, the system will use the 'Default' site.

Measurement Delay

The measurement delay panel is used to select the amount of time to wait between measurements. This changes the number of data points being saved to the OneDrive, however, the system will still continue to request the data from the VNA once every 5 seconds. This is to ensure that the data is always available when the system needs it.

VNA Interface

The VNA interface screen is used to test the performance of the VNA. This displays the current S-Parameters, the return loss, stability.

This page is not intended for normal operation, instead it is only used to test the VNA when it is being installed.

Mounting System

The mounting system page allows the user to interact with the actuator on the mounting system. This allows them to test the movement. The layout of these buttons is shown in Figure 5. This page shows the current actuator position on the left side of the screen. This value is updated from the mounting system controller once per second. The right side has the controls for the actuator. This includes a home button (far right), which retracts the actuator to the 0 mm position. The other buttons are used to extend and retract the actuator by 10 mm. At the bottom of this section is the position input section, this allows the user to specify the exact position that the actuator is set to.

Note: the actuator has been set to use a positioning tolerance of 0.2 mm to prevent hunting around the target position.
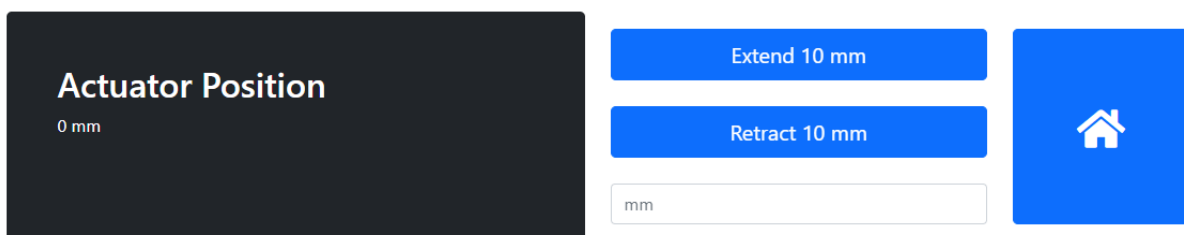

Figure 5: Mounting System control page.

Calibration

Calibration

[Calibrate] [Clear Calibration] [Start Measurements]

Actuator Position	Status [Idle]
0	✅
10	✅
20	✅
30	❌
40	❌
50	❌
60	❌
70	❌
80	❌
90	❌
100	❌
110	❌
120	❌
130	❌

Calibration Steps

Place Absorbers ⌃

Place the absorbers on the ground below the antenna, as seen in the image.

Perform Calibration ⌄

Help ⌄

Figure 6: Calibration menu screen.

Absorber Placement

Calibrating the system requires a series of measurements to be performed using RF absorbers placed on the ground in front of the antenna. The absorber should be placed in a similar manner to those shown in Figure 7. This is used to prevent ground-based reflections, to allow the antenna's response to be measured and calibrated.

Figure 7: Absorber placement in front of antenna.

After the absorber has been placed, navigate to the calibration menu on the device UI and follow the *Calibration Measurement Trigger* steps below.

Calibration Measurement Trigger

Calibration is handled automatically by the Python server. This will move the actuator through its range of positions, taking measurements with the antenna at each one. The calibration steps have been set to 10 mm, however, this can be modified in the config.py module.

To start a calibration, navigate to the calibration screen by pressing the 'Run' button on the main menu, followed by the 'Calibration' button. This screen has three buttons under the 'Calibration' heading. These buttons perform the calibration, clear the calibration data, and change to the measurement screen. This is show in Figure 8.
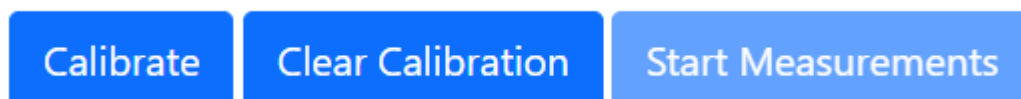

Figure 8: Calibration screen buttons.

The 'Calibrate' button will start the calibration process. This will move the actuator through the calibration positions. The progress of this is shown on the same screen. This is shown as a table with the actuator position on the left, and the calibration status for that position on the right. A red 'x' indicates that a calibration has not been performed for that position, a spinner indicates that the calibration is being performed for that position, and a green tick indicates that the calibration has been done for that position. The calibration list is shown in Figure 9 and a partial calibration is shown in Figure 10.

Actuator Position	Status Idle
0	✗
10	✗
20	✗
30	✗
40	✗
50	✗
60	✗
70	✗
80	✗
90	✗
100	✗
110	✗
120	✗
130	✗

Figure 9: Calibration positions, with no positions calibrated.

Actuator Position	Status Calibrating
0	✓
10	◯
20	✗
30	✗
40	✗
50	✗
60	✗
70	✗
80	✗
90	✗
100	✗
110	✗
120	✗
130	✗

Figure 10: Calibration being performed. Position 0 is completed, position 10 is being calibrated, and the rest are queued.

After a calibration has been performed, the 'Start Measurements' button will be set to active and the user will be able to start performing measurements.

The system will save any calibration data and load this at start up. This means that calibration would not need to be performed every time the machine is used, only when there are changes to the hardware.

A list of calibration steps is also shown on the 'System Calibration' page. The calibration steps/help are separated into three sections, and accessed through the accordion or the right-hand side of the screen. These are show in Figure 11, Figure 12 and Figure 13.

Calibration Steps

Place Absorbers ⌃

Place the absorbers on the ground below the antenna, as seen in the image.

Perform Calibration ⌄

Help ⌄

Figure 11: Calibration page help menu - absorber placement.

Calibration Steps

Place Absorbers ⌄

Perform Calibration ⌃

The calibration is automated. This is performed by lowering the antenna towards the ground and performing the calibration measurements at each point. The table to the left shows the current progress of the calibration measurements. Any measurements that have not been done are shown as a red cross and finished ones are shown as a green tick.

- ❌ - incomplete calibration measurement
- ○ - currently being measured
- ✅ - complete calibration measurement

Help ⌄

Figure 12: Calibration page help menu - performing calibration.

Calibration Steps

Place Absorbers	⌄
Perform Calibration	⌄
Help	⌃

Reset Calibration

Any previous calibrations are reloaded each time the machine is restarted. If you wish to clear the old calibrations, this can be done by either:

- Pressing the *Calibrate* button again, this will overwrite existing calibration measurments, or
- Pressing the *Clear Calibration* button, this will clear the calibration measurements, after which you will need to press *Calibrate* to perform the new calibration measurements.

Figure 13: Calibration page help menu - clearing previous calibration.

Measurements

After the system has been calibrated, or if there was calibration data already, you will be able to enter the 'Tailings Measurement' section of the app. This will set the machine to its measurement mode, where it will perform continuous measurements of the tailings. The interval between measurements can be configured in the system settings. An example of the measurement page is shown in Figure 14.
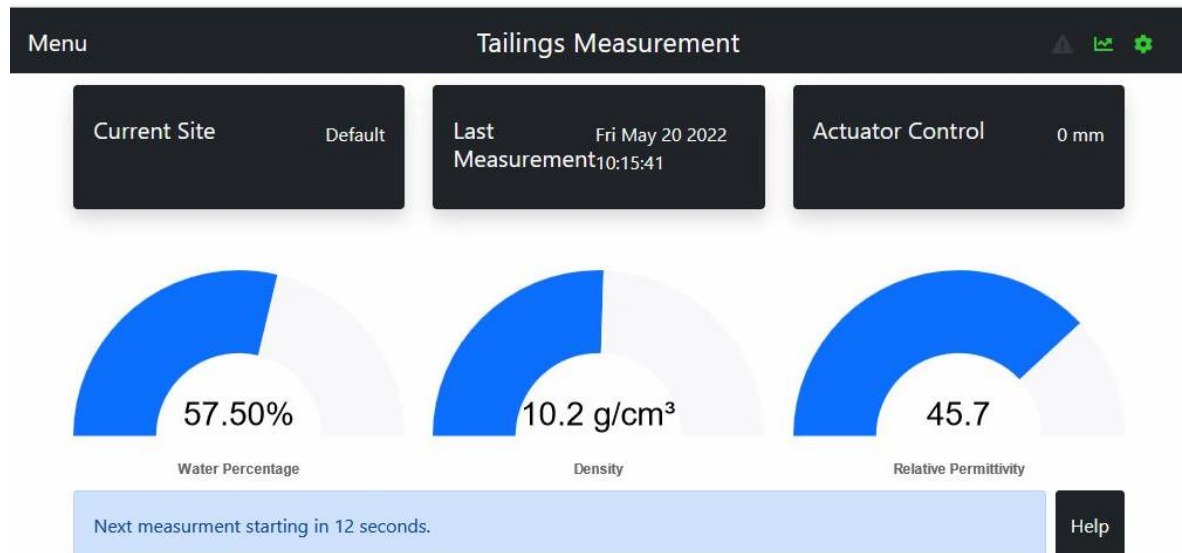

Figure 14: Measurement page.

The top row of the page shows the current site, the time the last measurement was taken and the current position of the actuator. The actuator control menu can be opened by clicking on the 'Actuator Control' box. This will open the mounting system control menu, shown in Figure 15.

The next row shows the current measurements, using gauges and numbers. This includes the water percentage on the left, density in the centre, and the relative permittivity on the right.

The bottom row shows the remaining time to the next measurement and has a help button which will open the help menu for this page.
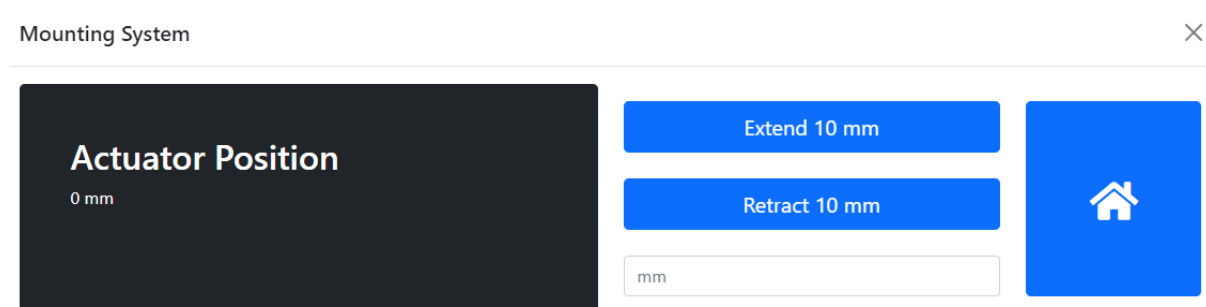

Figure 15: Mounting system control menu.

Each measurement that is performed will be saved to the OneDrive folder for the machine. This will save the main measurement data as a csv file, with an s1p file being used to save the raw VNA data. The VNA data will be saved in a subdirectory.

System Connections

Electrical Connections

The power cable used for this system contains a brown wire for 12 V power and a blue wire for GND (0 V). The VNA and motor controller are both powered from the same power supply.

VNA

The VNA is powered through a DC barrel jack. This feeds in through the gland on the back of the box and plugs into the VNA.

The VNA also uses a USB cable for the data back to the computer. This is run through the other gland.

Motor Controller

The motor controller is powered through the same power line as the VNA, however, it uses a separate USB cable.

Power is supplied to the Arduino through the power input points on the motor driver shield's screw terminals. This shield provides power to the Arduino through the header pins.

The USB cable for the Arduino is plugged into the USB-B type connector.

The actuator for the arm is connected to the Port B connection on the motor driver shield. With the red wire connected to the pin with '+' in the silkscreen, while the black wire is connected to the pin with '-' in the silkscreen.

The actuator also has an analogue feedback to the motor driver shield. This plugs into the analogue input pins on the shield. Orange is the potentiometer 0 V pin, purple is wiper (feedback), and yellow is the potentiometer +5 V pin. The signal from this is fed back to the analogue input on the Arduino and used to calculate the actuator position.

Internal Software Connections

This system operates using a combination of two web servers and the Megiq MVNA software. The MVNA software is the primary connection to the VNA. It is the software provided by Megiq to operate the VNA. Software version 1.9.015 is used for this system.

Megiq VNA Server

A web server built using the C# ASP.NET framework is used to interface with the MVNA software. This will spawn a new instance of the MVNA software when the server is started, and will handle the API calls for the VNA. The server makes itself available at 127.0.0.1:5000. This server exposes the necessary information from the VNA through the following routes detailed in Table 1.

Endpoint	Inputs	Outputs	Information
VNA/hello	None	String	VNA controller test string.
VNA/settings/frequency	float(*frequencyMin*), float(*frequencyMax*), float(*stepSize*)	Frequency settings	Sets the frequency minimum, maximum and step size for the VNA.
VNA/settings/power	float(*power*)	Output power settings	Sets the output power of the ports on the VNA.
VNA/status	None	VNA status as JSON	Returns the VNA's current status and list of status codes.
VNA/set-connection	True = connect, False = disconnect	Current connection	Instructs the MegiQ VNA software to connect to the VNA.
VNA/set-sweep	0 = stop, 1 = single, 2 = continuous	same as **'status'**	Sets the VNA's sweep state to the specified input.
VNA/get-new-measurement	None	Measurement data as JSON: [{frequency, amplitude (dB), phase (degree)}]	Returns a new set of sweep data. If a sweep has been done since data was last requested, it will return that, otherwise it will trigger a new sweep.

UI and Measurement Server

The measurement processing and user interface are managed using a separate server. This server makes itself available at 127.0.0.1:8080. It is built using the Python Flask framework. This server will spawn a number of threads, including the web request handler, VNA interface, measurement manager, and mounting system controller.

This server handles the requests necessary to display the data and control the device using a web browser. It will also handle the calibration of the antenna, using previous calibration data if it existing, and the measurement of permittivity, water content and density.

Site Calibration

The MudMasterUI server contains a number of configuration files, one of which is the config_site.py file. This is used to store the calibration information for each site. The calibrations are used to convert the permittivity from the neural network to water content (as a percentage) and tailings density (in grams/cm^3).

Calibrations are stored in the SITE_CONFIG object in the Site_Config class in the config_site.py file. New sites can be added by copying the 'default' site and pasting it after the sites below it. Table 2 lists the parameters that need to be changed.

Table 2: Site config file parameters to change.

Parameter to change	Description
'default'	The site name, with underscores replacing any spaces and no capital letters. This is the primary key for the config entry.
'name'	The site name.
'country'	The country the site is in.
'calibration_date'	The date that the calibration samples were taken/the date the calibration was made.
'model_water'	Change the values for 'gradient_value' and 'intercept_value'.
'model_dry_unit'	Change the values for 'G' and 'S' (note: 'gamma_w' is the gravitational constant).

The following shows the site calibration data. The values that need to be changed for each site are coloured red.

```
'default': {
    'name': 'Default',
    'country': 'Default',
    'calibration_date': '01 January 2022',
    'model_water': partial(
        model_water_percentage,
        gradient_value=0.16601,
        intercept_value=36.1093
    ),
    'model_dry_unit': partial(
        model_dry_unit,
        G=2.57,
        gamma_w=9.81,
        S=1.0,
    ),
}
```

It is best to add the new calibration data to the code stored in the repository. After committing and pushing the updated code to the repository, it will be made available to all of the machines. New calibration data can be applied by pulling the updated code on the machine and restarting the Python server.

WP3: Library of calibration functions for tailings materials

Introduction

The quantification of the water content and the density from the dielectric permittivity measured with the antenna system requires a thorough laboratory calibration covering a wide water content range. The knowledge of the specific gravity is then required to be able to determine the density from the water content. With the result of a fall cone test, shear strength parameters, such as the undrained shear strength and water contents related to the liquid limit can be provided. All this analysis is based on a calibration function describing the relationship between the dielectric permittivity and water content.

Methodology

The use of electromagnetic method requires calibration to link soil properties to measured parameters. In our application, we are interested to link electrical permittivity to water content and from the water content to density. Within the first IC project it was shown that dielectric properties can be derived from the scattering measured by an antenna, and it was found to work for a given material with water. Increases in scattering are caused by both, dielectric permittivity as well as loss. Permittivity is linked to water content (high water content = high permittivity), and high loss is usually related to the amounts of salts (high salt content = high degree of loss). The impact of high salt contents on the scattering measured with an antenna was not considered in detail so far, and requires some special consideration within the calibration procedure and probably in the analysis of antenna data.

Within a conventional calibration, the relationship between water content and dielectric permittivity has to be determined over the frequency range investigated by the antennas (0.7 GHz up to about 2 GHz). To do so, laboratory experiments are performed using open ended (OE) probe and Vector Network Analyzer measurements (Figure 16). To cover a broad range of density, dynamic measurements are performed: the permittivity of samples undergoing evaporation is measured over a broad range of frequencies (over 1 MHz to 3 GHz). The evolution of the mass is measured simultaneously for a witness samples (from the same batch). Based on a basic assumption that both samples are identical and tests have started with the same initial conditions, these experiments can provide a direct link between electrical permittivity, water content and density. Otherwise, it is well known that the electrical permittivity is not dependent of the frequency over the 500 MHz – 3 GHz. In this frequency range, the electrical permittivity is mainly a function of the permittivity of the different phase and the volume fraction of the different phase: this is why it is possible to average the value over the frequency bandwidth of the antennas and build a proper relationship between the average permittivity and density. The experimental set up is represented on the following picture:
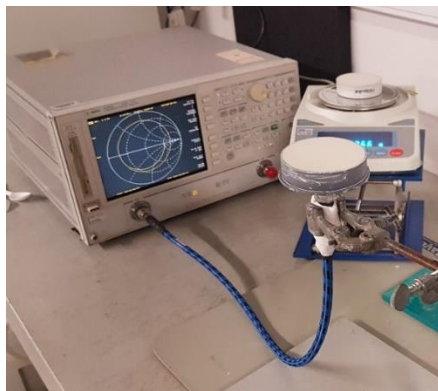

Figure 16: Experimental set up for the calibration

Results

As the site for the field trial was only selected towards the end of the project and the field trial was only carried out shortly before the end of the project's funding period, no calibration function was determined. This will be done later for the different areas of the field trial, as described in the chapter on the results of the field trial and will be provided as an addition to this report. By determining the calibration functions for four different areas from the same tailings material, possible variations in the calibration function become visible and can give a first indication of the achievable accuracy of measurements to be taken with the antenna system.

WP4: Field test with data analysis

Introduction

The new technology, consisting of the antenna system, the field calibration procedure and measurement analysis, was tested for the first time under field conditions at the Ravensthorpe Nickel Mine in Western Australia. The field trip took place between 16 and 20 January 2023. The duration of the stay in Ravensthorpe was from 17 to 19 January. Installation and preparation of the measurement system on the MudMaster, including field calibration of the measurement system, took place on 17 and 18 January, and the actual field trial was conducted on 19 January. In the following, the two most important activities at the Ravensthorpe Nickle Mine, namely the integration of the system on the MudMaster including the calibration and the results of the field test are presented together with some geotechnical tests of the material.

Integration of the Measurement System on the Mudmaster and Field Calibration

The antenna arm mounting system was developed for the latest generation of the MudMaster series from Phibion Pty Ltd. The machine used in the Ravensthorpe Nickel Mine, which was available for this field test, belonged to the first generation of the MudMaster. For this reason, some minor modifications had to be made in order to be able to attach the mounting system for the antenna and the control unit to the MudMaster. Thanks to the strong support of Mr David Fraser, the system was easily attached to the MudMaster and was ready for use within 24 hours. Figure 17 shows a close-up of the mounted antenna system with control unit before calibration.

Figure 17: Close view of the antenna system and control unit on the MudMaster at Ravensthorpe Nickel Mine.

For implementing the field calibration, absorbers (blue) were placed below the antenna at a vertical distance of about 50 cm from the antenna system. The distance between the antenna and the absorbers depends on the position of the MudMaster and the ground conditions. At the location where the calibration was carried out, the ground conditions were relatively firm. In some cases, it was necessary to underlay the absorbers with loose soil in order to achieve a more or less horizontal arrangement of the absorbers. A total of eight absorbers were placed under the antenna for the field calibration (Figure 18). As can be seen from Figure 18, the absorbers were not placed perfectly horizontally and should ideally be closer to the machine to close the gap underneath the ladder. The calibration procedure was then carried out automatically by the system without any disturbances for the different assigned distances from antenna to absorber.
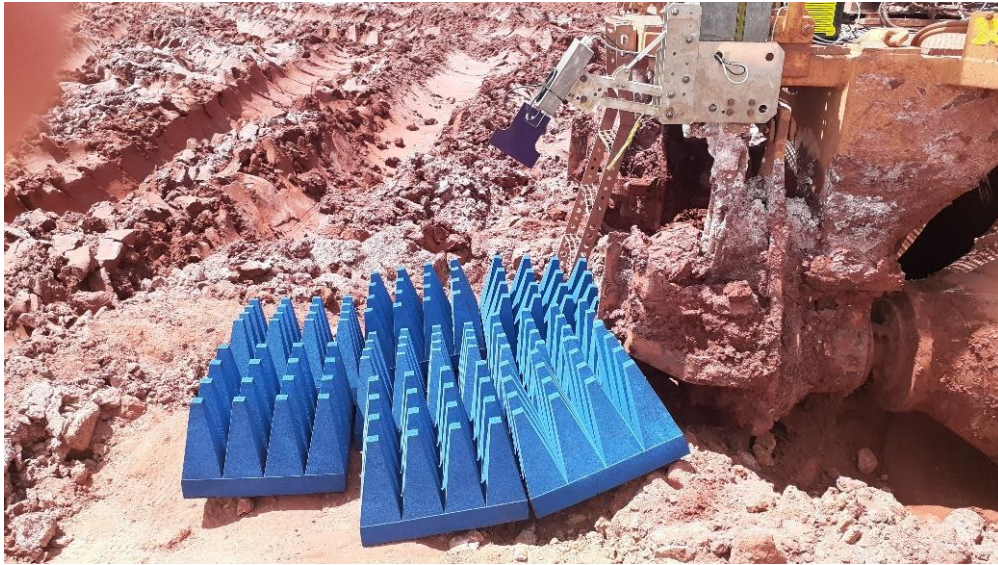
Figure 18: Antenna system during field calibration.

Field Trial and Results

For the actual field trial, it was planned to drive the MudMaster to different positions within the tailings with significantly different soil conditions to cover as large a water content range as possible. The pilot of the MudMaster knew from his operation where the best places were to take measurements and collect soil samples. Figure 19 shows the heat map of this field trial on 19 January. Soil samples were taken at various locations along the path shown in Figure 19 , always after the MudMaster had passed, i.e. after the soil had been worked by the machine. The duration of the field trial was about 90 minutes.
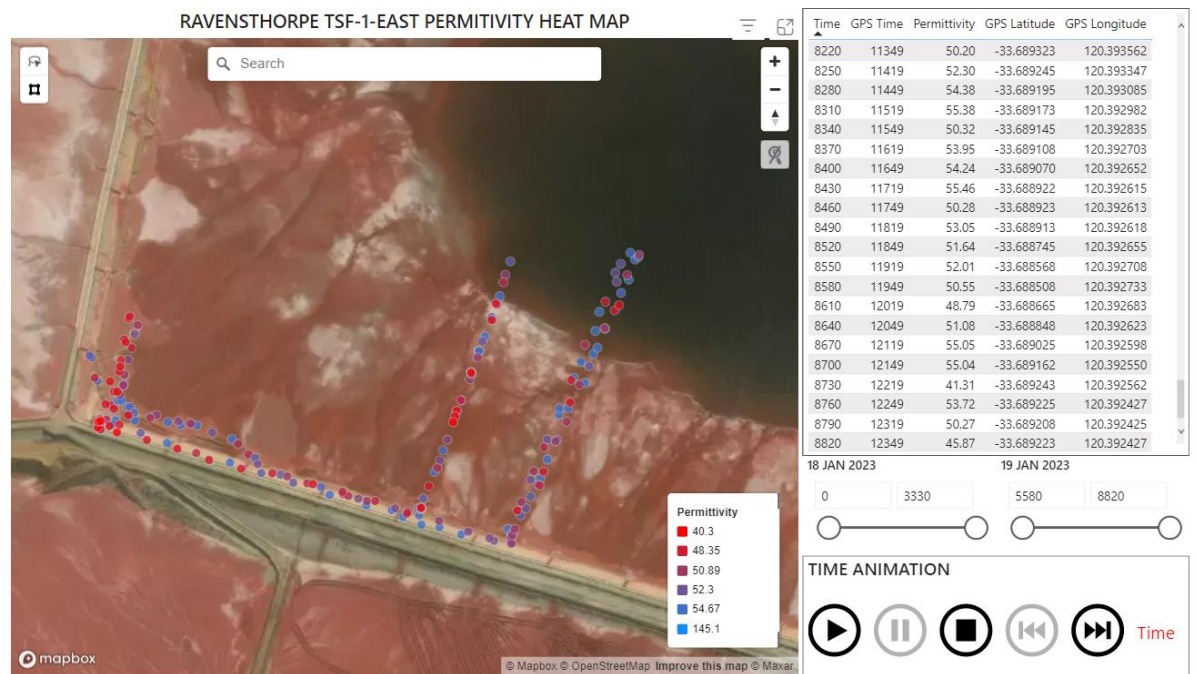

Figure 19: Heat map of dielectric measurements taken during the field trial on 19th Jan 2023 at Ravensthorpe Nickel Mine (note: the underlying picture was taken at another time before the field trial).

When looking at the heat map, some first observations can be made.

- The permittivity range between 40 and 57 (the maximum number given in the legend seems to be an artifact) is absolutely reasonable for dielectric measurements in soils.
- Blue dots (higher permittivities meaning higher water contents) and red dots (lower permittivities meaning lower water contents) appear together along one path. This is connected to the fact, that measurements are taken once in front of the machine (untreated area) and once in the back of the machine (after surface treatment).
- In the south/west corner, where the field calibration was made and the field trial started and ended, more red dots occur, which corresponds to the overall observation that this part of the tailings seemed to be dryer.

Altogether, seven samples have been taken during the field test, which have been used to determine the field gravimetric water content. Additionally, a fall cone test was conducted to identify the liquid limit (transition from soil paste to plastic soil in terms of water content). This additional information allows the representation of the results as a distribution of consistency conditions (above, below and transitional liquid limit state). Table 3 summarizes the measurement results of the sampling, and Figure 20 shows the locations of sampling.

Figure 20: Locations of measurements taken during the field trial on 19th Jan 2023 at Ravensthorpe Nickel Mine (for comparison with heat map see also Figure 19).
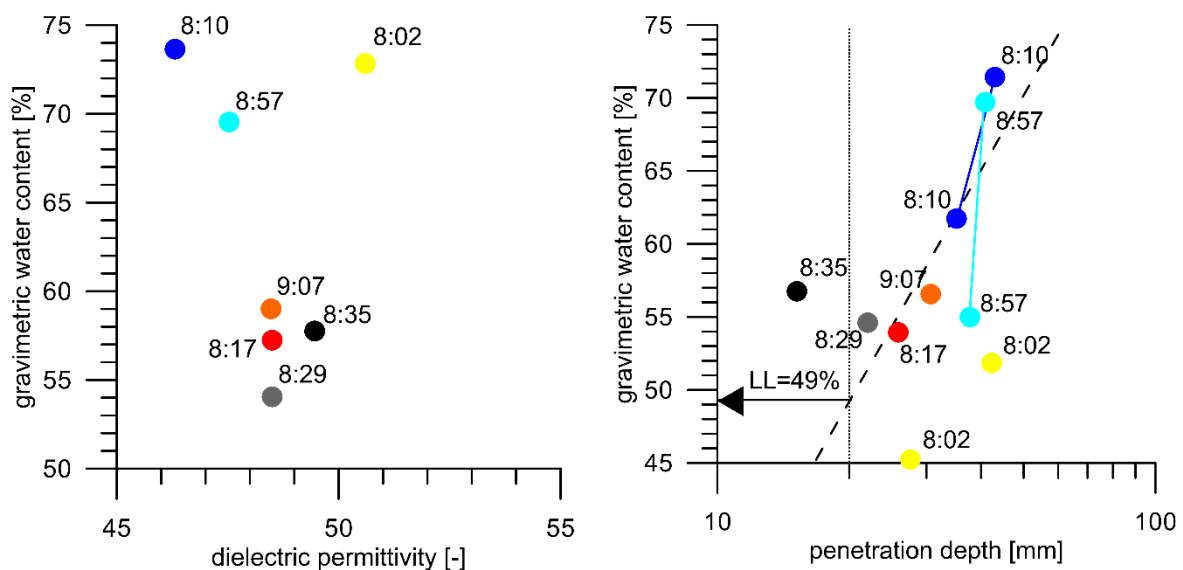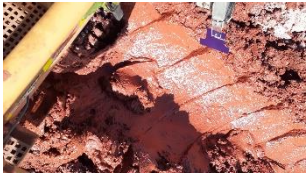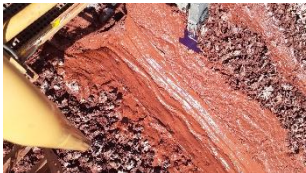

Figure 21: Left: Water content vs. dielectric permittivity, right: result of fall cone test with resulting liquid limit.

Table 3: Results of field trial with time and location of measurements and a picture showing the conditions during sampling.

Time	GPS Latitude	GPS Longitude	W [%]	e [-]	Picture
8:02	-33.68826	120.39572	78.0	72.9	
8:10	-33.68904	120.39536	78.6	73.7	
8:17	-33.68974	120.39505	61.3	57.3	
8:29	-33.68855	120.39269	59.1	54.2	
8:35	-33.68898	120.39259	62.0	57.8	
8:57	-33.68883	120.39548	75.0	69.5	
9:07	-33.78977	120.39507	63.1	59.1	

Discussion

The first impression of the measured dielectric permittivities was positive for the reasons mentioned above. However, the comparison of water content and dielectric permittivity in Figure 21, left, did not show the expected correlation. Usually, the dielectric permittivity increases with increasing water content, but even this simple relation is not visible in the graph. The hoped-for in situ calibration curve could therefore not be produced.

From Figure 20, four distinctive regions can be recognized and have been grouped in colour groups (see also photos in Table 3): the dryer region in the west (times 8:29 and 8:35am – grey/black), the repetition measurement in the south corner (times 8.17am and 9:07am – red/orange), the measurements in the middle section (times 8:10am and 8:57am – blue/light blue) and the measurement point closest to the water line (time 8:02am - yellow). The results of the fall cone test show some correlation with these groupings. The blueish and reddish points show a correlation that is to be expected between water content and penetration depth of a cone within 5 seconds. These measurements have been used to determine the liquid limit of 49% for the tailings material. The yellow and black/grey measurements have been discarded for this analysis. Usually, the fall cone experiments provide a nice correlation, which allows to determine the liquid limit accurately. For the field trial samples, the measurements haven been made at in situ the water contents without adding or removing water. Some samples were allowed to dry a bit leading to measurement pairs connected with a line in Figure 21, right. Nevertheless, the overall results show very distinctive scattering.

This scattering is also visible in Figure 21, left, representing the relationship between water content and dielectric permittivity, for which the same colour grouping has been used. There is a distinct difference between the measurements taken at the border of the tailings (dryer region represented by black, grey, red and orange) and the wetter region (blue, light blue and yellow). The measurement near the waterline at 8:02 (yellow) is a clear outlier, as was the case with the result of the fall cone test. Even if one disregards this observation, it results in no correlation, or at best a spurious correlation, between water content and dielectric permittivity. There are several possible explanations for this observation:

- There is an extremely high salt content of the material, which becomes visible after drying of the samples in the oven for determining the gravimetric water content (see Figure 22). The salt concentration can be locally different due to the introduced irrigation with salt water. Salt has a big influence on the relationship between water content and dielectric permittivity.
- The materials at the border of the tailings can have experienced some drying and wetting cycles which can alter the strength and can influence the relationship between water content and dielectric permittivity.
- The antenna covers a much larger area with one measurement than it can be represented by one sample taken from somewhere in the middle of the zone treated by the MudMaster. The non-treated areas still influence the antenna measurements. One soil sample might not be representative enough to characterize the zone of indluence.
- The field calibration influences the quality and accuracy of the measured dielectric permittivities. For the field trial, the absorbers could have been placed closer to the machine and the ladder should have been pulled up (Figure 18). The influence of the presence of the machine on the antenna measurements is still an open question.
- The penetration depth of the radio signals into the material is unknown. A salt crust of film water can strongly influence the measurement results.
- The water content range is still too small to allow the development of a calibration function that is representative for the tailings material.

Figure 22: Left: Formerly red samples after drying in the oven over 24 hours at 60°C.

These possible explanations require further in-depth investigations to be able to quantify the accuracy and representability of the measurement results obtained with the antenna system. The field trial has provided some valuable results and insights into the possible complications of using the antenna technology in practical applications. In particular, with regard to possible variations in the properties of the tailings material itself, it might be necessary to take several samples at different times in order to establish a range of calibration relationships that form the basis for quantifying the water content and density state in a tailings. For this reason, laboratory calibrations will be carried out for the four different regions sampled during the field trial.

Summary, Conclusions and Recommendations

The project presented in this report is based on a previous project funded by Phibion Pty Ltd. and Innovation Connection to develop a technology for the non-invasive determination of water content and density of tailings material using a radio antenna. The previous project laid the foundation for this project by developing a design for an antenna operating in the radio frequency range and producing a prototype antenna, developing an analysis approach for antenna measurements based on simulation data and conducting a proof-of-concept experiment at the premises of Phibion.

Both, antenna design and analysis method remained unchanged and were not considered further in this second phase of the development of this new technology. Rather, the aim of this project was to develop a mechanical connection of the antenna to the Mudmaster that allows the position of the antenna to be changed at will, which is necessary to perform a calibration of the antenna on the Mudmaster in the field. The measurements with the antenna should also be integrated into the already existing data acquisition system of the Mudmaster. An important aspect of the project was the development of a largely automated on-site calibration procedure that can be carried out by a non-expert person with only a short training session. Finally, a laboratory procedure had to be developed to establish a calibration between water content/density and dielectric permittivity for the frequency range in which the antenna operates, and calibration functions had to be established for the materials of interest. Finally, the applicability of the technology for practical applications was to be tested in a final field trial.

The objectives of the project have all been achieved and the technology has been developed to a level that now allows its performance to be quantified and improved. It is the opinion of the project team that the technology has reached a Technology Readiness Level 5 based on the definition of the Australian Defence Force. The components of the technology have been tested and validated in a relevant operational environment.

At the current stage of development, the technology can be used to perform initial measurements in the field. However, to be able to make a reliable statement about the water content and density of tailings on the basis of these measurements and also to optimize the system for field application, further development steps are required:

1. Quantification of the accuracy of the dielectric measurements in the field. This includes quantifying the spatial coverage of the antenna measurements and the depth of penetration of the measurements into the tailings material. Operational aspects related to measurements at the front and back of the Mudmaster also need to be considered.
2. Development of a simple technology to develop a calibration procedure that can preferably be performed on site. This aspect requires the development of a device that allows the rapid measurement of the dielectric permittivity for the relevant frequency range.
3. Improving the robustness of the antenna and the mechanical connection between antenna and Mudmaster. The antenna needs an enclosure that allows it to be protected against all weather conditions and against contamination. Any vibrations that may occur must not affect the measurements.

Points 2 and 3 are technical developments that do not require further investigations. However, point 1 requires further in-depth research, which may lead to a change the existing design of the antenna. In the opinion of the project team, it is imperative for the further development steps of the technology to take a closer look at these aspects, especially before considering series production of the technology.