LOW FREQUENCY APERTURE ARRAY

Field Test Result of the 11-km Buried Fibre-optic Cable at the MRO

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LIST OF ABBREVIATIONS

AADC	Aperture Array Design and construction Consortium
AAVS	Aperture Array Verification System
ADC	Analog to Digital converter
Ad-n	nth document in the list of Applicable Documents
AIV	Assembly Integration and Verificatio
ASIC	Application Specific Integrated Circuit
CAD	Computer Aided Design
CCB	Configuration Control Board
CDR	Critical Design Review
CI	Configuration Item
COTS	Commercial Off The Shelf
CPF	Central Processing Facility
CM	Configuration Manager
CW	Continuous Wave
DMS	Document/Data Management System
ECP	Engineering Change Proposal
EMI	Electro Magnetic Interference
FO	Fibre Optic
FoV	Field of View
FPGA	Field Programmable Gate Array
FTR	Full Text Retrieval
HW	Hardware
ICD	Interface Control Document
INFRAAUS	Infrastructure Australia
ISO	International Organisation for Standardisation
LFAA	Low Frequency Aperture Array
LFAA-DN	Low Frequency Aperture Array – Data Network
LNA	Low Noise Amplifier
LMC	Local monitoring and Control
LOFAR	Low Frequency Aperture Array
MBSE	Model Based Systems Engineering
MCCS	Monitor, Control and Calibration servers
MOM	Minutes of Meeting
MPO	Multi-Purpose Optic (connector)
MRI	Master Record Index
MRO	Murchison Radio-astronomy Observatory
MWA	Murchison Widefield Array
NRE	Non Recurring Engineering
OCR	Optical Character Recognition
PA	Product Assurance
PDF	Portable Document Format
PDR	Preliminary Design Review
PC	Project Controller
PO	Project Officer
QA	Quality Assurance
RBS	Re-Baselining Submission
RD-N	nth document in the list of Reference Documents
RF	Radio Frequency
RFI	Radio Frequency Interference
RFoF	Radio Frequency signal over Fibre
RPF	Remote Processing Facility
SaDT	Signal and Data Transport

SDP	Signal Data Processing
SEMP	System Engineering Management Plan
SFDR	Spurious Free Dynamic Range
SKA	Square Kilometre Array
SKA-LOW	SKA low frequency part of the full telescope
SKAO	SKA Office
S/N	Signal to noise
SOW	Statement of Work
SW	Software
TCP-IP	Transmission Control Protocol – Internet Protocol
TBC	To Be Continued
TBD	To Be Done
TBS	To Be Supplied
TM	Telescope Management
TPM	Tile Processor Module
TRB	Test Review Board
WBS	Work Breakdown Structure
WDM	Wavelength Division Multiplexing
WP	Work Package

1 Introduction

Temperature effects on a fibre optic (FO) link have gained considerable attention in establishing the suitability of RF-over-Fibre (RFoF) technology for transporting RF signals for the LFAA front-end. There have been measurements on the RFoF link performed in the lab [RD-1], as well as field measurements at the Murchison Radio-astronomy Observatory (MRO) over 2-km surface laid cable [RD-2].

The results of the field test in [RD-2] indicate that outdoor exposure mainly affects the phase stability of the RF signal transmitted over the FO cable. One possible option to minimise the temperature variation of the cable is by underground burial. To gauge the phase variation over the buried FO cable and to validate a few of our analyses on our initial field results [RD-2], we report measurements of phase stability of the RF signal transmitted over a 5.5-km buried FO cable, looped back to form an 11-km long fibre path. The measurements were started on 18 May and ended mid of July 2015 as had been proposed in [RD-3]. The data presented here are based on a selection of the measurement data taken between this May to July period.

1.1 Purpose of the document

This document summarises the initial results and data analysis to assess the effects of temperature variation on the buried FO cable and its contribution to the gain and phase stability of the RFoF link. The purpose of this report is to formally record the measurement set-up, to indicate the typical phase variations of RF signal transmitted over buried long-distance (11-km) FO cable and to provide guidance on the implication of scaling the length of the fibre optic cable.

1.2 Scope of the document

This document will be focused on the case of buried FO cable, and the discussion will be based on the analysis of the results obtained through the use of the existing 5.5-km buried FO cable available at the MRO. Only the effect of temperature on the FO cable will be considered in the analysis. RFoF transmitter and receiver (transceiver) modules are all located inside a temperature-controlled environment, therefore we assume the relative thermal variations between them are negligible. The RFoF modules operate at approximately 1310 nm wavelength and the optical light propagates over G.652.D fibre, which has a zero-dispersion wavelength typically close to 1310 nm. Note that the operating wavelength and zero dispersion wavelength of the cable are matched, therefore obviating complications due to dispersion effects.

The RFoF modules used in this test are placed indoors in a temperature controlled environment; therefore any temperature effect on the wavelength and phase stability of the laser diode in the RFoF transmitter is implicit in the measurement result. We monitored the ambient temperature of the set-up and the temperature of each individual RFoF transmitter channels. Based on these temperature measurements, we estimate dispersion-induced phase variation of the 1310 nm laser on G.652.D fibre. As expected, the resulting phase variation and the wavelength instability due to ambient temperature of the set-up is small. As such, we will not treat these effects separately but subsume their contribution into the standard deviation of the set-up.

Note that the effect of outdoor temperature variation on the phase of each RFoF transmitters and the resulting dispersion-induced relative phase variations are beyond our current scope.

2 References

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

Id	Title	Code	Issue
AD-1	SKA Request for Proposals	SKA-TEL.-SKO-0000020	01
AD-2	Statement of work for the study, prototyping and design on an SKA element	SKA-TEL.-SKO-0000021	01
AD-3	Statement of Work for the Study, Prototyping and Preliminary Design of an SKA Advanced Instrumentation Programme Technology	SKA-TEL.-SKO-0000022	01
AD-4	SKA Pre construction Top Level WBS	SKA-TEL.-SKO-0000023	01
AD-5	SKA-1 System Baseline design	SKA-TEL.-SKO-0000002	01
AD-6	The Square Kilometre Array Design Reference Mission: SKA Phase 1	SKA-TEL.-SKO-0000002	03
AD-7	SKA System Engineering Management Plan	SKA-TEL.-SKO-0000024	1
AD-8	The Square Kilometre Array Intellectual Property Policy	SKA-GOV-0000001	1.3 Draft
AD-9	Draft Consortium Agreement	PD/SKA.26-4	Draft
AD-10	Document Requirements Description	SKA-TEL.-SKO-0000029	1
AD-11	SKA Document Management Plan	SKA-TEL.-SKO-0000026	2
AD-12	SKA Product Assurance and Safety Plan	SKA-TEL.-SKO-0000027	1
AD-13	Change Management Procedure	SKA-TEL.-SKO-0000028	1
AD-14	SKA Interface Management Plan	SKA-TEL.-SKO-0000025	1
AD-15	SKA Phase 1 System (Level 1) requirements specification	SKA-TEL.-SKO-0000008	3

2.2 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

Id	Title	Code	Issue
RD-1	LFAA: Preliminary Report on RFoF Cost and Performance	SKA-TEL.LFAA.RE.AST-AADC-R-001	Rev. 2
RD-2	LFAA: Field Test Result at the MRO to Assess Gain & Phase Variation of Fibre-optic Cable	Part of (addendum to) SKA-TEL.LFAA.RE.AST-AADC-R-001	Rev. 1
RD-3	Proposal for Field Test to Evaluate the Stability of Buried Fibre Optic Cable at the MRO	ICRAR Internal document, 17 April 2015	draft
RD-4	Test Set-up and Procedure for Assessing Gain & Phase Variation of Fibre-optic Cable	ICRAR Internal report, 4 September 2104	draft
RD-5	LFAA: Preliminary Report on the LFAA Receiver	SKA-TEL.LFAA.RX.MGT-AADC-R-002	Rev. 2
RD-6	Baseline Connection Topologies for SKA1	SKA-TEL.SKO-DD-002	Rev. 2
RD-7	Memo on the Phase Measurement of RFoF links for LFAA	ICRAR Internal report, 28 July 2104	draft
RD-8	System requirements LFAA L1/L2/L3 requirements and compliance matrix	SKA-TEL-LFAA-0000025	Rev. 1

3 Measurement Setup

The measurement set-up for evaluating the RFoF link gain and phase stability is depicted in Fig.1, and the set-up has been described in detail in [RD-4]. The RFoF transmitter and receiver used in this experiment are Optel Modules provided by INAF (Receiver model R-2105 and transmitter model T-0651) with an operating wavelength of 1309.7nm. The cable used in the measurement is an existing 5.5-km G.652.D cable at the MRO, buried at the depth of approximately between 1 - 1.5 m. The cable is looped back to form a total of 11-km path length.

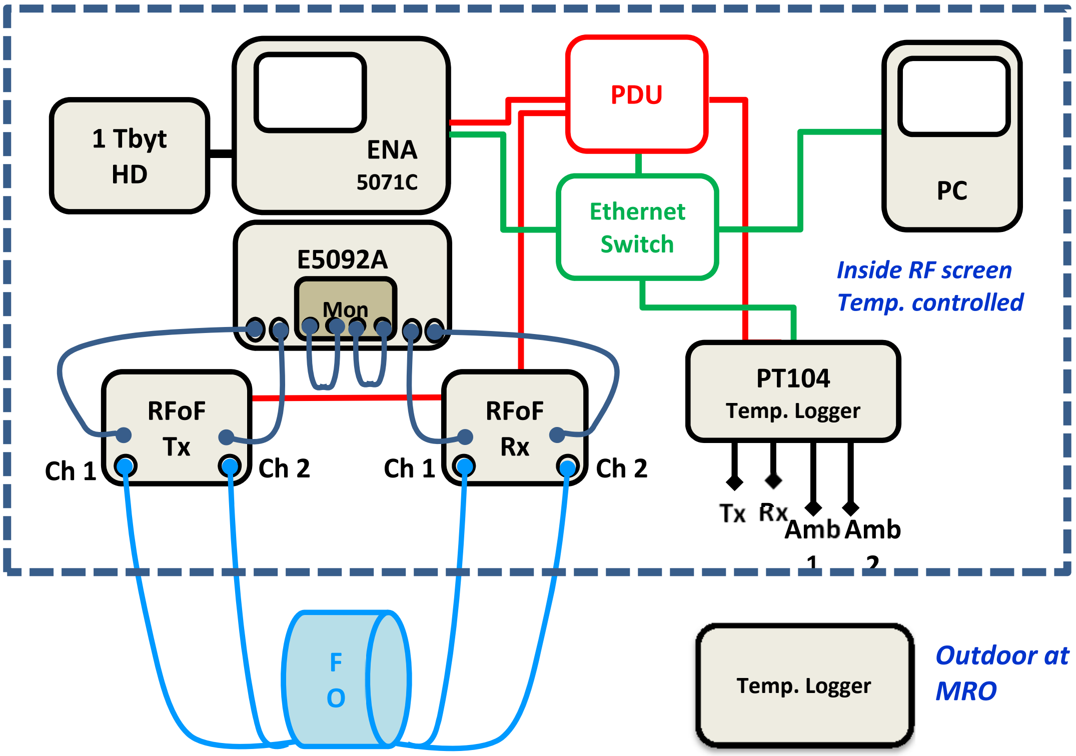

Figure 1: Simplified block diagram of the measurement set-up

The group delay of the RF signal travelling through the fibre-optic medium, τ, is described by the following equation:

$$\tau = l\,.\frac{n}{c} \qquad (1)$$

where *c* is the speed of light in vacuum (2.99x10^8 m/s), n is the refractive index of the fibre (1.47), and *l* is the length of the fibre. From Eq. (1), the time delay of a signal propagated along a **11-km** fibre optic cable will be approximately **54 µs**. To ensure accurate tracking of the unwrapped *phase vs frequency*, the frequency span and the number of points of the VNA should be chosen such that the phase shift between each adjacent frequency points does not exceed 180° , to avoid unwrapped phase ambiguity between a phase shift of *Ө* or (*Ө* +n.360°) in the VNA. For a 54 µs propagation delay along the fibre and following the sampling interval rule of thumb of $\Delta f = \frac{0.3}{\Delta\tau}$, results in sampling interval of **5 kHz.**

The ENA vector network analyser used has limited combinations of channel configuration and no. of point settings that we could utilise. For 2-channel setting, one channel monitoring a pair of RFoF links (FO1 & FO2) and the other channel recording the set-up standard deviation (Monitor channels), we can have a maximum of 20,001 points in the frequency sweep. This means that we are limited to have a frequency bandwidth sweep of 100 MHz for the 5 kHz interval. To cover the critical frequency of 160 MHz (the upper in the LFAA L3 requirements with this 100 MHz bandwidth limit, we decided to sweep from 100 MHz to 200 MHz.

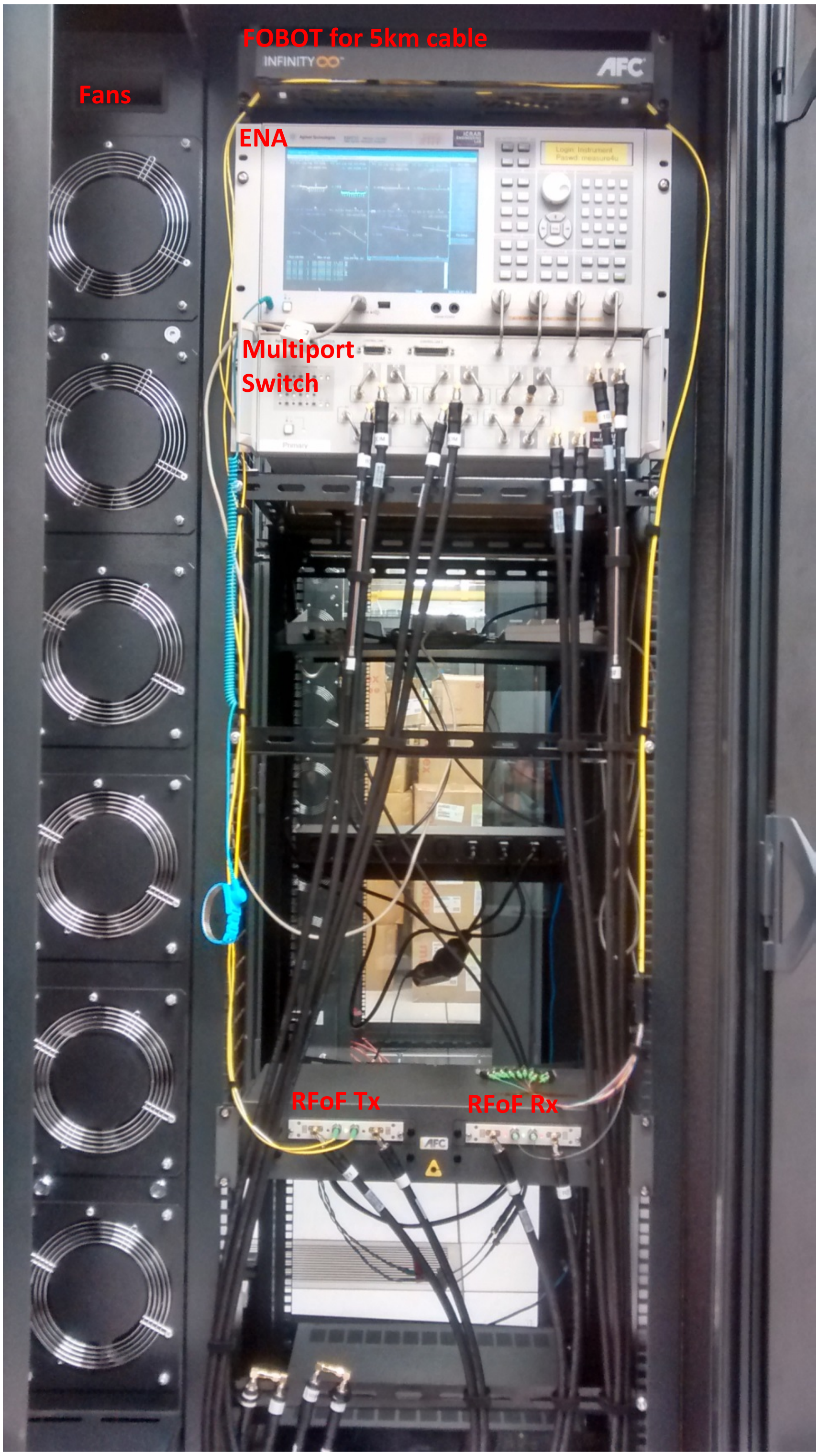

Figure 2: Instrumentation set-up for evaluating RFoF gain and phase stability

We also establish and record the standard deviation of the set-up, including the 11-km cable assemblies due to random errors. The instrumentation set-up on the site is depicted in Figure 2. The measurement is set-up in the server rack (No. 57) at the correlator room inside the CSIRO building at the MRO. The temperature inside the server rack is controlled and set to 20° C.

4 Fibre Optic Cable Evaluated

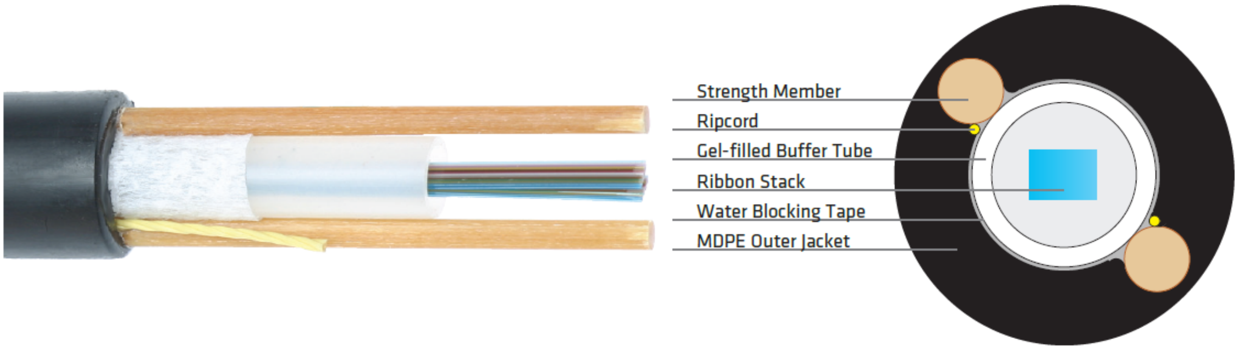

Figure 3: Cross sectional view of the multicore fibre optic cable used for the evaluation

The preliminary LFAA L3 specifications indicates that the RFoF links will be typically 2 km in length, with additional provision for routing, making the total length of up to 10 km [RD-5, RD-6]. Since there is an existing MWA fibre optic cable available in the field, we utilised this cable for the buried FO cable evaluation. Figure 3 shows the cross sectional view of the existing MWA FO cable used in the evaluation. The optical fibre cores conform to the G.652.D SMF specifications, and length of the cable is approximately 5.5 km. To simulate the maximum length requirements as stated in [RD-5, RD-6], we placed loop-back connections at the far end of the FO cable, such that the total FO transmission length is approximately 11 km.

The cable is a Prysmian FusionLink^{tm} cable, and consists of 216 fibre cores organized in 18 fibre ribbon stacks, where each ribbon contains 12 fibres. *Each fibre conforms to G.652.D single-mode fibre (SMF) standard.* Note that due to the ribbonisation, the buffer tube in the cable is larger and stiffer than loose tubes typically found in non-ribboned fibre cables. There is a continuous water-repelling gel loaded inside the buffer tube. This gel needs to be cleaned off the ribbons prior to splicing the fan-out termination.

Initially, each ribbon was fusion-spliced to a *12-core ribbon to LC-parallel breakout*, at both ends. These fusion splices were performed after the cable was laid in the trench, i.e. all ribbon splicing was done in the field after the routing. The spliced ribbons were then loaded into splice cassettes, and the LC pigtails plugged into the back of LC-LC bulkhead joiners. Subsequently, in May 2015, there were some modifications in the connectors, where at the cable-end located at the CSIRO Correlator room, three ribbons out of the 18 were re-terminated with LC/APC connectors, while one fibre ribbon fan-outs was re-terminated with FC/APC connectors. At the cable-end located at the MWA Fibre Hub, all four fibre ribbons were re-terminated with LC/APC connectors. OTDR measurements were performed by the cable supplier, where optical attenuation as well as information on physical length of each fibre is available from the MWA team.

We measured the phase and group delay of the cable, and derived the equivalent physical length of each fibre using the method described in [RD-7], and obtained cable loop-back length of around 11,150 m, which is in agreement with the OTDR data as given by the manufacturer. The refractive index value used in this calculation is 1.47 in accordance with the typical value used in the OTDR measurement by cable suppliers.

5 Fibre Optic Cable Routing in the Field (MRO)

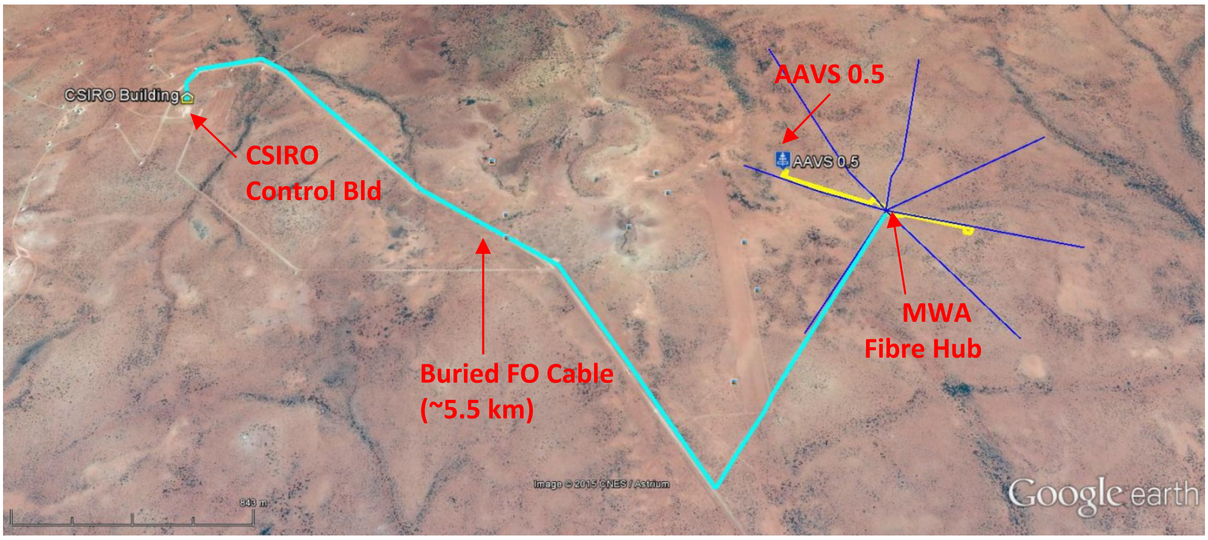

Figure 4: The map depicting the 5.5-km buried fibre optic cable routing in the field (MRO)

Figure 4 is a map depicting the location of key infrastructure at the MRO and the routing of the 5.5-km buried FO cable. One of the FO cable ends terminates in the Fibre hub at the Murchison Widefield Array (MWA) location. The other end terminates at the CSIRO Fibre panel in the correlator room inside the shielded CSIRO Control Building, where the measurement set-up (Fig. 1) was placed. Figure 5 shows the fibre connector terminations in the CSIRO correlator room and the MWA Fibre Hub.

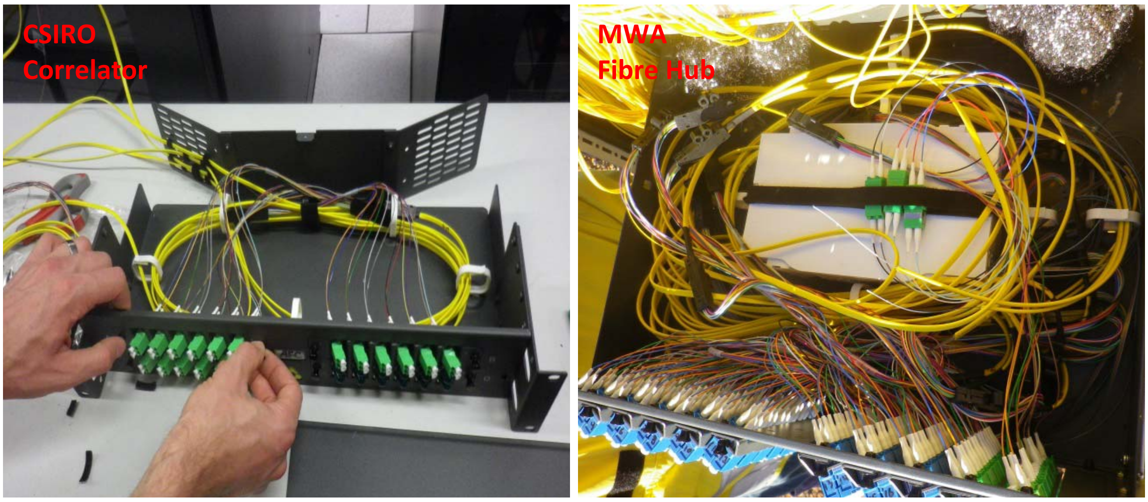

Figure 5: The fibre cable connector termination at the CSIRO Correlator room (left) and the termination at the MWA Fibre Hub (right), showing the loop back connection

To form an 11-km fibre path from this 5.5 km cable, the end of a fibre terminated in the cabinet inside the MWA Fibre hub was looped back directly into another fibre through LC/APC-female to LC/APC-female adapter (LCA-LCA adapter), as can be seen in Fig. 5 (right). A total of six fibres are looped back in this manner and are available to be used to form a pair combination. The other end of the FO cable is in the CSIRO correlator room, where all connectors are terminated inside the fibre-optic-break-out-tray (FOBOT) at the top mounting position inside the server rack (Fig. 5 (left)).

We performed measurements on two fibre pair connections, described as follows:

5.1 Measurement of a pair from the same fibre ribbon loop (May 2015)

During the field evaluation in May 2015, the measurements were taken from a pair from the same fibre ribbon in the loop-back, as depicted in Fig. 6. This is realised from the parallel breakout of different fibre ribbons (cross patch) forming the loop-back, and that an independent fibre channel is parallel to its pair on the same ribbon before and after the loop-back. We denoted RFoF Channel 1 (FO1) for RFoF T1 and R1 pair and Channel 2 (FO2) for T2-R2 pair.

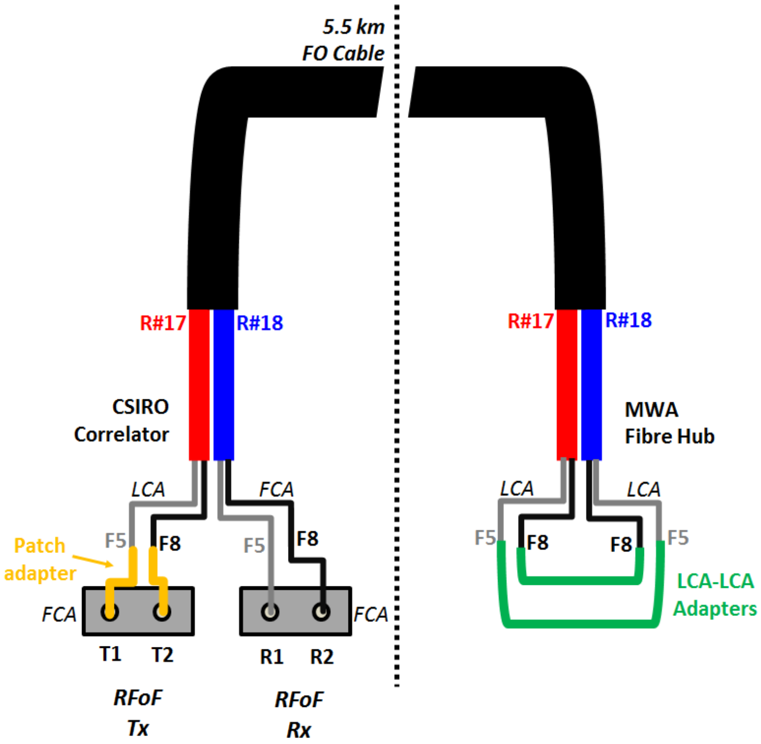

Figure 6: The fibre connections for the pair from the same fibre ribbons

Inside the CSIRO correlator room, fibre 5, (denoted as F5 in Fig. 6 and colour coded 'slate') from cable ribbon # 17 is connected to RFoF transmitter 1 (fibre 2.17.5), whereas fibre 8 (denoted as F8 in Fig. 6 and colour coded 'black') is connected to RFoF transmitter 2 (denoted as fibre 2.17.8). In the MWA fibre hub cabinet some 5.5 km away at the other end of the cable, fibre 2.17.5 and 2.17.8 are each respectively looped back into fibre 5 and fibre 8 from ribbon # 18 (fibre 2.18.5 and fibre 2.18.8 pair). The RFoF receiver module is connected with the pair from ribbon # 18.

Cables from ribbon #17 are terminated with LC/APC connector, whereas fibres from ribbon # 18 are terminated with FC/APC. As the RFoF modules are terminated with FC/APC, we used a 2-m FC/APC to LC/APC patch adapter cables for connection at the transmitters, whereas the connections to the RFoF receiver are direct without any adapter. We obtained the length difference of fibre cores (FO1 and FO2), using the *relative phase difference* of the whole cable assembly of the two RFoF channels. The relative difference between the pair is found to be ~1.5 m. The estimated physical length of FO1 (2.17.5-2.18.5 fibre) is 11,158 m and the length FO2 (2.17.8-2.18.8) is 11,156 m.

5.2 Measurement of a pair from separate fibre ribbon loop (July 2015)

In July 2015, measurements were taken from a pair selected from different fibre ribbons in the loop-back, as depicted in Fig. 7.

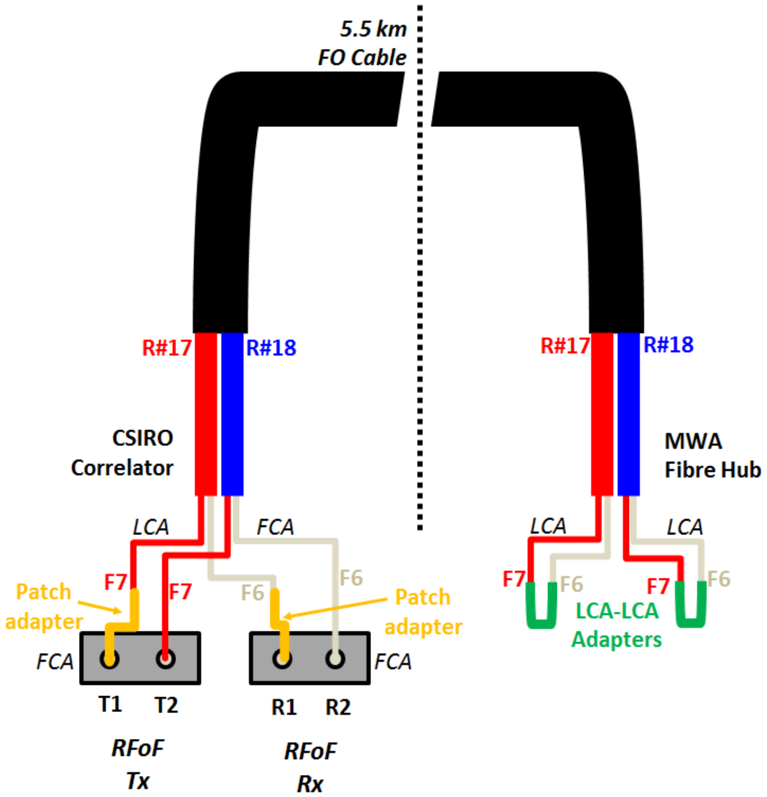

Figure 7: The fibre connections for the pair from different fibre ribbon loops

Inside the CSIRO correlator room, fibre 7 (denoted as F7 with LC/APC (LCA) connector in Fig. 7 and colour coded ‘red’) from cable ribbon #17 (fibre 2.17.7) is connected to RFoF transmitter (T1) via the 2-m FCA-to LCA optical patch cable. At the MWA fibre hub cabinet at the other end of the cable, fibre 2.17.7 is looped back into fibre 6 (colour-coded white) from the same ribbon (fibre 2.17.6), and the other end of fibre at the CSIRO correlator room, fibre 2.17.6 is connected to the first RFoF receiver (R1) via another 2-m patch adapter cable, forming the first fibre optic channel (FO1).

Another fibre 7 from ribbon #18 (fibre 2.18.7), denoted as F7 with FC/APC (FCA) connector in Fig. 7) is directly connected to RFoF transmitter 2 (T2). At the MWA fibre hub, fibre 7 from ribbon # 18 (fibre 2.18.7) is looped back into fibre 2.18.6. Back at the correlator room, the second RFoF receiver module (R2) is connected directly with fibre 2.18.6, forming the second optical channel (FO2).

We obtained the length difference of fibre cores (FO1 and FO2), using the *relative phase difference* of the whole cable assembly of the two RFoF channels. The relative difference between the pair is found to be 10.18 m, where the estimated physical length of FO1 (2.17.7-2.17.6 fibre) is 11,151 m and the length FO2 (2.18.7-2.18.6) is 11,161 m.

6 RFoF Requirements from LFAA L3 Receiver Specifications

Table 1 lists the relevant parameters that are used to assess the gain and phase stability of the FO cable used for the RFoF links with respect to ambient/temperature variation in the field. It is selected from a list of L3 LFAA receiver specifications as presented in Table 8 of Preliminary Design Report on the LFAA Receiver [RD-5], as well as in the LFAA System requirement documents [RD-8].

The requirements as stated in [RD-8] pertain to the relative variation of a pair of RF chain (two links), and are derived based on the variation of RF receiver chain across 256 parallel links.

We quote the LFAA L3 requirements to provide the context for our results (Table 1).

Table 1: Extract of relevant LFAA L3 receiver RF requirements [RD-8].

	Requirements	Notes
Relative gain variation between two links (within 600 seconds)	< 0.42, 0.17, 0.17 and 0.42 dB at 50, 100, 160 and 220 MHz	Based on variation (dB) of entire RF link. Specification at 350 MHz to 650 MHz is TBC.
Relative phase variation between two links (within 600 seconds)	< 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.
Maximum gain drift (within 600 seconds)	± 3dB (1-bit)	Absolute gain drift of any of the RF (RFoF) link within 600-seconds after each calibration.

7 Results from a Pair from the Same Fibre Ribbon (May 2015)

The results of the FO cable measurement in May 2015 are summarised in Table 2. The measured results indicate good RF gain and phase stability over the 11-km buried cable. Note that the frequency span is limited to 100-200 MHz; as such we could only have data points at 100 MHz and 160 MHz that match with LFAA L3 requirements. Values for 200 MHz are provided as well, and the specification is marked with (*) as it is derived from the LFAA requirements.

We presented both **24-hour max** values for **standard deviation** and the ***maximum value*** (max. hold) in any 600-sec window. The maximum values are provided to give an indication of the 'worst-case' figure for each window for a given condition of the measurement, for comparison with the standard deviation figures. Also note that **data fitting** is adopted on the measured results, and where **cubic spline** interpolation is used to smooth out these maximum window values. The entire figures for maximum value are therefore obtained by cubic spline interpolation taken across the 20,001 frequency points.

Table 2: Summary of the preliminary results of the RFoF link gain and phase stability evaluation over 5.5-km buried FO cable transmission (10-km looped back) in the field (MRO). The results were based on fibre 5 (slate) and fibre 8 (black) looped-back pair (cross-patch), the looped-back pair forming same fibre ribbons. The measurement was taken from 5.00 pm on the 28th of May to 4.00 pm on the 29th of May 2015. Shown here are the processed results that have corresponding LFAA L3 specifications, except for 200 MHz (marked *) where the requirement is based on the interpolation of the values for 160 and 220 MHz.

Specifications	Description	Frequency (MHz):	50	100	160	*200**	220
Relative gain variation between two links (within 600 seconds) Outcome ID: Out_1	24-hr max. of the *relative gain of either* window standard deviation or Window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (dB)**	**0.42**	**0.17**	**0.17**	***0.34****	**0.42**
		Preliminary results (dB) **Std.dev[Win]** (24-hour σ max)	-	*0.007*	*0.007*	*0.007*	-
		Preliminary results (dB), **Max[Win]** (24-hour max)	-	*0.027*	*0.028*	*0.028*	-
		Measurement set-up noise (dB) (RFoF + 11 km FO Cable + ENA +coax)	***0.005***				
Relative phase variation between two links (within 600 seconds) Outcome ID: Out_2	24-hr max. of the *relative phase of either* window standard deviation or window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (degree)**	**2.9°**	**1.2°**	**1.2°**	*2.33°**	**2.9°**
		Preliminary results (deg) **Std.dev**[Win] (24-hour σ max)	-	*0.011°*	*0.014°*	*0.017°*	-
		Preliminary results (deg), **Max[Win]** (24-hour max)	-	*0.045°*	*0.056°*	*0.070°*	-
		Measurement set-up noise (deg) (RFoF + 11 km FO Cable + ENA +coax)	***0.01°***				
Maximum abs gain drift (within 600 seconds) Outcome ID: Out_4	24-hr max. of the *absolute gain of either* window standard deviation or window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (dB)**	**± 3**	**± 3**	**± 3**	*± 3**	**± 3**
		Preliminary results (dB) **Std.dev[Win]** (24-hour σ max)	-	*0.006*	*0.006*	*0.006*	-
		Preliminary results (dB), **Max[Win]** (24-hour max)	-	*0.022*	*0.022*	*0.022*	-
		Measurement set-up noise (dB) (RFoF + 11 km FO Cable + ENA +coax)	***0.004***				

Figure 8 shows the plot of relative phase drift over ~24 hour period from 5.00pm on the 28th May to 4.00pm on the 29th May. Notice that the variation is fairly flat across frequency, and that the standard deviation of the results is close to the measurement set-up noise as indicated in Table 2. This suggests stable RF signal amplitude transmission over the buried 11-km fibre optic cable on a pair of fibre cores from the same ribbon.

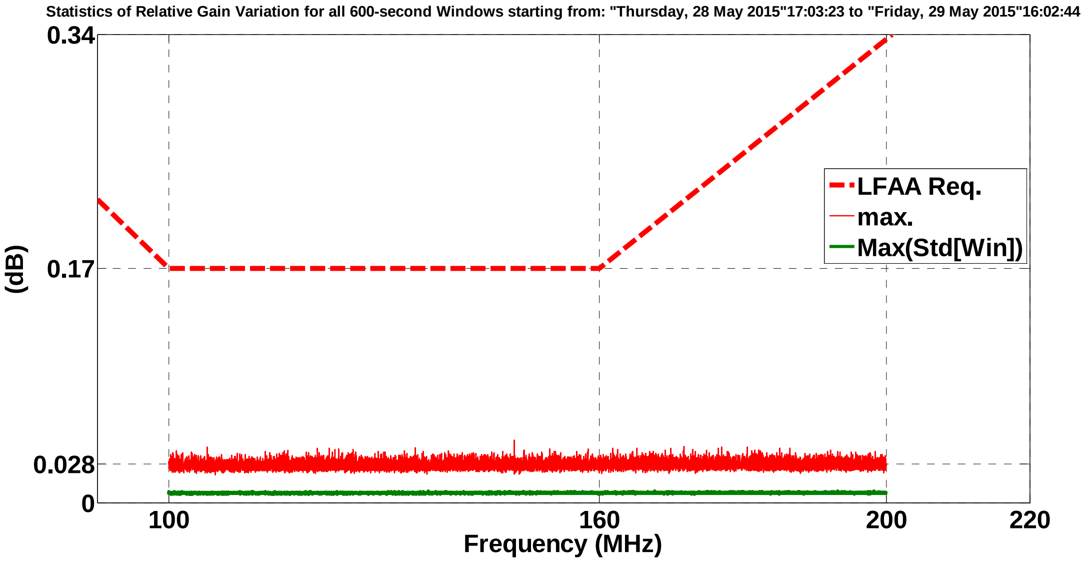

Figure 8: Statistics of the relative gain variations of two RFoF links from the same fibre ribbon for RF frequency starting from 100 to 200 MHz (28/5 – 29/5). Shown here are the 24-hour maximum plots for both standard deviation and the maximum values of the 600-sec window.

In contrast to our finding that the diurnal temperature cycle has virtually no effect on the gain stability of RF signal transmitted over the fibre, we observe some weak temperature effect on the phase drift of the RF signal. Figure 9 shows the raw relative phase drift (no calibration applied) over ~24 hour period from 5.00pm on the 28th May to 4.00pm on the 29th May. Note that there is a typical rise in the drift after 8.00 am until 8.00 pm, which correspond to the diurnal cycle of the ambient temperature. However, the drift is relatively stable and has small variation within ± 0.06 degree over the 24-hour period.

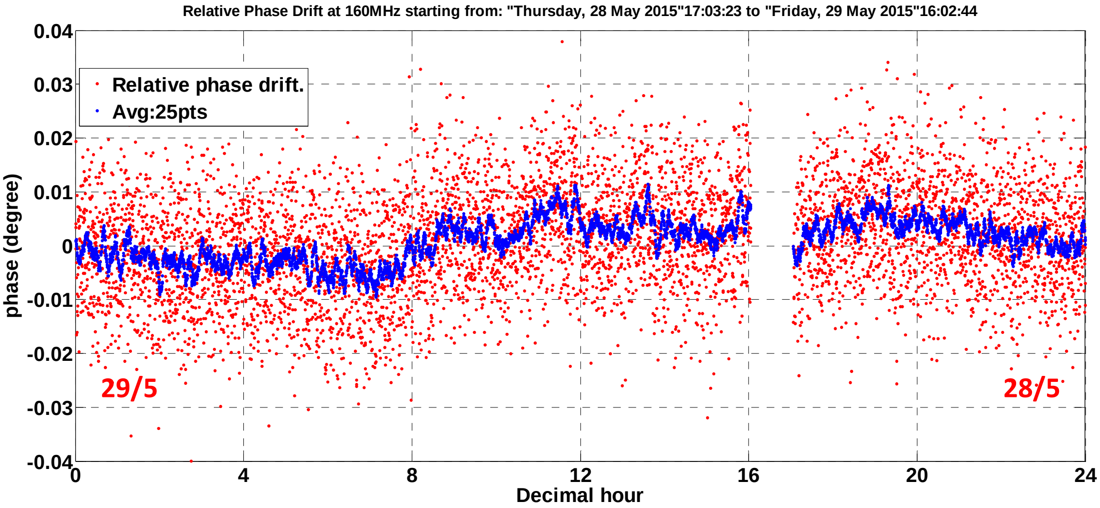

Figure 9: The diurnal relative phase drift variation (no calibration window processing applied) of the RF signal transmitted over 11-km fibre optic pair from the same ribbon at 160 MHz.

The maximum relative phase variation of the 600-second Window across 100-200 MHz over 24-hour period is shown in Figure 10. Both Fig. 9 and Fig. 10 indicate that the temperature of the cable buried underground seems to be stable over the 24-hour period. Although the diurnal temperature variation signature could be seen in the plots, the resulting elongation and refractive index changes have little effect on the relative phase stability of the RF signal transmitted over the fibre pair.

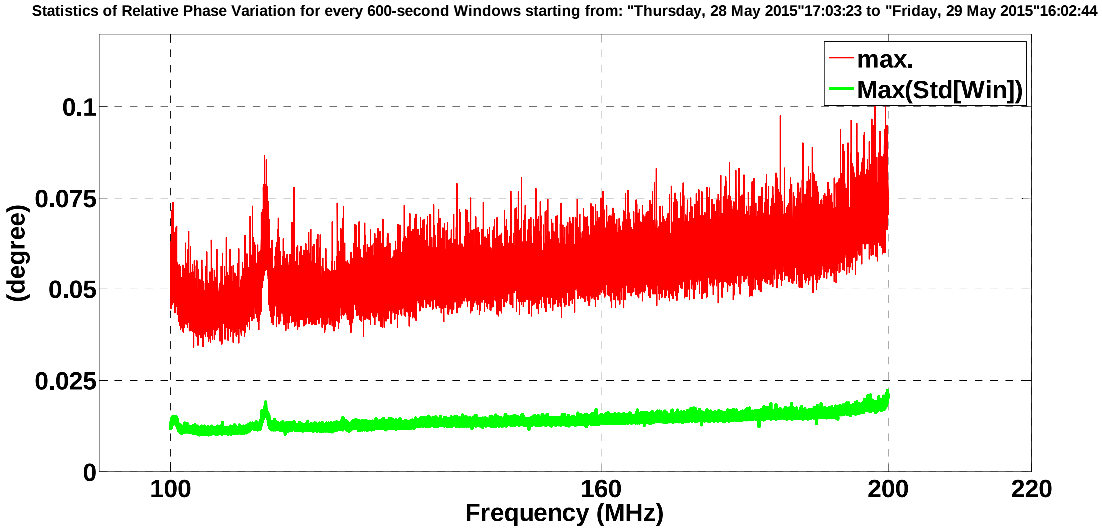

Figure 10: Statistics of the relative phase variations for RF frequency starting from 100 to 200 MHz (28/5 – 29/5). Shown here are the *24-hour* maximum plots for both standard deviation and the maximum values of the 600-sec window of the pair from the same ribbon.

Figure 11 shows the plots of the standard deviation and maximum relative phase variation over 5 days from 29th May to 2nd June 2015. These plots indicate the relative phase stability of the buried fibre cable over extended period of time over a few days.

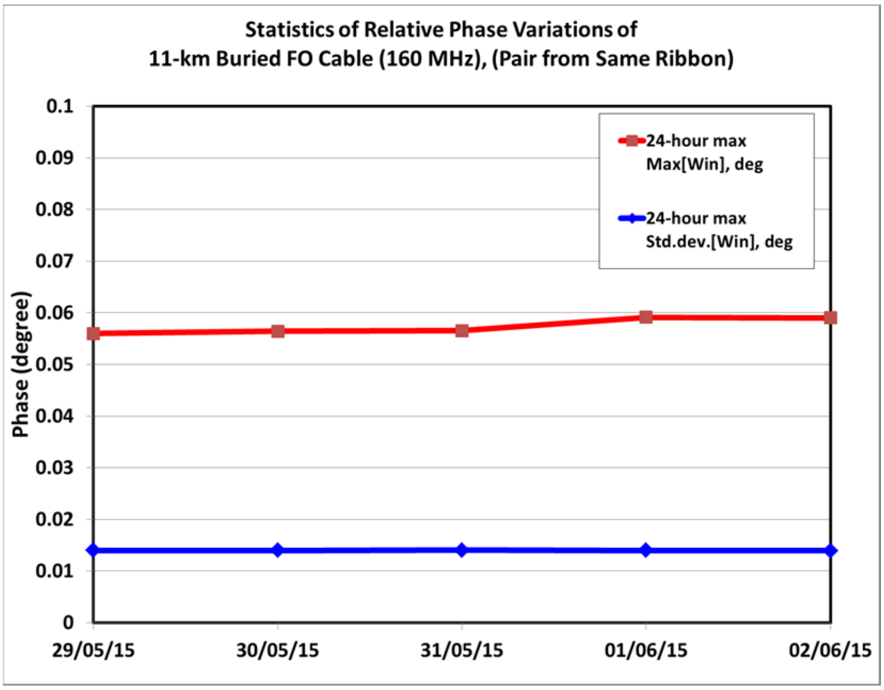

Figure 11: Statistics of the *24-hour* maximum plots of relative phase variations for both standard deviation and the maximum values of the 600-sec window for 160 MHz signal taken over a few days from (29/5 – 2/6), taken from the same ribbon

8 Results from a Pair from Different Fibre Ribbons (July 2015)

The results of the FO cable measurement from 11-km pair selected from different fibre ribbons are summarised in Table 3. Compared with the results of the pair from same fibre ribbon presented in Section 7, the measured results also indicate RF gain and phase stability over the 11-km buried cable.

Table 3: Summary of the preliminary results of the RFoF link gain and phase stability evaluation over 5.5-km buried FO cable transmission (11-km looped back) in the field (MRO). The results were based on fibre 7 (red) and fibre 6 (white), each pair looped-back to form a pair from separate and different ribbons. The measurement was taken from 11 am on the 1st of July to 10 am on the 2nd of July 2015. Shown here are the processed results that have corresponding LFAA L3 specifications, except for 200 MHz (marked *) where the requirement is based on the interpolation of the values for 160 and 220 MHz.

Specifications	**Description**	**Frequency (MHz):**	**50**	**100**	**160**	*200**	**220**
Relative gain variation between two links (within 600 seconds) Outcome ID: Out_1	24-hr max. of the *relative gain of either* window standard deviation or Window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (dB)**	**0.42**	**0.17**	**0.17**	***0.34****	**0.42**
		Preliminary results (dB) **Std.dev[Win]** (24-hour σ max)	-	*0.006*	*0.006*	*0.006*	-
		Preliminary results (dB), **Max[Win]** (24-hour max)	-	*0.023*	*0.024*	*0.024*	-
		Measurement set-up noise (dB) (RFoF + 11 km FO Cable + ENA +coax)	***0.005***				
Relative phase variation between two links (within 600 seconds) Outcome ID: Out_2	24-hr max. of the *relative phase of either* window standard deviation or window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (degree)**	**2.9°**	**1.2°**	**1.2°**	*2.33°**	**2.9°**
		Preliminary results (deg) **Std.dev**[Win] (24-hour σ max)	-	*0.013°*	*0.019°*	*0.023°*	-
		Preliminary results (deg), **Max[Win]** (24-hour max)	-	*0.051°*	*0.071°*	*0.088°*	-
		Measurement set-up noise (deg) (RFoF + 11 km FO Cable + ENA +coax)	***0.014°***				
Maximum abs gain drift (within 600 seconds) Outcome ID: Out_4	24-hr max. of the *absolute gain of either* window standard deviation or window max between 2 links within 600-sec window and 13-sec sweeping interval.	**LFAA L3 Req. (dB)**	**± 3**	**± 3**	**± 3**	*± 3**	**± 3**
		Preliminary results (dB) **Std.dev[Win]** (24-hour σ max)	-	*0.004*	*0.004*	0.004	-
		Preliminary results (dB), **Max[Win]** (24-hour max)	-	*0.017*	*0.017*	*0.017*	-
		Measurement set-up noise (dB) (RFoF + 11 km FO Cable + ENA +coax)	***0.004***				

Figure 12 shows the plot of relative phase drift over 24 hour period from 1.00 pm on the 1st of July to 1.00 pm on the 2nd of July. Notice that the variation is fairly flat across frequency, and that the standard deviation of the results is close to the measurement set-up noise as indicated in Table 3. This suggests stable RF signal amplitude transmission over the buried 11-km fibre optic cable on a pair selected from different fibre optic ribbon.

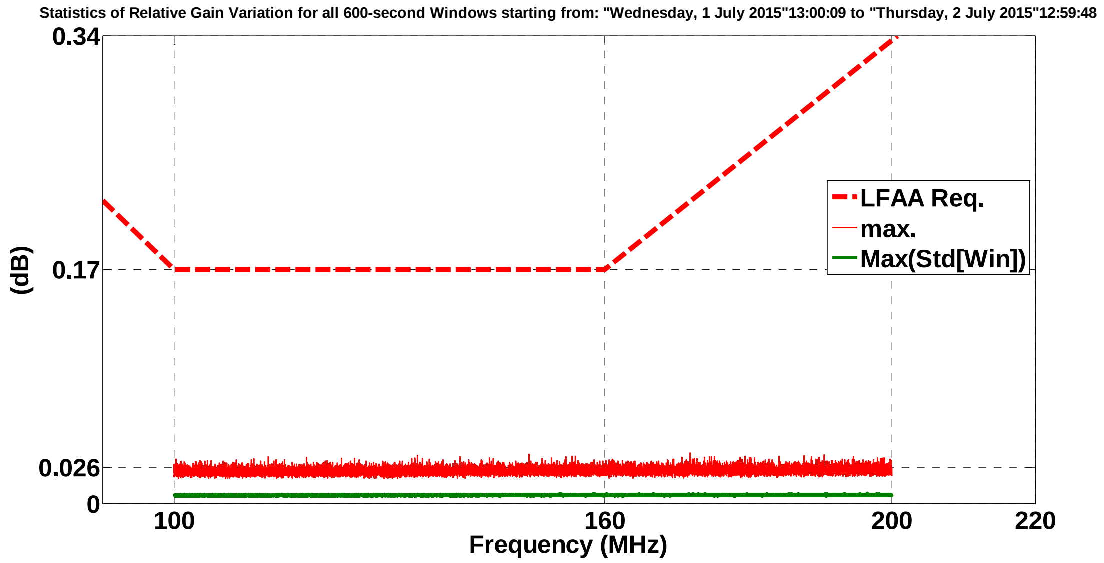

Figure 12: Statistics of the relative gain variations of two RFoF links for RF frequency starting from 100 to 200 MHz (1/7 – 2/7). Shown here are the 24-hour maximum plots for both standard deviation and the maximum values of the 600-sec window of the fibre pair from separate ribbons.

Figure 13 shows the plot of relative phase drift (no calibration window applied) over ~24 hour period from 1st of July to 2nd of July. Note that we observe a rise in the drift after 8.00 am and typical drop of temperature after 8.00 pm, which correspond to the diurnal cycle of the outdoor temperature. The phase drift follows the diurnal cycle strongly, which profile will depend on the outdoor ambient temperature profile, and the thermal temperature underground surrounding the buried fibre cable. Note that the outdoor ambient temperature on the 2nd of July is much lower than the temperature on the 1st of July. As a result the raw relative phase drift of the 2nd of July is much lower than that of 1st July at around the same time (1.00 pm) in the afternoon, and thus the gap as can be seen in Fig. 13.

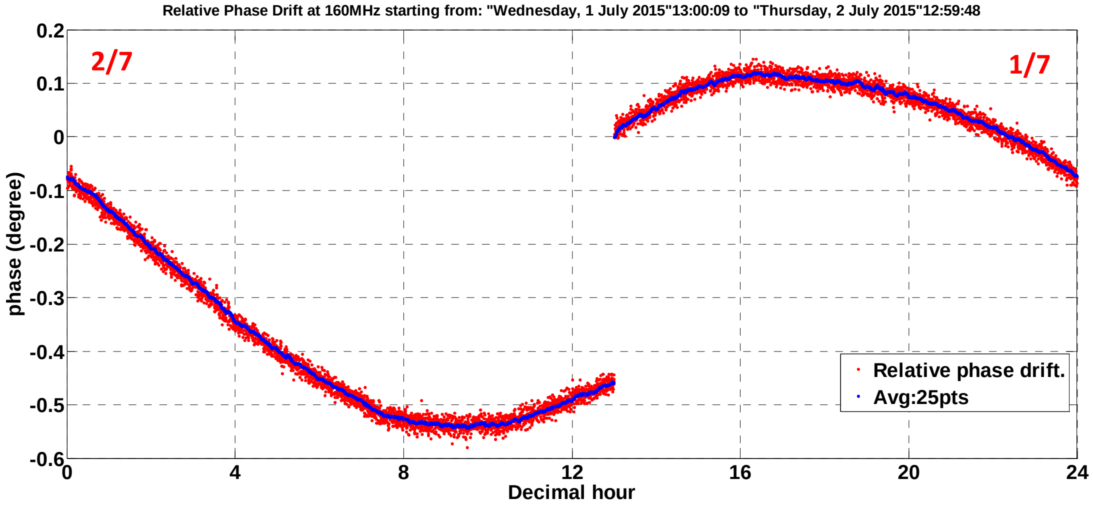

Figure 13: The diurnal relative phase drift variation (raw, no calibration applied) of the RF signal transmitted over 11-km fibre optic pair from separate ribbons at 160 MHz.

The maximum relative phase variation of the 600-second Window across 100-200 MHz over 24-hour period is shown in Figure 14. The relative phase variation of the set-up with fibre pair coming from different fibre ribbons (Fig. 14) seems to be slightly higher than the phase variation of the set-up with the pair from the same fibre ribbon (Fig. 10). However, it can be argued that the temperature differences across the pair for both set-ups are relatively low within the 600-sec window, hence resulting in relatively similar phase variation outcome for both set-ups.

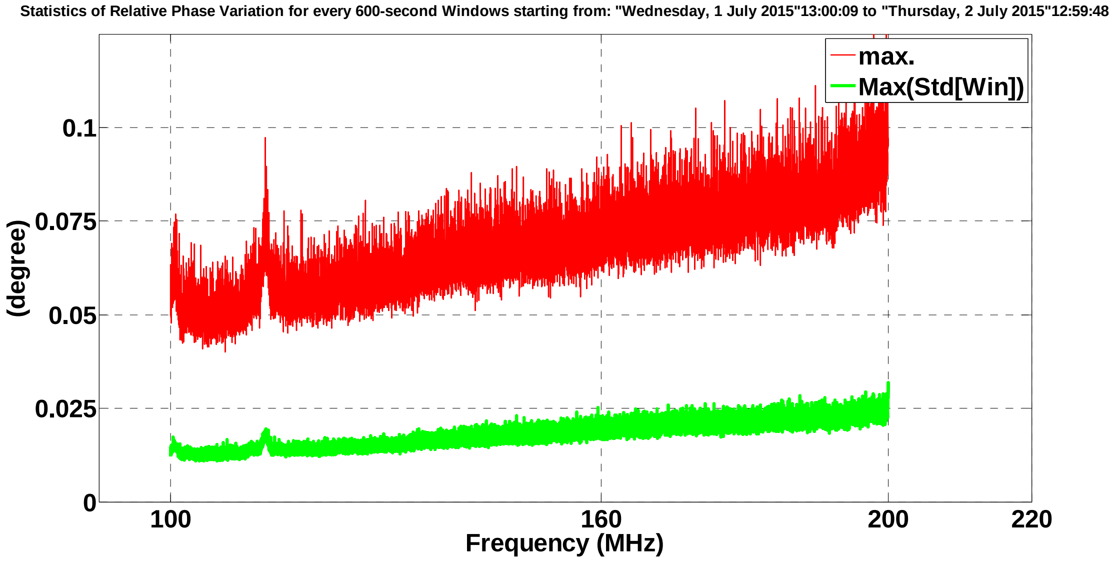

Figure 14: Statistics of the relative phase variations for RF frequency starting from 100 to 200 MHz (1/7 – 2/7). Shown here are the *24-hour* maximum plots for both standard deviation and the maximum values of the 600-sec window, of a pair of fibre optic from different ribbon.

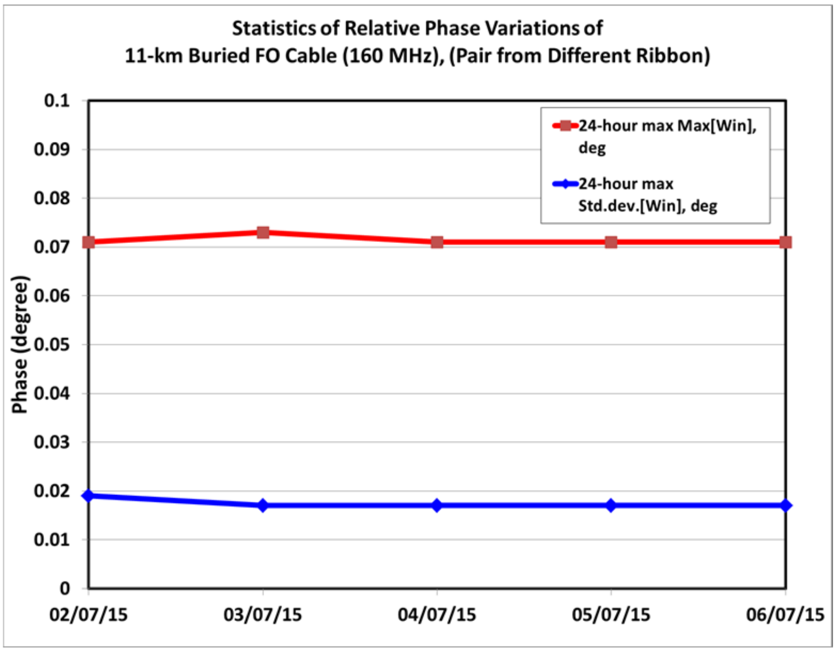

Figure 15: Statistics of the *24-hour* maximum plots of relative phase variations for both standard deviation and the maximum values of the 600-sec window for 160 MHz signal taken over a few days from (2/7 – 6/7). The results are taken from a pair of fibre optic from different ribbon

Figure 15 shows the plots of the standard deviation and maximum relative phase variation over 5 days from July 2nd to July 6th 2015. These plots demonstrate the relative phase stability of the RF signal transmitted over a pair from different ribbon in the buried fibre cable over an extended period of few days.

9 Case Studies Based on the Field Results

Now that we have results from field measurement, it is interesting to utilise the data to predict the performance of the cable as we vary a few cable parameters. We present a few examples to consider. Note that in the following examples, unless otherwise stated, we assume all other conditions remain identical to the state during which the data were collected (e.g., same surface laid cables, identical RFoF TX and RX and identical environment).

9.1 Extrapolating the Cable Length to 50-km

As has been established in [RD-2], for a pair of fibres, the relative phase variation due to temperature fluctuation can be estimated as:

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

where *f* is operating frequency (Hz), L_o = initial fibre length (m), *n* is the refractive index of the fibre core (1.47), α = linear thermal expansion coefficient (m/m $°C^{-1}$), $\beta = \frac{\Delta n}{\Delta T}$ is the temperature coefficient of refractive index (m/m $°C^{-1}$), ΔT = temperature change (°C), and), *c* is the speed of light in vacuum (2.99×10^8 m/s).

Eq. (2) gives us an estimate of the relative thermal difference between the pair, based on the measured phase variation. By using this estimate, we can then calculate back the phase variation as we scale the length of the cable, assuming the same condition of the cable as seen during prior cable measurement.

From the 5-day measurement result of the buried cable (Table 2 & Table 3), the **maximum 24-hour** figure of the maximum relative phase variation for 600-sec window is approximately **0.07°** (phase) at 160 MHz. This value correspond to a calculated temperature difference between the fibre pair, **[ΔT_{FO1} - ΔT_{FO1}]**, of **0.00165°C**. Assuming similar environmental condition and cable tolerance as stated in Section 4, if the buried FO cable length is extended up to **50 km**, the estimated phase variation will be a maximum of ~**0.31°** (phase) over the 24-hour period. As the relative phase variation of the buried cable is fairly stable over 24-hour within those 600-sec calibration window as observed in Fig. 10 & Fig. 14, there is no separate analysis to limit the analysis to dark hour operation only.

Note that the scaling from 11-km to 50-km is a fairly large, and the analysis offered in this section is a back-of-the envelope estimate given the available data.

9.2 Comparison between Buried vs. Surface Laid Cable

The relative phase stability comparison between 11-km buried cable and 2-km surface laid cable is given in Figure 16. Shown in the plots are the 24-hour max figures for window max and window standard deviation for each day up to five days. It can be seen that the surface laid cable fluctuate broadly subject to variation in environmental temperature, whereas buried cable has relatively stable phase even though the length is more than five times longer than the surface laid cable.

If we use an FO cable with fibre length difference of 0.2% of the total length (similar tolerance to those used for the 2-km surface laid cable measurement), assuming that the relative temperature difference profiles are identical to the measured differences in temperature profile, *the FO cable length* can be extended to **8.6 km** based on *measured standard deviation* (or **3.36 km** if we use the ***max** value)* such that 1.2°phase variation is reached. Whereas the data for 11-km buried fibre for both pair from the same ribbon and a pair from different ribbons indicate that the cable length could be extended to 50-km while still resulting in a relatively stable phase characteristic as has been described in Section 9.1.

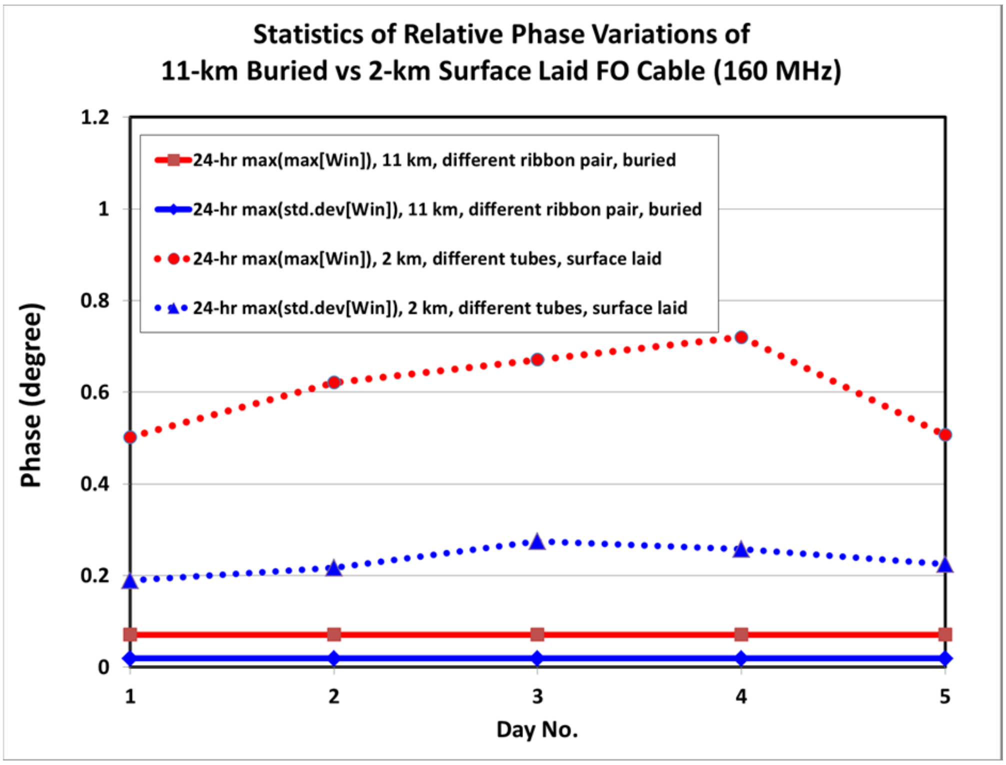

Figure 16: Five-day comparison of the relative phase stability between 11-km buried FO cable and 2-km surface laid cable. The frequency of the signal is 160 MHz.

10 Conclusion

We report the results from the field measurement of 5.5-km buried fibre optic (FO) cable (forming 11-km loop back) at the Australian SKA site. By establishing the physical model of the cable, analysing the data, and verifying the results with the model, we have a better understanding as well as establishing the limitation on the RFoF technology for RF signal remoting in Australian outdoor environment, in particular at the MRO.

It is found from the measurement results that buried FO cable has very good gain and phase stability; and ambient temperature changes have negligible effect on the stability of the phase of the RF signal transmitted through the cable in the 600-sec window throughout a 24-hour period. The measurement data for this experiment are used to estimate the phase variation of the RF signal transmitted over the fibre, as the length of the cable is extended to 50-km, though it should be noted that this scaling is a conjecture based on the data we could practicably obtain from the field.

The results so far demonstrate the viability of the RFoF technology for RF signal transport for SKA_LOW under a few constrains, which need to be clarified further (such as routing implementation, operating time, calibration specifications [i.e.: Window duration/ interval, limit values, and whether to take max or std.dev], operating wavelength and dispersion characteristic of cable. The results and developed model can also be used further to recommend a best cable routing deployment strategy for LFAA to find an optimised solution between infrastructure implementation cost and stability trade-off.

Note that the discussions in this report are limited in analysing the effect from the elongation and refractive index changes due to temperature variation on the cable only. The results are based on the measurement for RFoF modules operating at 1310 nm, and optical signal transmitted over G.652.D cable.

Apart from the relative gain and phase variation induced by the temperature variation on FO cable, there will be some contributions from other part in the RF signal chain. As active electronics devices such as LNA and RFoF transmitters will be distributed randomly in the field in an area of up to 35 meter in diameter in a typical LFAA station, they are subjected to different temperature profile at different locations.

Outdoor temperature variation in physically separate RFoF transmitter modules will have some effects on the ***relative gain and phase stability of the RF signal transmitted*** by the modules, as well as inducing ***relative wavelength variations*** to the laser diodes inside the transmitter pair. Wavelength variations, coupled with dispersive long-transmission fibre optic cable, might induce significant delay variations, and impact the overall phase variations of the RFoF link. These dispersion-induced phase variations, together with RFoF transmitter gain and phase thermal stability, are not covered in the analysis presented in this report, as they are beyond the scope of the report.

We further performed a series of outdoor measurements and indoor experiments, as well as analytically examined and quantified the significance of the gain and phase variation of a pair of RF electronics subjected to different temperature profiles. The results will be presented in a separate document.

Finally, the support from MWA-AAVS team for the May and June 2015 field deployment of the FO cable is to be acknowledged, in particular the following individuals: *David Kenney, David Emrich, Brian Crosse, Andrew Williams, Jon Tickner and Adrian Sutinjo*.