Email: Budi.juswardy@curtin.edu.au
Phone: +61 8 9266 9224
Fax: +61 8 9266 9246

Building 610, 1 Turner Avenue
Technology Park
BENTLEY WA 6102
Australia

Report on the Assessment of Thermal Insulator for RFoF Optical Link Cable

Client:	Mr. Tom Booler Assistant Director, Engineering Operations ICRAR/ Curtin, Curtin Institute of Radio Astronomy
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Test engineer(s):	Budi Juswardy, Research Engineer, ICRAR/ Curtin (CIRA)
Report prepared by:	Budi Juswardy

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Contents

List of Figures

List of Tables

Executive Summary

This report documents the selection process, characterisation and analysis of insulating solutions for surface-laid fibre optic cable from outdoor elements (ambient temperature fluctuations, wind and solar irradiation) in the field at the Murchison Radio-astronomy Observatory (MRO), in the context of SKA Bridging Array activity. The objective of the investigation is to find a solution that potentially mimic the response of underground cable burial (1.5 m) in reducing thermal effect on the fibre cable, to achieve reasonable phase stability of the transmitted RF signal, without actually trenching the cable.

Worst-case estimates of the *relative phase variation* and the *24-hour relative phase drift* of the installation (with and without the insulator) are provided, which are derived from actual cable measurements in the field, as well as calculated from characterisations of insulation sample in the lab. These estimates can then be used to predict the performance of future fibre cable installations for any given length, and *to make an informed decision whether or not trenching the cable underground/ cable insulation is required, or weather cable performance is acceptable without any insulation*.

For SKA Bridging Array station with 200 m length fibre transmission distance, the *worst-case* estimate for the *24-hour relative RF phase drift* between two RF links at 160 MHz would be in the order of: 1.5° (phase) for surface laid cable without insulation. Depending on the thickness of the insulator as evaluated, the *relative phase drift* is calculated to potentially be reduced down to approximately: 0.9° - 0.45° (phase) for insulator thickness between 25 mm – 75 mm, and the 50 mm wall thickness is found to be capable of providing damping and delayed temperature response, similar to the profile of cable buried 1.5 m underground.

1 Background and Scope

1.1 Introduction

RF-over-fibre (RFoF) optical link has been identified as an attractive solution for transporting analogue radio frequency (RF) signal for the LFAA front-end (SKA-low project). By using RFoF link, analogue radio signal is transmitted from antenna directly into the central processing facility (CPF) via fibre optic media, rather than the conventional coaxial cable. However, in a long-distance RF transmission, the effect of temperature fluctuations on the cable due to direct environmental exposure could be significant.

There have been calculations, lab simulations, as well as field measurements to ascertain the effect of the temperature fluctuation of the fibre optic cables, and relating the results in the context of the SKA LFAA L3 requirements [1], [2], [3], [4] and [5]. Several cables have been evaluated (buried underground in a trench or routed on the ground), including those cables currently used in AAVS 1 project, as well as the SKA-low Bridging Array. In particular, field measurements at the Murchison Radio Observatory (MRO) have been performed on two types of cable currently in used in the field, i.e. the conventional loose tube cable manufactured by Shenzhen DGI (referred to as SDGI cable), as well as the Spider Web Ribbon cable from AFL-Fujikura (AFL SWR cable), where these cables were laid and routed on the ground along the 5-km distance between AAVS station (at the MWA location) and the MRO Correlator Building.

From the lab evaluations and field measurements, it has been found that **temperature exposure on the cable mainly affects the *phase variations* and *phase drift* of the transmitted RF signal.** A few set of 24-hour data taken from fibre-pair combinations were analysed, from which we could ascertain the phase stability performance of the cable used in the field, and estimate the maximum allowable transmission distance, for a given phase stability requirement.

Moving forward to 2019 for the SKA Bridging Array activities, there is a plan to build a few LFAA stations, where the tile processing module (TPM) will be placed relatively close in the field inside a mobile RFI shielded enclosure/ structure. The distance between a station and the RFI enclosure is envisaged to be around 200 m. As the type of the cable is yet to be known, and as well as various discussions in the SKA community to ensure temperature effect on the fibre optic cable is *"eliminated"* during the characterisation of the RF receiver chain (especially when assessing the calibration, radiation beam and visibility/ imaging of the station array), the inclination is to bury the fibre cable underground to ensure phase stability.

However, as the transmission distance for Bridging Array is relatively short and that the RFI structure is planned to be a temporary deployment, it is not practical and economical to dig a trench at the MRO to bury the fibre optic cable for the Bridging Array. This motivates us to search and evaluate a suitable cable insulation solution that could provide us thermal stability comparable with buried cable, while still enable us to place and route the cable on the ground. The goal is to find a solution that potentially could help in reducing thermal effect on the fibre cable, justify the selection within the limitation of the investigation and experimental set-up; while comparing the performance of the potential solution with burying the cable under the ground.

Also, from our past measurements, we found that even for buried cable, the diurnal temperature variations to a certain degree still affect the phase stability of the RF signal transmitted on the fibre. It is therefore more meaningful to provide the estimates for both the *relative phase variations* and the *24-hour relative phase drift* for surface-laid cable installation for a given transmission length as implemented in the field, and to provide comparisons between the performance of the cable with, and without the insulator.

These estimates can then be used to estimate the temperature-induced phase drift and phase variation of future fibre cable installations for any given length, and ultimately to be considered when making an informed decision whether or not trenching the cable underground or insulating the cable is required for a given phase drift or phase variation requirements.

1.2 Scope and Objective of the Investigation

The objective of the investigation are as follow:

a. To find a solution that mimic the thermal response of underground burial (1.5 m) in reducing thermal effect of the surface-laid fibre cable to achieve comparable thermal response of the buried cable, without actually trenching the cable underground.
b. To document the selection process, and the characterisation of potential insulating solutions.
c. To provide the insulation model and the worst-case estimates of the phase stability performance of the fibre cable, both *with* and *without* the insulation.

The scope of the investigation as presented in this report are:

1. To outline several potential solutions for insulating the fibre optic cable specific for SKA Bridging Array project, with transmission distance of 200 m.
2. To characterise the thermal property and response of suitable solutions, including subjecting the insulation solutions to simulated temperature at the field (MRO) in the lab.
3. To determine and recommend a reasonable insulation solution specific for SKA Bridging Array project, and provide estimated *phase drift* and *phase variation* response derived from the characterisation results, **assuming the surface-laid fibre cable will be insulated regardless of whether insulation is need or not**, in which the decision will be out of the scope of this report.

As the solution is intended to be a temporary measure, the long-term reliability or lifetime of the solution will not be used as a selection criteria. The cost will also not a limiting factor in the selection of the solution, although it is expected that the cost of implementing this solution should be significantly lower than the cost of digging trench for burying the fibre optic cable. Also, assessment of relative ease of deployment of potential solutions (weight, installation, space required, and installation time) although briefly provided, will not be extensively discussed in this report.

1.3 Methodology

The steps used in assessing the suitability the insulation solution are as follow:

1. Investigation on the temperature profile of the soil below the ground surface and use the damping and delay profile as a comparison to facilitate a suitable solution.

2. Assessment of the insulation property of the potential solutions through obtaining the thermal properties of the material used in the potential solution, such as the thermal conductivity/ resistance whenever possible. Combustibility, toxicity and water repellent properties will be briefly assessed as well, to ensure the solution could reasonable be deployed at the MRO, and within the lifetime of the Bridging Array (expected to be less than 3 years).

3. Characterisation of the thermal insulation of a few short-listed solutions, by subjecting each solution to simulated field temperature in the lab, as well as obtaining the transient response of the solution against a sudden temperature rise/ drop.

4. Assessment of the response of the potential solution, based on the comparison with the temperature profile expected from underground burial at the depth of around 1.5 m.

5. Recommendation of a solution that reasonably simulate the thermal stability of underground burial, **assuming that the *relative phase response* of the fibre in the cable bundle inside the insulating solution is *linearly proportional* with the temperature damping due to the application of the insulation solution** (which will be covered in Section 2.5 of this report)**.**

6. Comparing the response of the solution with the SKA Low-frequency Aperture Array Level-3 (LFAA L3)/ the proposed LFAA requirements, and providing a comparison of the 600-sec *relative phase variation* and 24-hour *phase drift* estimates between un-insulated and insulated cable.

2 Investigation Results

2.1 Soil Temperature Profile

It is known that the temperature of the soil below the surface of the ground more or less follow closely the temperature fluctuations of the ambient air temperature above the ground surface, up to a depth of 0.5 m [6]. At the depth of below 1 m, the soil temperature usually becomes less sensitive to the diurnal cycle of the air temperature and solar radiation, for which the average seasonal temperature will be dominant and extends to a depth of between 10 to 15 meters [6] & [7]. Temperature between 15 meter and 50 meter is reported by Kasuda [8] to be more or less constant due to underground water damping effect on the seasonal variations.

Following the Kasuda model, the soil temperature profile at a certain depth can be obtain through the following formula [7]:

$$T_{soil}(z,t) = T_m - T_p e^{-z\sqrt{\frac{\omega}{2\alpha}}} \cos\left(\omega t - \varphi - z\sqrt{\frac{\omega}{2\alpha}}\right) \tag{1}$$

Where z is the depth (m), t is the time, T_m is the annual average ambient temperature (°C), T_p is the peak deviation of the ambient temperature (°C), α is the ground thermal diffusivity (m^2 / s), ω is the angular frequency (rad/s) of the temperature cycle, and φ is the time shift adjustment of the cycle.

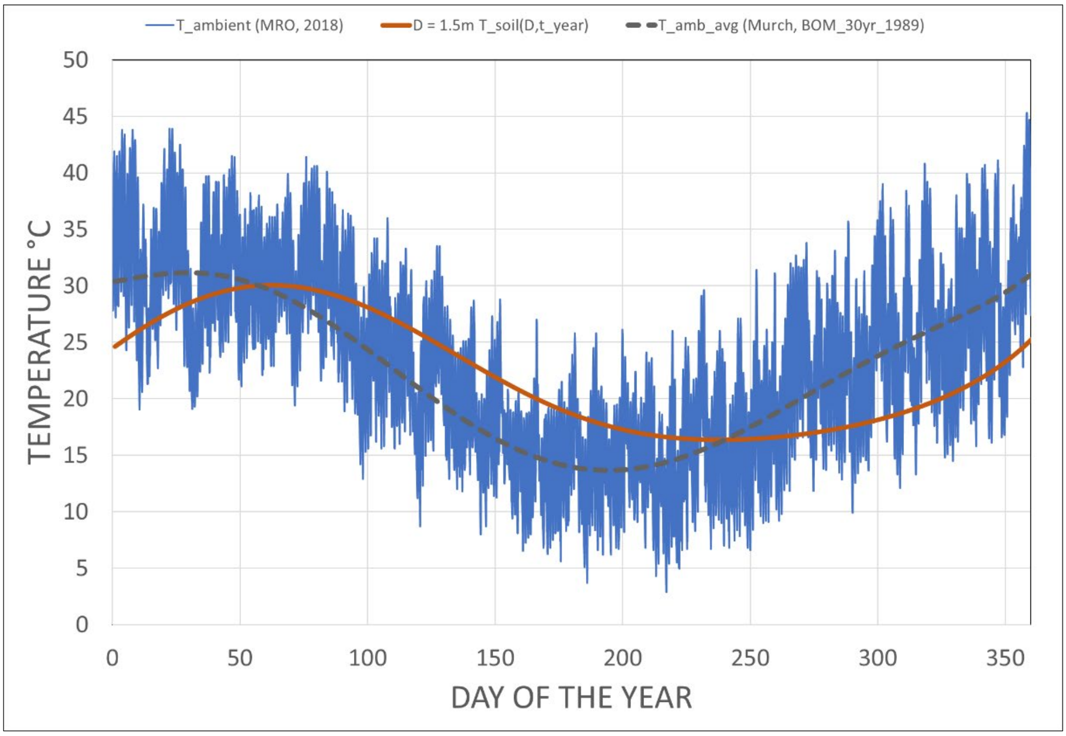

Figure 1: The plots of: daily ambient air temperature at the MRO in 2018 (thin blue line), the 30 years monthly average at Murchison region (dashed grey line), and the calculated average soil temperature at the depth of 1.5 m following the Kasuda model (brown continuous line).

By applying Equation 1 into the ambient temperature profile at the MRO (2018 data), and assuming that the soil at the depth of below 0.5 m is mainly granite bedrock (typical $\alpha = 1.13 \times 10^{-6}$ m^2/ s) [7], we could numerically estimate the average annual profile of the soil temperature at the depth of 1.5 m (assumed to be the depth at which the cable is buried) at the MRO, as depicted in Figure 1. In this figure, it can be observed that the ambient temperature at the MRO throughout 2018 follows closely the 30-year monthly average temperature of the Murchison region. Note that the temperature profile of the soil at the depth of 1.5 m is estimated to be higher than the mean ambient temperature between March to

August (autumn and winter months), and lower during September to February (spring and summer months). Also to be noted is that the amplitude of the temperature at the depth of 1.5 m is reduced/ dampened (calculated by about 4.5°C) relative to peak-to-peak of the average ambient temperature of the Murchison region.

In July 2015, we performed the measurement of the phase stability of the RF signal on the 5 km buried fibre optic cable (looped back to form an 11-km loop), in which the result was reported in LFAA document [3]. At 160 MHz, the relative phase drift between the two selected fibre optic channels was measured to be between 0.1° (phase) and -0.5° (phase) during one of the 24-hour measurement performed between noon time on the 1 July up to mid-day on the following day on 2nd of July (Fig. 2).

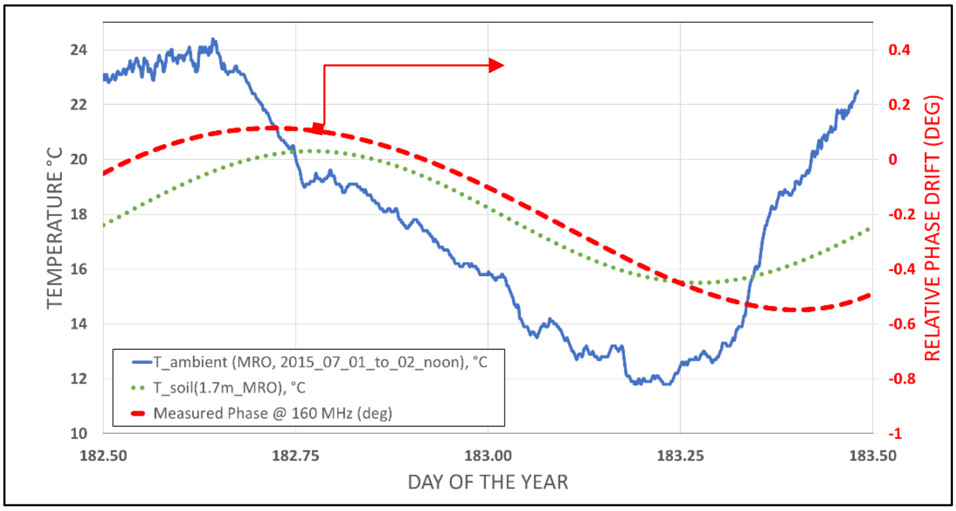

Figure 2: The plot of the 24-hour ambient air temperature at the MRO (continuous blue line), overlaid with the measured *relative phase drift* at 160 MHz transmitted over 5.5 km buried fibre optic cable, looped backed to form 11-km transmission distance (dashed red line) as reported in [3], as well as the *estimated temperature profile of the soil at the depth of 1.7 m* (dotted green line), which is found to be the closest to the profile of the relative phase drift.

When the 24-hour *ambient air temperature* data starting mid-day of July 1st is plotted against the measured relative phase variation, we could see that the *relative phase drift* (dashed red line, Figure 2) follows the *ambient temperature profile* (continuous blue line), albeit it appears that the response is dampened and delayed. Note also that the RF phase variation profile follows a smooth sinusoidal-like response, and appear to be insensitive to the relatively rapid ambient temperature fluctuations.

Applying the Kasuda soil temperature model and adjusting for different soil depth, *we obtained comparatively similar response between the relative phase drift and the temperature profile at the soil depth of 1.7 m* (shown as the dotted green line in Fig. 2). At this depth underground, the estimated peak-to-peak amplitude of the soil temperature is estimated to be around 4° C, *a reduction of* $^{1}/_{3}$ *from the ambient air temperature profile* which has a peak-to-peak amplitude of 12° C.

Also note that there is *delayed peak response of approximately 2-3 hours* between the measured *peak ambient temperature* and the estimated *peak of the soil temperature* at the depth of between 1.7 m -2 m below the surface, and the associated peaks of the relative phase drift profile from the cable buried underground.

As the objective is to replicate thermal response of underground burial, therefore, we will use **a reduction factor of $^{1}/_{3}$ between external temperature and internal temperature, as well as delayed peak response of 2-3 hour** as a selection criteria in determining a suitable insulation solution.

2.2 Short-listed Solutions

As the objective has been set into find a solution that enable us to route the fibre optic cable above the ground while providing relatively similar thermal insulation, we are constrained into finding the solution that allow us not to dig the trench. The idea is to route the cable inside a structure or insulating material that could perhaps replicate the temperature profile of soil underground at a depth. Several solutions were considered, and there are a few short listed solutions evaluated in out lab, in which the highlights are as follow:

2.2.1 ACO Cablemate Ducting

ACO Cablemate is a surface cable ducting solution, with the sample evaluated in our lab having 30 cm width and typically having the length of 1 (one) meter per module (CD3015-75733), as can be seen in Fig. 3. It is made of polymer concrete, both on the U-shaped modular ducting channel as well as the top lid, and can be terminated with end caps made of the same material. When the lid and the end-cap are installed with the modular ducting channel body, together they provide IP4x protection on the cable against foreign object ingress.

The weight of each ducting channel is 21 kg per one-meter length, and the lid will be an extra 17 kg each. The price of the ducting channel is Au$39/m and the lid is Au$27, making the cost of the solution per meter is Au$66/ meter excluding the end cap (each cost $6.75) [9].

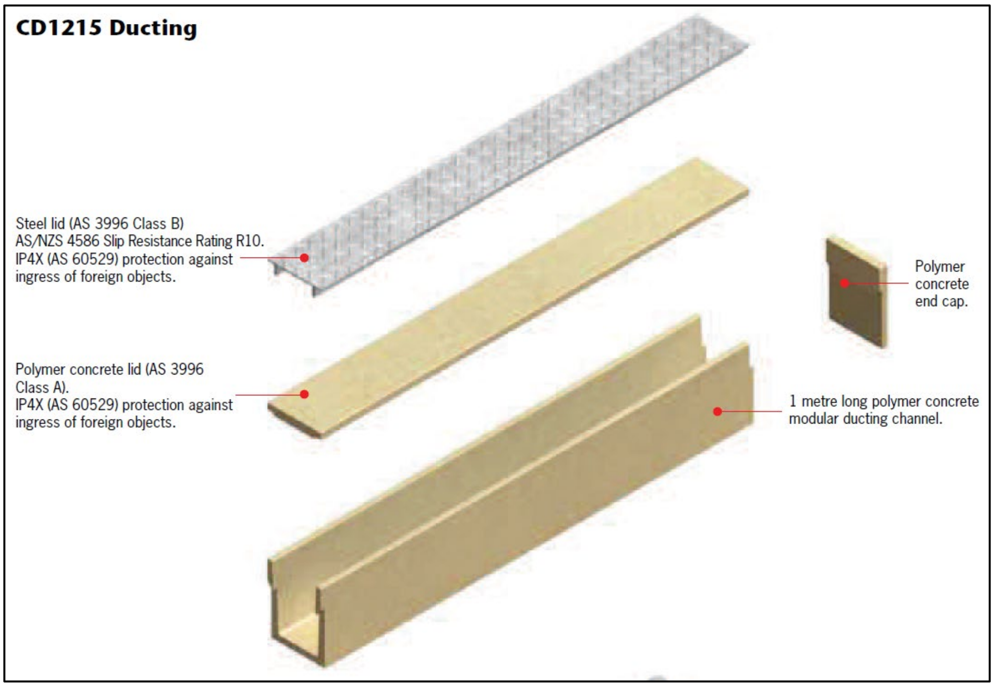

Figure 3: ACO light duty cable ducting system (CD series) made of polymer concrete. (Image: ACO Cablemate)

2.2.2 Roxul RockTech SPI & Sebald EKATEC Silvercladd

Roxul stone wool/ Rockwool pipe insulations are made of basalt (a type of volcanic stone), and provide non-combustible, non-toxic, water repellent properties, as well as ability to withstand up to 650 °C [10]. As the fibre is inorganic and contains no nutritious substance, it does not attract vermin, termites or will not rot due to infestation by microorganisms. Rocktech SPI is a product specific to cater piping thermal and acoustic insulation, supplied as one piece section of 1 (one) meter length, with a selection of inner diameter of between 20 – 800 mm, and wall thickness from 25 mm up to 1000 mm . There is a slit along the longitudinal axis for ease of piping installation, and additional metal foil jacket can be applied at the outer surface of the insulator, which can be supplied with overlapping adhesive flap for ease of installation (Fig. 4).

Figure 4: Roxul Rockwool pipe insulation, with aluminium foil-facing outer jacket. (Source: AIS Pty Ltd).

There is a list of outer jacket type and material that can be selected. For our evaluation samples, we requested for the UV-stabilised EKATEC Silvercladd foil (Fig. 5). The foil is a double layer of laminated aluminium operating up to -25 °C to 75 °C, and coated with a special UV protection and PVC backing: providing corrosion resistance, vapour barrier, water tightness and puncture/ tear resistant outer jacket for the Roxul Stone Wool pipe insulation [11].

Figure 5: UV-stabilised EKATEC Silvercladd foil (Source: AIS Pty Ltd & Sebald ISO-Systeme Gmbh & Co).

We obtained a few samples of 1-meter Roxul Piping Insulation and UV stabilised Silvercladd jacket attached, with three different wall thickness of 25 mm (Sample #1), 50 mm (Sample #2) and 75 mm (Sample #3), all samples having 25 mm inner hole diameter for fitting and routing the fibre optic cable at the core (outer diameter of the between 14.5 mm to 27 mm as reported in [1]). Having the density of 150 kg/ m^3, the weight of the Roxul piping insulation including the EKATEC Silvercladd jacket is 0.7 kg for Sample #1, 2 kg for Sample #2, and 3.8 kg for Sample #3. The quoted price for the Roxul insulating pipe together with the UV-stabilised EKATEC Silvercladd foil jacket are: Au$20/m for 25 mm, Au$32/m for 50 mm, and Au$52/ m for 75 mm wall thickness [12].

2.2.3 Thermotec 4-Zero Pipe Insulation

Another piping insulation solution that we obtained and evaluated was Thermotec 4-Zero, which is a closed cell polyethylene foam, having a density of around 40kg/ m^3 (much lighter than the Roxul Rocktech SPI) [13]. It is non-toxic, fire retardant, anti-microbial, and resistant to moisture and vapour suitable for underground burial (Fig. 6).

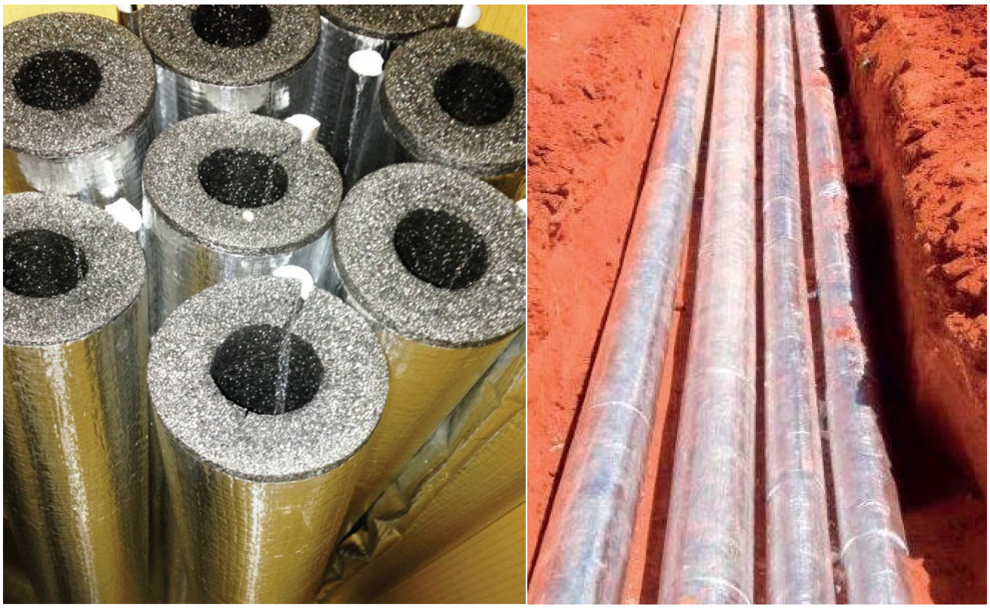

Figure 6: Thermotec 4-Zero with aluminium foil jacket, (Source: Thermotec Australia Pty Ltd).

Like Roxul piping insulation, Thermotec solution comes pre-slit, with heat laminated, factory fitted reinforced aluminium foil jacket. The operating temperature insulation solution is specified from -40 °C - 90 °C. The material is usually factory pre-formed to suit pipe diameters from 13mm to 101.6mm, with insulation thickness of 15mm, 20mm, 25mm, 38mm & 50mm.

We obtained one sample with 25mm internal pipe diameter (hole), 25mm wall thickness and the weight of around 0.2 kg, which is quote at Au$6.00 per 1 meter length [14].

The properties of the short-listed solutions are summarised in the Table 1.

Table 1: The Summary of the properties of the short-listed solutions

No.	Property	ACO Cablemate Ducting	Roxul Rocktech SPI & Seabald UV Silver Cladding	Thermotec 4-Zero & Aluminium jacket
1.	**Length:**	1 m	1 m	1 m
2.	**Wall Thickness:**	10 mm	25-100 mm	15-50 mm
3.	**Inner hole Φ:**	(width: 300 mm)	17-400 mm	13-101.6 mm
4.	**Material:**	Polymer concrete	Natural Mineral Rockwool	Polyethylene (PE) plastic, 50% recycled
5.	**Weight (kg/m):**	38 kg	0.7 kg (25mm), 1.2 kg (50mm)	0.2 kg (25 mm)
6.	**Operating temperature (°C):**	-	Up to 650 °C (inner) -25 °C to 75 °C (cladding)	-40 °C to 90 °C (inner)
7.	**Thermal conductivity:**	2.8 W/m.K @ 25°C	0.034 W/m.K @ 20°C	0.032 W/m.K @ 23°C
8.	**Water absorption:**	-n.a-	1% (BS 2972 Section 12)	2% (DIN53434)
9.	**UV resistance:**	Unknown, expected	YES (with Al Silvercladding) ISO 4892-2 & ASTM G 26A	YES (Aluminium jacket)

10.	**Puncture/ tear resistance:**	Unknown, expected	YES (prEN 14 477/ EN ISO 527-3)	NO (Info not available)
11.	**Toxicity:**	Unknown	Non-hazardous/ carcinogenic (Cat O, 67/548/EEC)	Non-toxic (BS6853)
12	**Biological Property:**	Not established	Contains no nutrients: Resistance to fungi, moulds or bacteria; does not attract insects, rodents or vermin.	Resistance to rodents/ pests.
13.	**Fire:**	Unknown	Non-combustible (ISO 1182)	No Ignitability
14.	**Corrosion/ Acid resistance:**	Unknown, expected	YES ASTM C795, AGIQ135	YES (ASTM543.56T)
15.	**Price (Au$ @ 1 m):**	$66	$20 (25mm, with UV cladding) $32 (50mm, with UV cladding)	$6

2.3 Thermal Response under Controlled Ambient Temperature

Included in Table 1 is the Thermal Conductivity values of the short-listed solution. Note that the Thermal Conductivity of the ACO Cablemate solution is found to be relatively high (2.8 W/m.K @ 25°C) compared to Roxul Rockwool and Thermotec (~0.03 W/m.K @ 20°C – 25 °C). What it means is that although the thermal mass of the ACO Cable mate is relatively large, it could potentially also be more sensitive to thermal fluctuation it is exposed to, relatively compared with the Rockwool and Thermotec solutions.

As it is difficult to evaluate the big bulky concrete due to the weight and the size in the lab, we decided to initially measure the thermal response of the ACO Cablemate ducting, and compare the relative performance with other short-listed solutions. This was performed by measuring the thermal response inside each solution when subjected to exposure to the ambient temperature in the lab, where the temperature of the lab is controlled using HVAC (Heat Ventilation Air Conditioning) System during the day, and the Inverter Air Conditioner during the night time.

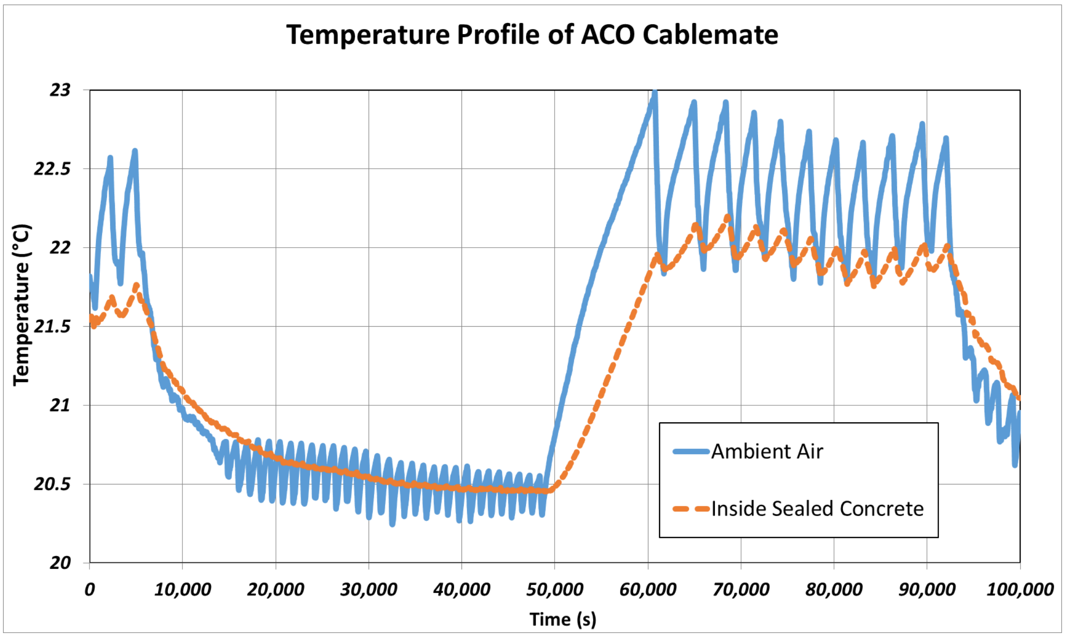

Figure 7: Temperature profile inside the ACO Cablemate Ducting when exposed to varying ambient temperature in the lab.

Figure 7 shows the temperature measurement inside the sealed ACO Cablemate concrete ducting responding to ambient air temperature inside CIRA lab. At around 18:00, the Inverter Air Conditioning is activated (5,000 seconds after the measurement was initiated), and the temperature is cycling rapidly around 20.5°C ± 0.25°C every 15 minutes throughout the night until 6:00 the following day (48,000 seconds from the start). It can be seen that the temperature inside the sealed concrete ducting is relatively stable during this rapid cycle of temperature at night.

During the day starting from 6:00, the HVAC system kicked in, and appears to cycle the ambient temperature to around 22 °C on the day the test started (15/1/2019). The temperature inside the concrete ducting appears to follow the temperature fluctuations, though damped and attenuated. With ambient air temperature fluctuation of about 1 °C peak-to-peak cycling about 40 - 60 minutes, the temperature inside the concrete ducting was cycling to about 0.3 °C peak-to-peak, a reduction by a scale factor of around $^{1}/_{3}$ from the ambient air temperature amplitude profile hovering around 22.5°C. Note that this reduction scaling is similar to the estimated temperature profile at the depth of around 1.7 meter, as discussed previously in Section 2.1.

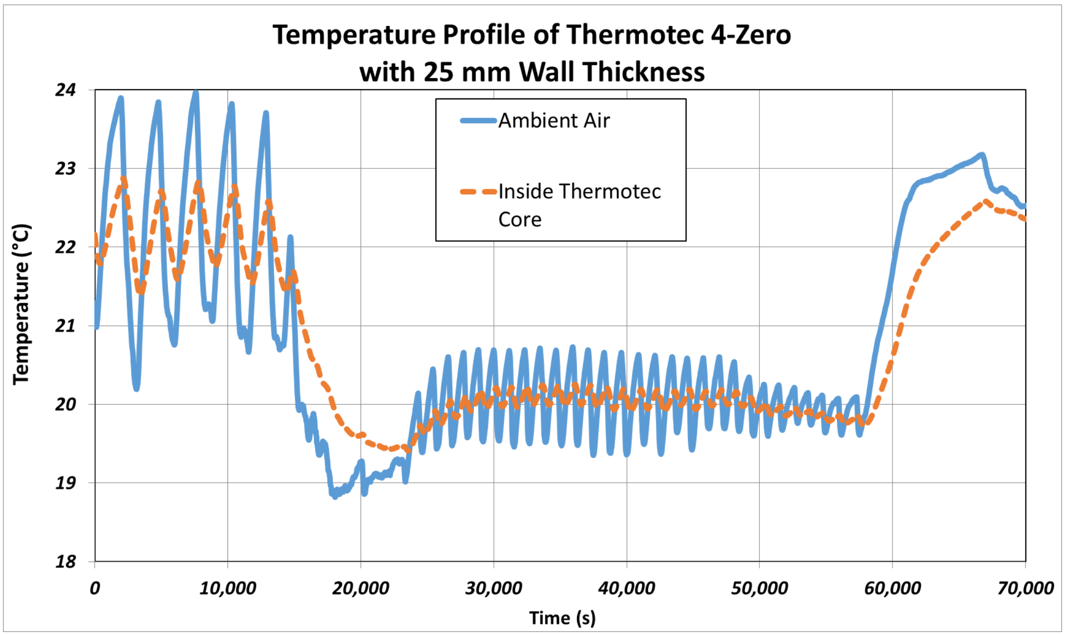

Figure 8: Temperature profile inside the core of the Thermotec 4-Zero insulator when exposed to varying ambient temperature in the lab.

Figure 8 shows the temperature measurement inside a sealed Thermotec 4-Zero piping insulator with respect to ambient air temperature inside CIRA lab. The thickness of the cylindrical material is 25 mm, with 20 mm diameter hole inside and a length of 1 m. The insulator material comes with the aluminium outer jacket.

On the day it was measured (starting 22 January 2019), during the day at the start of the measurement around 13:00, the HVAC system was operating, and appears to cycle the ambient temperature to around 22 °C. The temperature inside the Thermotec appears to follow the ambient air temperature fluctuations, though damped and attenuated. With ambient air temperature fluctuation of about 3 °C peak-to-peak cycling about 40 - 60 minutes, the temperature inside Thermotec insulator was cycling to about 1 °C peak-to-peak, a reduction by a scale factor of $^{1}/_{3}$ from the ambient air temperature profile hovering around 22°C. Like the case of the concrete block this reduction factor is also similar to the calculated temperature profile at the depth of 1.7 meter, as discussed preciously in Section 2.1.

At around 18:00, the Inverter Air Conditioning is activated (around 16,000 seconds after the measurement was initiated), and the temperature is cycling rapidly around 20°C ± 0.7°C every 15 minutes throughout the night until 6:00 in the morning the following day (57,500 seconds from the start of the measurement). It can be seen that the temperature inside the sealed concrete ducting is attenuated during this rapid cycle of temperature at night, though not as smooth as the temperature profile inside the sealed concrete (ACO Cablemate Ducting) shown in Figure 8. This might be due to larger temperature swing than when the concrete ducting was measured. As the peak-to-peak amplitude of the temperature cycle inside the Thermotec insulator is 0.22°C, the scale factor of the temperature inside the insulator at 20°C against rapid 15-minutes cycle during at night is around $^1/_6$ reduction with respect to the ambient temperature.

This results shows that based on the limited testing at controlled ambient air temperature of between 20 °C to 22 °C, the Thermotec insulator with 25 mm wall thickness and the ACO Cablemate concrete ducting has comparable and similar attenuation and damping profile of around $^1/_3$ scaling factor with respect to the ambient air temperature fluctuation in the lab.

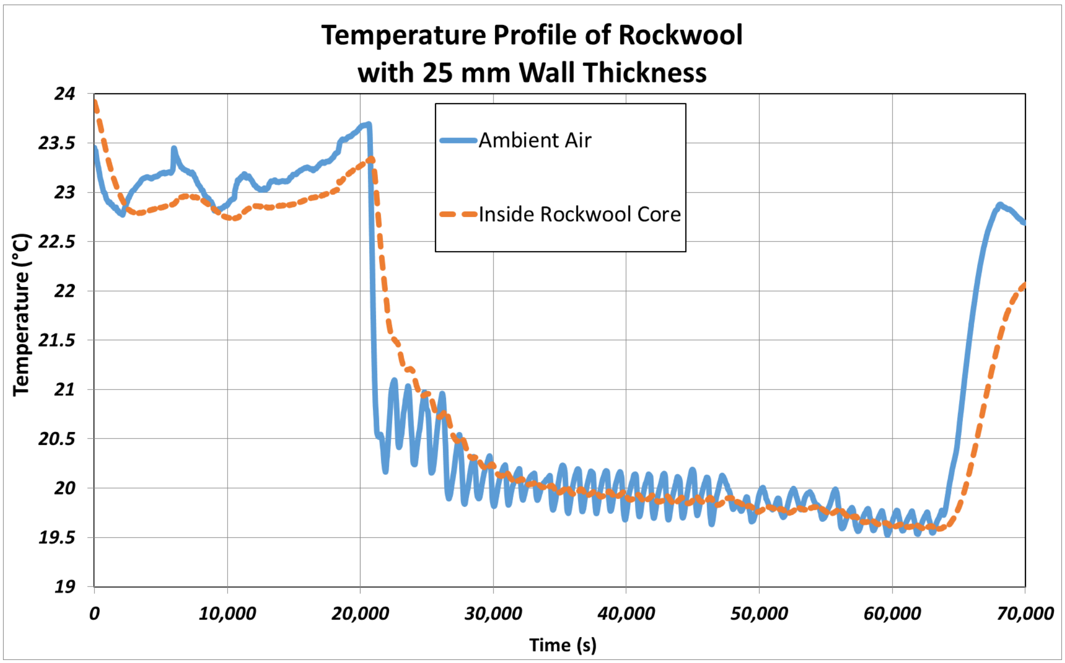

Figure 9: Temperature profile inside the core of the Roxul Rockwool insulator when exposed to varying ambient temperature in the lab.

Figure 9 shows the temperature measurement inside a sealed Rockwool piping insulator with respect to ambient air temperature inside CIRA lab. The thickness of the cylindrical insulating material is 25 mm, having 25 mm diameter hole at the core and a length of 1 m. The insulator material comes with the UV Silvercladding aluminium outer jacket, and exposed to the lab ambient air.

On the day it was measured (starting around noon time on 25 January 2019), at the start of the measurement, the HVAC system was in operation, and appears to have drifting ambient temperature at around 23 °C, without any cycling profile. The temperature at the core inside the Rockwool insulator appears to follow the ambient temperature fluctuations, though damped and attenuated up to 0.5 °C from the ambient. After 18:00 (20,000 seconds after the start), the Inverter Air Conditioning was activated, and ambient air temperature was cooled down to 20 °C fluctuation of about 0.4 °C peak-to-peak cycling for every 15 minute. The temperature inside Rockwool insulator was cycling with an amplitude of 0.1°C peak-to-peak, a reduction by a scale factor of between $^1/_4$ from the ambient air temperature profile, which is similar to the profile of the ACO Ducting concrete block and the Thermotec insulation, and seems to be similar to the reduction scaling factor of the soil at the depth of 1.7 meter (scaling factor of $^1/_3$), as discussed in Section 2.1.

Based on these limited assessments comparing the temperature profile inside/ in the core of each solution against ambient air temperature inside the lab (20 °C - 25 °C), *the results suggest that all of the solutions have similar performance in attenuating the ambient air profile by at least a scale factor* *of $^1/_3$, which is similar with the attenuation scaling factor of burying the cable underground at the depth of 1.7 m in attenuating the diurnal cycle of the ambient air in the field.* Note however that the peak-to-peak amplitude of the diurnal cycle is higher than the ambient air temperature in the lab, we proceeded with further characterisation of two of the insulations (i.e. Thermotec and Rockwool insulation), by subjecting both solutions with a wider temperature range simulating the condition in the field as well as characterising its profile against rapid temperature changes.

We decided not to proceed with ACO Cablemate ducting concrete, as we found after these evaluations that the temperature response of the is comparable to both Thermotec and Rockwool, but having the disadvantage of being heavier, bulkier and more costly to procure, as well as relatively difficult to deploy in the field.

2.4 Temperature Characterisation of Thermotec and Roxul Rockwool Insulators

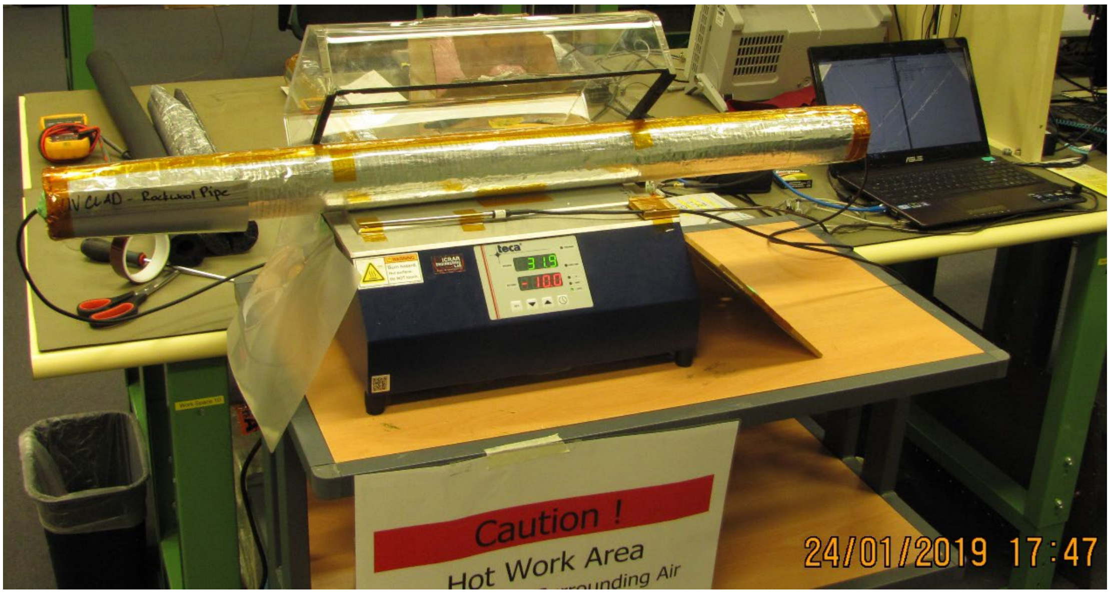

Figure 10: The set up for characterising the temperature profile insulation materials utilising a Hot/ Cold thermal plate (TECA AHP-1200 CPV).

We performed further characterisation of the insulating materials utilising Hot/ Cold thermal plate available at CIRA lab (TECA AHP-1200 CPV), as depicted in Fig. 10. In this set up, each sample-under-test was placed on the thermal plate. To preserve the condition of the material from deformation, no modification is performed on the insulating material (e.g. cutting the length to fit the thermal plate), where each insulation sample (1 meter) was placed on the thermal plate (with length of 30 cm) and only the middle $^1/_3$ section of the along the sample length was placed on the plate.

At every measurement, the temperature of the thermal plate, the ambient temperature immediately surrounding the set-up, the surface temperature of the material, as well as the core temperature inside right at the middle point of each material (~50 cm from both ends) were all recorded. Each material was sealed using Kapton tape during the measurement, along the longitudinal length, as well as at both ends of the sample, where any remaining holes were further sealed with Blu Tack. The temperature of the thermal plate was ramped up and ramped down between -10 °C - 70 °C at a rate of 0.1°C/ minute, to simulate the temperature condition at the MRO, where the 24-hour maximum temperature change in a 600-second window was reported as 1.1 °C [4]. Each measurement typically would run for 32 hours and 36 minutes.

Note that as only a small area of the sample is making surface contact to the Hot/ Cold thermal plate and that most of the surface of the insulating material are directly exposed to the ambient air, it was anticipated that the ambient air temperature fluctuation (due to the air conditioning) would affect the temperature measured at the surface of the sample.

As the remaining $^{2}/_{3}$ of the sample material was further away from the thermal plate and exposed to ambient air temperature of the lab, we monitored the surface temperature (aluminium jacket) of each sample just above the interface between the surface of the thermal plate and the sample-under-test, and used this data for relative comparison with the temperature at the centre of the cross-sectional core of the sample (i.e. used to calculate the temperature reduction scaling ratio).

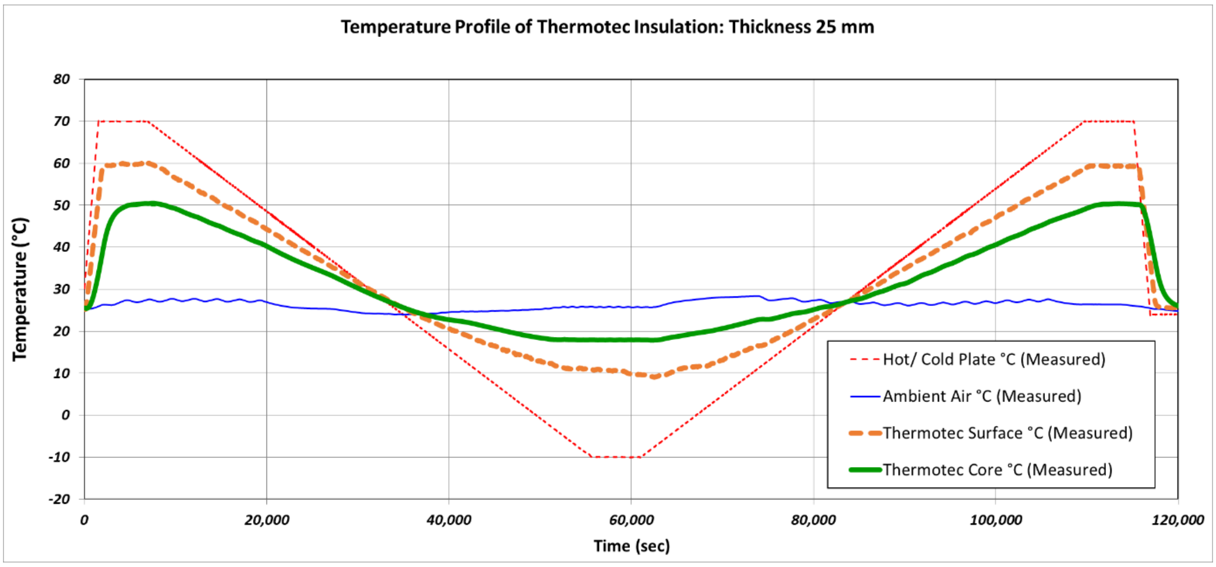

Figure 11: Temperature profile at the core of Thermotec 4-Zero sample with 25 mm wall thickness (thick green continuous line) responding to thermal ramp-up/ ramp-down of -10°C to 70°C on the plate (red dashed line). The ambient air temperature near the surface of the material is shown in the thin continuous blue line, and the surface temperature of the aluminium jacket is son as the thick orange dashed line. Note that the peak-to-peak amplitude of the temperature at the core of the sample is 32.65 °C.

Figure 11 illustrates the results of the measurement performed on Thermotec 4-zero sample with 25 mm wall thickness, where the temperature of the thermal plate is shown as the red dashed line, the ambient air temperature immediately surrounding the set-up is the blue continuous line, and the surface temperature is shown as the thick orange dashed line. The temperature profile at the core of the Thermotec sample can be seen as the thick green continuous line in Fig. 11, where the peak-to peak amplitude is calculated to be 32.65°C (max: 50.5°C and min: 17.85°C). At the surface of the insulating material, the peak-to-peak temperature amplitude of the aluminium jacket was measured to be 50.96°C (with max: 60°C and min: 9.1°C). The ratio between the amplitude of the surface temperature and the core temperature of the sample is calculated to be **0.64**.

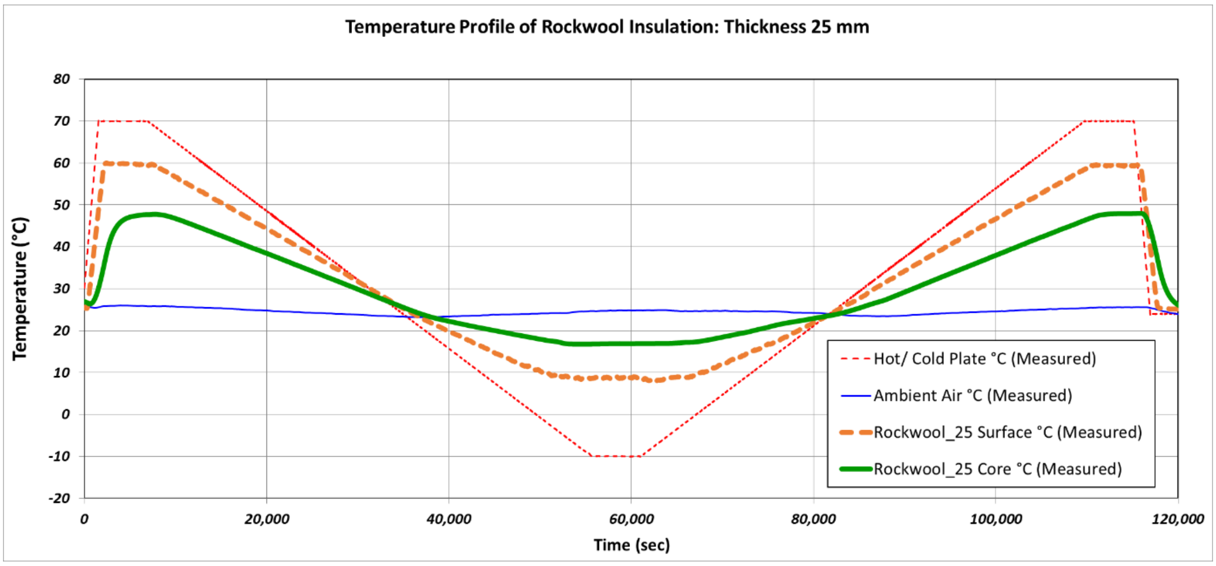

Figure 12: Temperature profile at the core of Roxul Rockwool sample with 25 mm wall thickness (thick green continuous line) responding to thermal ramp-up/ ramp-down of -10°C to 70°C on the plate (red dashed line). Note that the peak-to-peak amplitude of the temperature at the core of the sample is 31.22 °C.

Figure 12 shows the results of the measurement performed on Roxul Rockwool sample with 25 mm wall thickness, where the peak-to-peak temperature amplitude at the core of the Rockwool sample (thick green continuous line) is calculated to be 31.22°C (max: 47.98°C and min: 16.77°C). At the surface of the insulating material, the peak-to-peak temperature amplitude of the aluminium jacket was measured to be 52°C (with max: 60.1°C and min: 8°C). The ratio between the amplitude of the surface temperature and the core temperature of the sample is calculated to be **0.60**, slightly lower than the calculated ratio of the Thermotec sample.

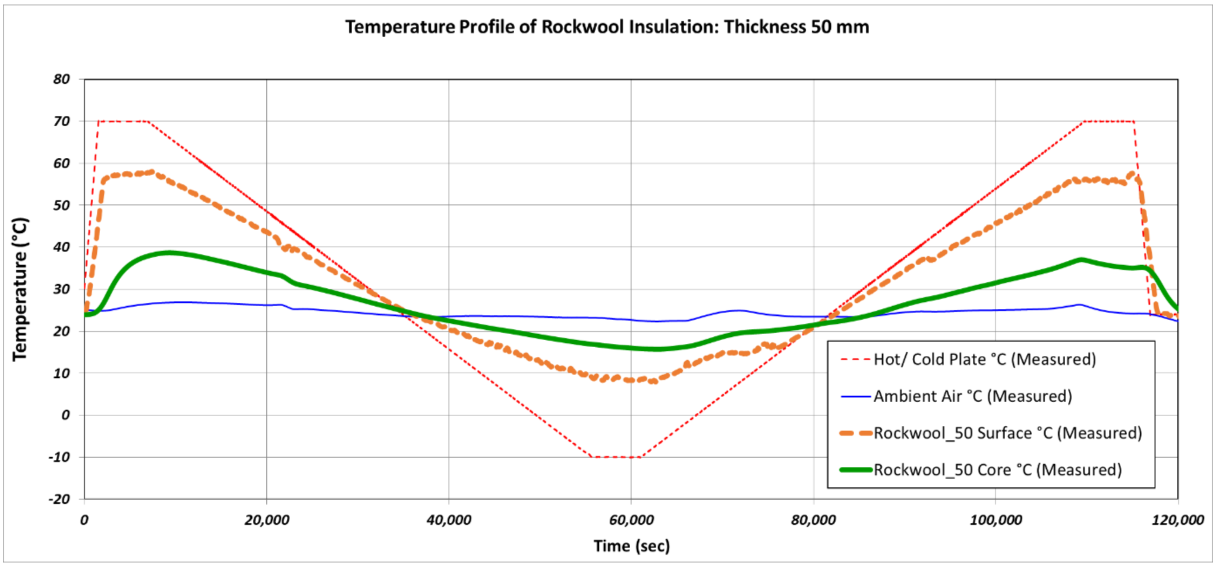

Figure 13: Temperature profile at the core of Roxul Rockwool sample with 50 mm wall thickness (thick green continuous line), where the peak-to-peak amplitude of the temperature at the core of the sample is 22.99 °C.

The measurement results of the Roxul Rockwool sample with 50 mm wall thickness is shown in Fig. 13, where the peak-to-peak temperature amplitude at the core of the Rockwool sample (thick green continuous line) is calculated to be 22.99°C (max: 38.69°C and min: 15.71°C). At the surface of the insulating material, the peak-to-peak temperature amplitude of the aluminium jacket was measured to be 50.15°C (with max: 58.1°C and min: 7.93°C). The ratio between the amplitude of the surface temperature and the core temperature of the sample is calculated to be **0.46**, relatively closer to the reduction scaling factor of the soil at the depth of 1.7 meter (scaling factor of $^1/_3$).

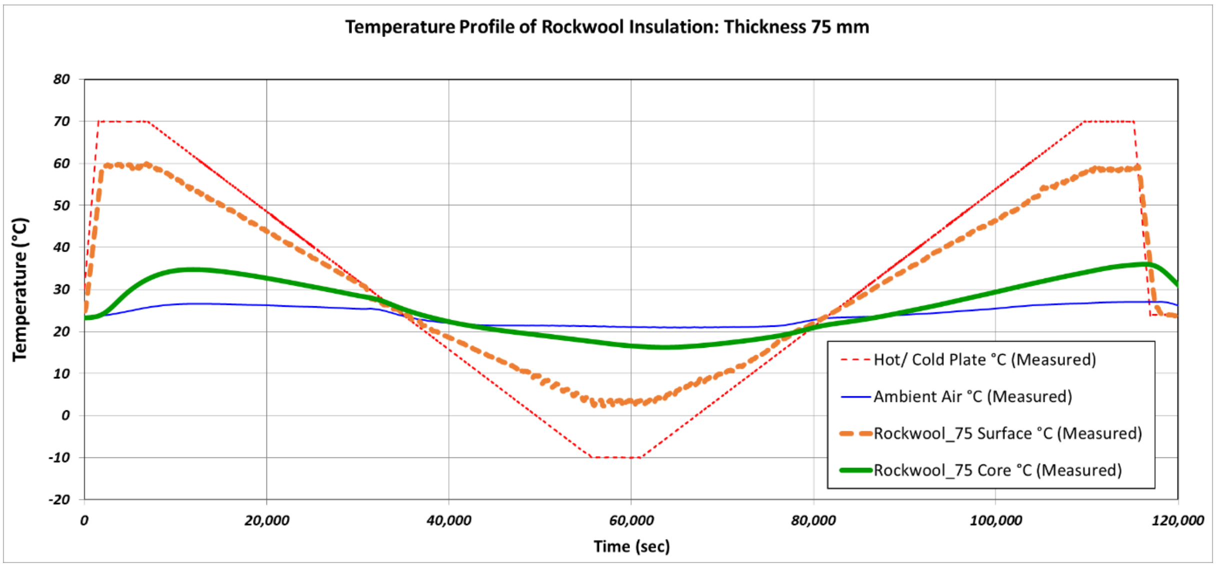

Figure 14: Temperature profile at the core of Roxul Rockwool sample with 75 mm wall thickness (thick green continuous line), where the peak-to-peak amplitude of the temperature at the core of the sample is 19.77 °C.

Figure 14 shows the results of the measurement performed on Rockwool sample with 75 mm wall thickness, where the peak-to-peak temperature amplitude at the core of the Rockwool sample (thick green continuous line) is calculated to be 19.77°C (max: 36°C and min: 16.23°C). At the surface of the insulating material, the peak-to-peak temperature amplitude of the aluminium jacket was measured to be 57.81°C (with max: 59.81°C and min: 2.14°C). The ratio between the amplitude of the surface temperature and the core temperature of the material is calculated to be **0.34**, making this Rockwool insulation sample (75 mm wall thickness) to be the closest to the reduction scaling factor of the soil at the depth of 1.7 meter (scaling factor of $^1/_3$) compared those samples with thinner wall (25 mm and 50 mm).

While the results shows that the thickness of 75 mm seems to be close to the temperature profile of the soil at the depth of 1.7m, upon further analysis of the measured results, **it is found that for surface temperature above 25°C, the profile of the Rockwool material in attenuating the surface temperature with 50 mm wall thickness is relatively close to those of the 75 mm sample**, as can be seen in Figure 15.

Since the response of the 50 mm Roxul Rockwool material is close to the 75 mm Rockwool material, and there is a significant weight and size reduction as well as cost (as summarised in Section 2.2.2), Rockwool insulator with 50 mm wall thickness is selected for further evaluation.

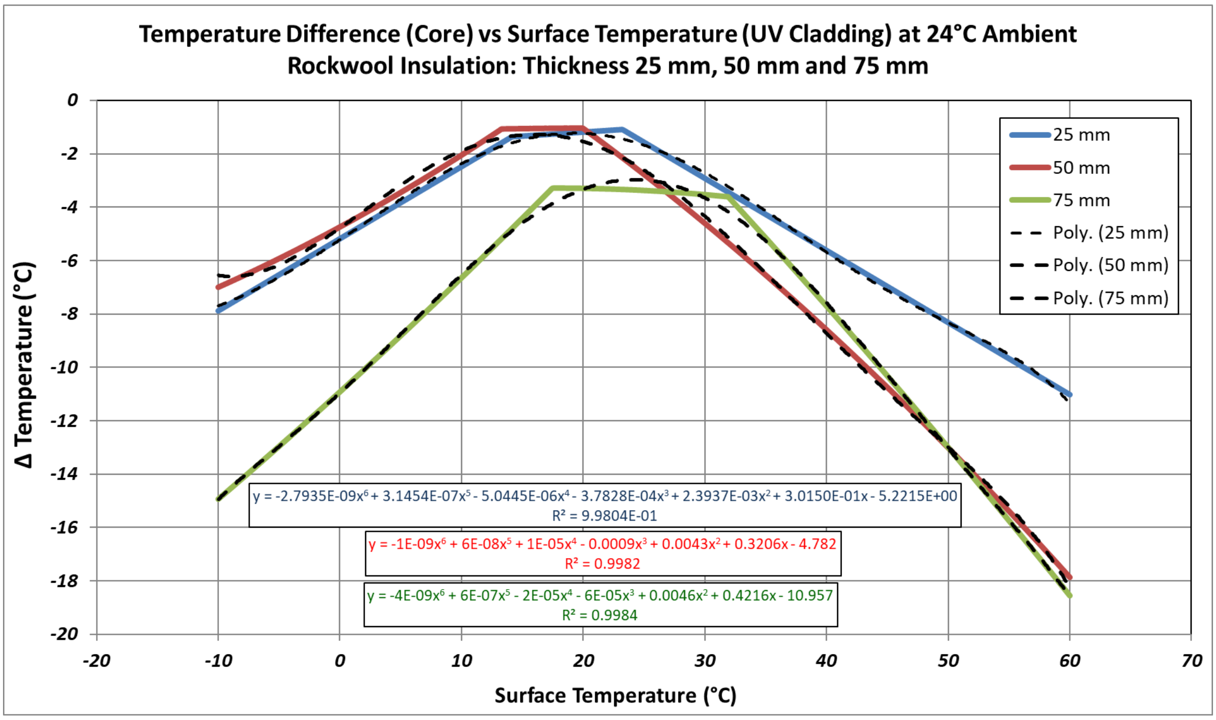

Figure 15: Calculated temperature difference between the core of the Roxul Rockwool sample and the surface temperature (UV cladding) for different wall thickness (25 mm, 50 mm and 75 mm). Note that the values below 10°C and above 55°C are based on extrapolating measured results. Polynomial fittings are provided on the traces to enable estimation of attenuation profile across the temperature.

Note that because of the limitation in the lab set-up where lab ambient temperature is affecting the temperature of the set-up (especially the surface temperature of the sample), we could not consistently heat-up and cool-down the temperature of the surface of the samples evaluated to the desired temperature, especially when the applied temperature on the thermal Hot/ Cold plate was set below the ambient air temperature. This can be seen by observing the surface temperature of the 75 mm thick sample, where the minimum surface temperature (thick dashed orange line) is 2.14°C (Fig. 14), compared to other measurements, where the minimum temperature is around 8°C - 9°C. (Fig. 11- Fig 13).

Note also that the ambient temperature (shown in the continuous blue line, Fig. 14) during the measurement is lower (min: 20°C) than when the minimum ambient temperature during other measurements (Fig. 11- Fig 13). Nevertheless, for temperature above ambient air temperature, the surface temperature on the jacket seems to be less affected by the fluctuation of the ambient air temperature.

In the future, if access to full environmental chamber is available, we could revisit these measurements again to isolate the effect of ambient air temperature (especially reassessing those profile below the ambient air temperature as shown in Fig. 11- Fig 14), and update the fitting model for improving the accuracy of the estimated temperature profile inside the core of the insulator.

To determine the transient response and the rise time/ fall time temperature delay profile of the insulating material, we performed thermal characterisation against rapid temperature rise and fall, as depicted in Figure 16.

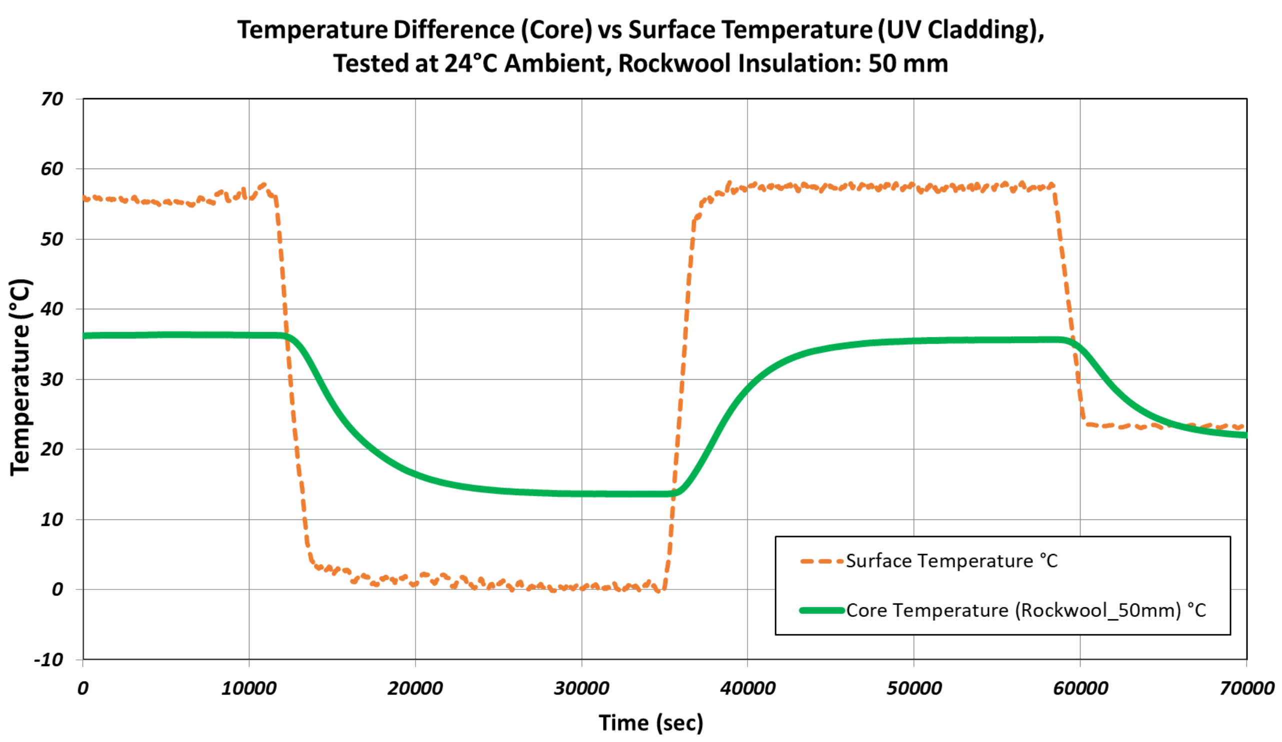

Figure 16: Transient response profile of the temperature at the core of the Roxul Rockwool sample (green continuous line) with UV Silvercladding aluminium jacket and 50 mm wall thickness, responding to a rapid temperature cycle of the imposed on the surface ranging, as measured from 0°C to 58°C (orang dashed line).

In the set-up, Roxul Rockwool sample with 50 mm wall thickness and UV Silvercladding jacket was placed on the thermal Hot/ Cold plate. The thermal plate was then set to rapidly from -10°C to 70°C within 10 minutes (600 seconds), with the ambient temperature of the room recorded at 24°C ± 2 throughout the measurement.

As can be seen in Fig. 16, the surface temperature of the insulator was measured to be fluctuating between 0°C to 58° (orang dashed line), responding to the thermal cycle applied though the surface contact to the thermal plate, as well as the ambient temperature. Note that during this measurement, as the ambient temperature of the lab was low during the measurement, the surface temperature of the sample-under-test could be pull down near 0°C (Fig. 16), compared to previous evaluation depicted in Fig. 13, where the minimum surface temperature was just around 8°C.

It took on average around 45- 50 minutes for the surface temperature at the cladding jacket to settle to the steady state condition, responding to the thermal plate rapid temperature square response. The temperature at the core of the 50 mm thick Rockwool insulator was recorded to fluctuate between 13°C to 36°, resulting in the **peak-to-peak ratio of around 0.37** between the surface temperature and the core temperature. **The temperature reduction profile at the core of the 50 mm Rockwool material obtained through this measurement is close to the temperature reduction scaling factor of $^{1}/_{3}$ due to 1.7m underground burial** (as described in Section 2.1), as well as close to the 0.34 ratio of the Rockwool material with 75 mm wall thickness shown in Fig. 14.

Note also that the delayed rise time and the fall time response of the temperature profile in the core of the insulator responding to the change in surface temperature is approximately 8,300 seconds (160 minutes), which is around **3.5 times slower** than the time it takes for the surface temperature to rise and fall settling into the steady state response when fluctuating between 0°C to 58°.

2.5 Estimating the Effect of Rockwool Insulation on the Relative Phase of the Transmitted RF Signal over the Fibre.

Noting that LFAA L3 requirement specifies relative phase variation between two links are specified for every 600-seconds (10 minutes) as summarised in Table 2. There are two requirements listed in Table, 2, the first is based on the LFAA L3 requirement as captured in the AAVS1 System requirement [15], and the proposed "new" requirement as reported in [16].

Table 2: Extract of relevant LFAA L3 receiver RF requirements [15] and the proposed revision [16].

	Requirements	Notes
Relative phase variation between two links (within 600 seconds), LFAA L3 requirements [15]	< 2.9°, 1.2°, 1.2° and 2.9° At 50, 100, 160 and 220 MHz	Based on phase variation (degree) of entire RF link. Specification at 350 MHz to 650 MHz is TBC.
Relative phase variation between two chains (within 600 seconds), Proposed revision of LFAA L3 requirements [16]	< 8.5°, 2.6°, 3.9°, 7.2° and 61.6 ° At 50, 100, 160, 220 and 350 MHz	Based on phase variation (degree) of entire RF links, from 50 MHz to 350 MHz. Derived from SKA1-SYS_REQ-2629

Based on the thermal characterisation of the insulation given earlier in Section 2.4, it can be predicted that with the estimated dampening effect of the Rockwool insulation with 50 mm thickness (**of up to 3.5 times slower in transient response and at least 0.46 factor reduction in the peak-to-peak temperature amplitude**), the relative phase variation of the RF signal in Bridging Array can further be reduced by applying the insulation encasing the fibre optic cable used for the Bridging Array, along the whole 200 m cable length as routed in the field. We could quantify and calculate the effect of this insulation, the relative phase stability of the fibre optic cable.

It has been previously discussed in [2] that for a pair of fibres, assuming α and β of each of the fibres are similar, the relative phase variation due to temperature fluctuation can be estimated as:

$$\Delta\varphi_{FO1-FO2} = 360^{\circ} \cdot f \cdot \left|[(n \cdot \alpha) + \beta] \cdot \left[\left(\frac{L_{0,FO1} \cdot \Delta T_{FO1}}{c}\right) - \left(\frac{L_{0,FO2} \cdot \Delta T_{FO2}}{c}\right)\right]\right| \qquad (2)$$

Where n is the refractive index of the fibre core (1.47, assuming that refractive index does not change with the elongation of the fibre nor with temperature change), α = linear thermal expansion coefficient (m/m °C^{-1}), $\beta = \frac{\Delta n}{\Delta T}$ is the temperature coefficient of refractive index (m/m °C^{-1}), L_o = initial fibre length (m), c is the speed of light in vacuum (2.99x10^{8} m/s), and), ΔT = temperature change (°C) over the time from a certain reference point. The value for α is ~0.56 x10^{-6} °C^{-1} and β is ~1.2 x10^{-5} °C^{-1} as reported in [2].

Eq. (2) gives us an estimate of the phase variation in a pair of fibre. We could also estimate the phase variation with respect to thermal expansion as we scale the length of the cable. Note that **the length and the temperature parameters of the cable as described in in Eq. (2) both have linear relationship with respect to the relative phase variation of the cable**.

During southern hemisphere winter in August 2016, we performed characterisation on the actual AAVS 1 fibre optic cables: the AFL SWR cable (Cable #1) and SDGI cable (Cable # 2), as described earlier in the Introduction Section. The result of the 24-hour relative phase measurements (600-second window) can be seen in Figure 18, where we measured combination of fibre core link pairs selected from different cross-sectional locations of the cable, as described in [2] and [1]. We selected the worst possible combinations of the relative phase variations of different WDM laser wavelengths (1270 nm for Channel 1 and 1330 nm for Channel 2 used in AAVS 1), each transmitted over different fibre core from different bundle (AFL SWR cable) or loose tube (SDGI cable) from the opposite location in the cross section of the cable. The measurement results were processed and corrected (scaled) to reflect the estimated relative phase response at the actual cable length of around 5 km, **assuming linear correlation between the length of the cable and the relative phase response**, as discussed in [2].

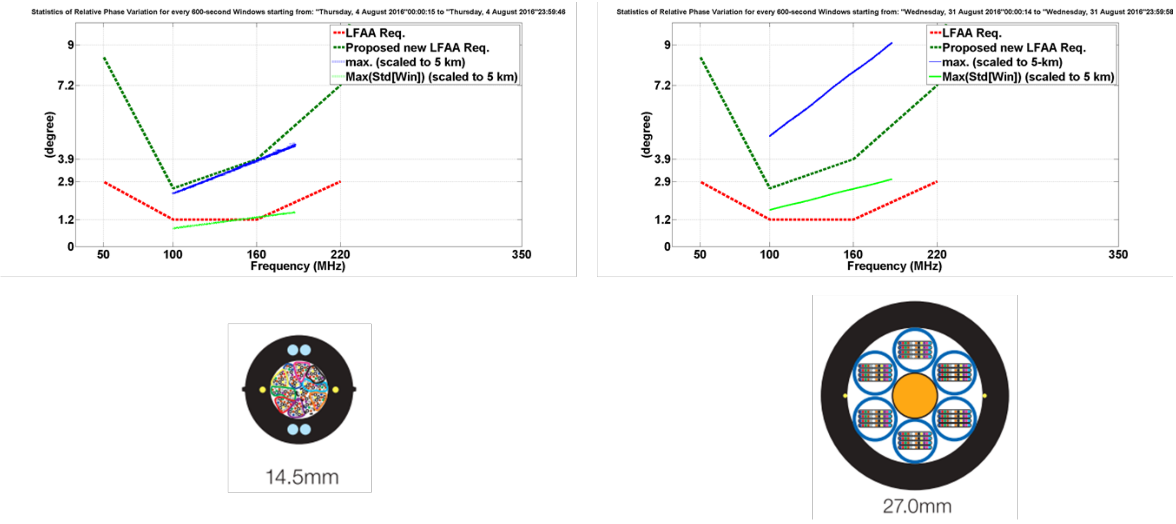

Figure 17: The statistics of 24-hour *relative phase variations* (600-second window) of the actual AAVS 1 Cable: AFL SWR fibre cable (left) and SDGI fibre cable (right). Shown are the results for the case where different transmission wavelengths were used, where each wavelength transmitted on different fibre core from selected from opposite locations inside the cable. Result are scaled to 5 km [1].

Shown in Fig. 17 is the processed *maximum relative phase difference* of the 600-sec window throughout the 24-hour measurement (***Max[Win]***, dark blue continuous line) and the *maximum standard deviation of the relative phase difference* of the 600-sec window in a 24-hour priod (***Max (Std[Win])***, light green continuous line). The dashed green line (top limit line) is the *Proposed New LFAA requirement* as discussed in [16], whereas the dashed red line (bottom limit mask) is *the LFAA L3 requirement* as stated in [15]. This results shows that for a 5 km transmission on a surface laid cable exposed to the elements in the field, only the *Max[Win]* of Cable # 1 (AFL SWR) is below the Proposed New LFAA requirements and that the *Max(Std[Win])* of Cable # 1 (AFL SWR) is below the LFAA L3 requirements.

The results indicated that the AFL AWR (Cable #1) generally has lower a relatively phase variation than the SDGI (Cable #2). This is not due to the quality of the fibre materials, but rather because of the structural construction and relative cross-sectional size of the cable. As has been discussed in [1], this is attributed to the fact that the relative phase stability of RF signal is strongly influence by the temperature difference each fibre core at any given time, as described earlier through Eq. (2). As a consequence, **a larger cable diameter results in a wider separation distance between each fibre cores, and a higher temperature difference**.

Looking closely to Cable # 2 (SDGI cable), i.e. the cable with the worse 600-sec *relative phase variation* response (Fig. 17), it is worth to plot the measured 24-hour relative drift of the 5 km surface laid cable, as shown in Figure 18, where the *relative phase drift* at 160 MHz is as this corresponds to the highest frequency point where the LFAA L3 requirements are at the minimum (least-upper-bound limit) [2].

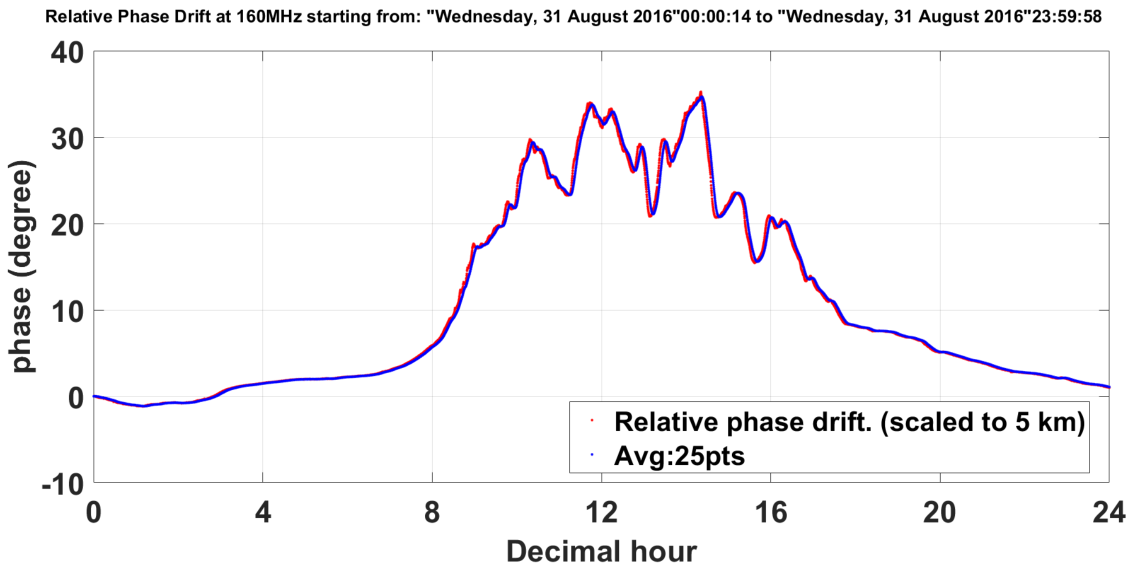

Figure 18: The 24-hour *relative phase drift* at 160 MHz of the actual AAVS 1 Cable: SDGI (Cable # 2). Shown are the results for the case where different transmission wavelengths were used, each wavelength transmitted on different fibre core from selected from opposite locations inside the cable. Results scaled to 5 km.

Figure 19 shows the *relative phase drift* at 160 MHz *scaled to 200 m* (to reflect the transmission distance of Bridging Array), assuming linear scaling between total length of the cable and the relative phase difference, as discussed in [2]. The *relative phase drift* of the bare fibre cable without insulation is shown as the dotted red line (top trace), and the estimated response after the application of Roxul Rockwool insulator with 50 mm wall thickness, shown as the continuous blue line (bottom trace), incorporating the damping and delay profile of the insulator as described in Section 2.4.

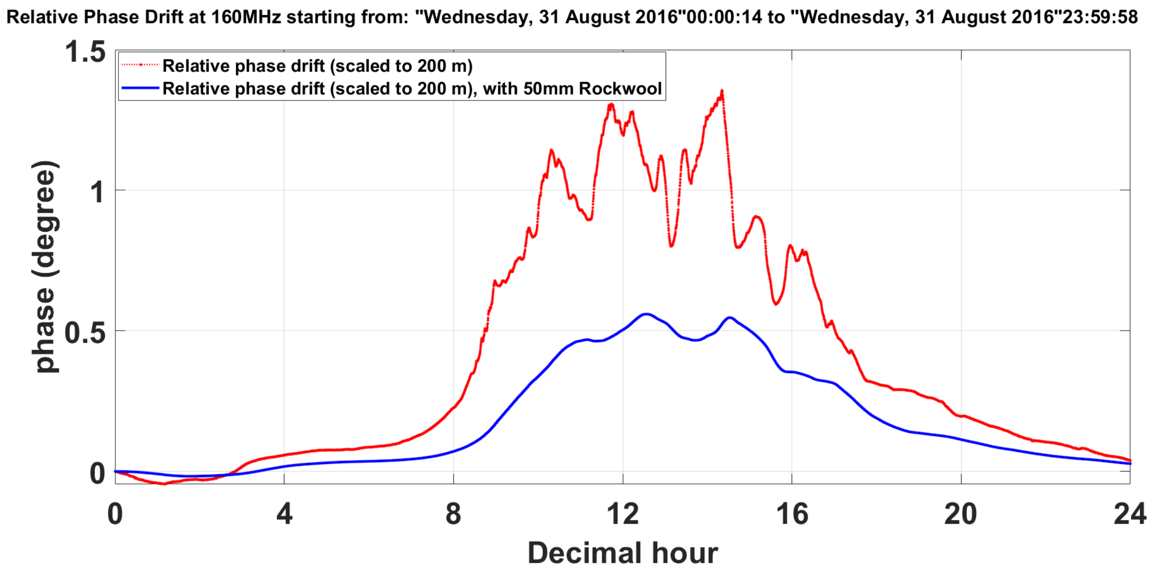

Figure 19: The 24-hour *relative phase drift* at 160 MHz of the actual AAVS 1 Cable: SDGI (Cable # 2), where results are scaled to 200 m cable length. The relative phase drift of the bare fibre cable without insulation is shown as the dotted red line (top trace), and the estimated response after the application of 50 mm Rockwool insulator shown as the continuous blue line (bottom trace).

As can be seen in Fig. 19, the *relative drift response* of the fibre is scaled down for 200 m transmission, with the *peak-to-peak phase amplitude* is now at 1.36° (phase) shown in red dotted line, a significant reduction from the 5 km transmission (with peak-to-peak phase amplitude of 1.36°) as shown in Figure 18. With the application of Roxul Rockwool insulation with 50 mm wall thickness, by applying the profile of the insulation described in Section 2.4 (Fig. 13 and Fig. 15), and adjusting for a reduction ratio of **0.46** (Fig. 13), the *peak-to-peak phase amplitude* is estimated to be further dampened to 0.58° (phase), shown as the continuous blue line (Fig. 19).

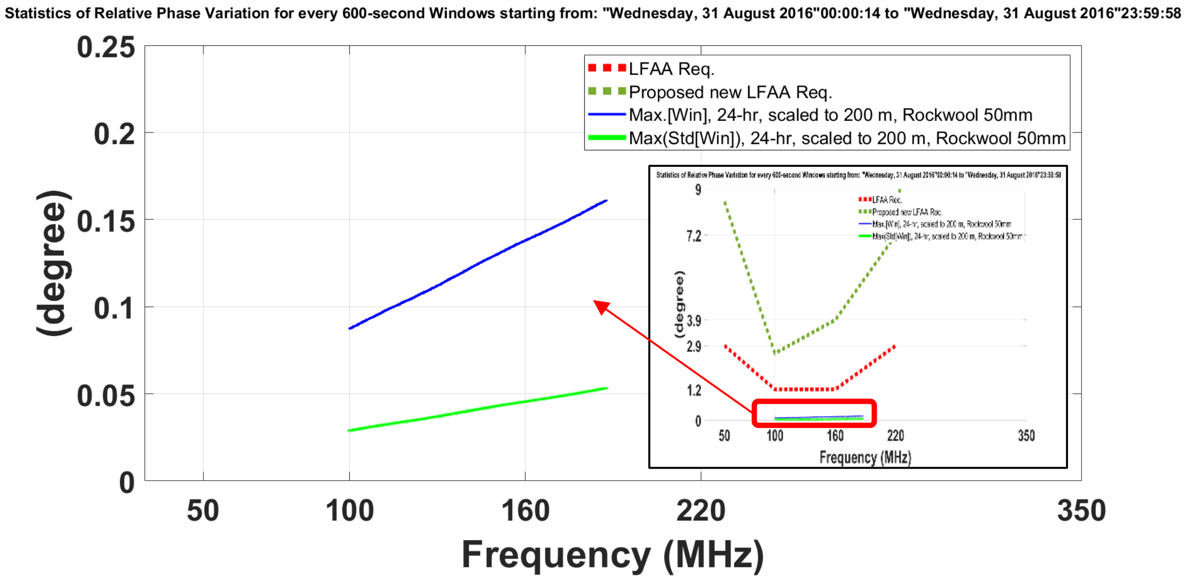

Figure 20: The estimated statistics of 24-hour *relative phase variations* (600-second window) of the SDGI fibre cable. Shown are the results for the case where different transmission wavelengths were used, where each wavelength transmitted on different fibre core from selected from opposite locations inside the cable. Result are scaled to 200m, with the application of Roxul Rockwool insulator with 50 mm wall thickness.

Note that with Rockwool insulation, beside a reduction in *peak-to-peak phase drift amplitude*, the profile of the **phase drifts also is estimated to be less sensitive to rapid change in phase variations due to temperature fluctuations** (from wind, solar irradiation and ambient temperature). To quantify this, the Roxul Roxul 50 mm damping profile, together with the cable length scaling correction to 200 m are applied into the statistical result of Cable #2 shown in Fig. 17 (right), estimating of what would be the statistics of the relative phase variation for 600-sec window, as seen in Fig. 20. Since the profile seems to be linear, result could also be extrapolated to estimate the response at higher frequency.

The statistical comparison between the estimated relative phase variations at 5 km of bare fibre cable without insulation, 200 m fibre bare cable, as well as 200 m cable protected by Roxul Rockwool insulation with 50 mm wall thickness is summarised in Table 3.

Table 3: Summary of the estimated statistics of 600-sec relative phase response (adopted from LFAA L3 requirements) for: the 5 km bare fibre optic cable, 200 m bare cable and 200 m cable with 50 mm Rockwool insulation.

Relative phase variation between two links (600-sec Win)	**5 km cable, surface-laid *Tx1 1270nm, Tx2 1330nm***	**Scaling to 200 m cable, uninsulated**	**200 m cable With 50 mm Rockwool Insulator**
Max[Win], 100 MHz:	*4.91°*	0.19°	0.09°
Max(Std.[Win]), 100 MHz:	*1.63°*	0.06°	0.03°
Max[Win], 160 MHz:	*7.80°*	0.30°	0.14°
Max(Std.[Win]), 160 MHz:	*2.58°*	0.10°	0.05°

3 Conclusion

This report presents the selection, characterisation and assessment of potential solutions for insulating surface-laid fibre optic cable from the elements (ambient temperature fluctuation, wind and solar irradiation) in the field at the MRO (Murchison Radio-astronomy Observatory), for the SKA Bridging Array activity.

Among short-listed solutions, the Roxul Rockwool insulation with 50 mm wall thickness is found to be suitable for insulating the fibre optic cable, having the temperature damping and delay profile estimated to be close to the temperature profile burying the cable underground at the depth of around 1.7 meter. It is also found to be suitable for outdoor deployment for a period of at least 3 years (UV stabilised, puncture resistant, water replant, non-combustible and rodent/ termite resistant), while it is relatively not too thick to be deployed in the field.

Based on past measurement results on the actual AAVS1 cables in the field (AFL SWR and SDGI Cables), the calculation to estimate the temperature effect of the 200 m cable on the relative phase variation and drift, as well as the performance of the selected insulating solution in the context of LFAA L3 (low-frequency aperture array, level 3) requirements, have also been discussed and presented.

Without the application of the insulation, it is expected that if the same type of cable is used (SDGI/ Cable #2 used in AAVS 1 project, which is the cable most effected by thermal effect), for a 200 m of fibre cable transmission length, the *relative RF phase drift* of the surface-laid cable would be in the ballpark of around 1.5° (phase) at 160 MHz in a 24-hour period. **The maximum 600-sec *relative phase variation* of a 200 m cable is calculated to be 0.3° (phase) at 160 MHz, with max. standard deviation of 0.1°, which is significantly lower than the LFAA L3 requirements of 1.2° (phase).** This is estimated based on the worst-case scenario of selecting larger diameter cable and a case of transmitting over different WDM (Wavelength Division Multiplex) wavelengths as used in AAVS 1 project, which is the same type of WDM lasers that will be envisage to be used as the RFoF solution in the SKA Bridging Array activities and beyond.

With the application of 50 mm Roxul Rockwool piping insulation on the same cable (SDGI cable/ Cable # 2) with 200 m length, it is expected that the *relative phase drift* will be further reduced to be around 0.6° (phase) at 160 MHz in a 24-hour period, and a significant reduction in the sensitivity against rapid relative phase variations due to thermal exposure. **The *maximum relative phase variations* and the *maximum standard deviation of the relative phase variations* in a 600-second window is estimated to be approximately 0.14° (phase) and 0.05° (phase) at 160 MHz in a 24-hour period.**

The cost of providing 50 mm Rockwool insulation to 200 m cable will be Au$6,400 excluding transportation and installation cost. This raises questions of whether the insulation is needed in the first place, and whether the performance improvement through the application of this insulation provide the best-value-for-money against the phase stability it provides. With clear specification on the *phase drift* and *phase variation* requirements, we could then answer these issues better.

Finally, even though it is out-of-the-scope of this report, the method as outlined in this report can be adopted to select and assess a suitable insulation for surface-laid coaxial cables and fibre cables for other radio astronomy projects, such as MWA and EDA, if the needs arise.

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