PAFAR2022

Workshop – Program and Abstracts

15-17 November 2022

Table of Contents

PAFAR 2022 Workshop - Program ... 3
The Development of Focal Plane Arrays in Radio Astronomy ... 6
The LOFAR2.0 upgrade ... 7
ALPACA: The Advanced L-band Phased Array Camera for Astronomy ... 8
Overview and outlook of space surveillance systems at Fraunhofer FHR ... 9
ASKAP's primary beams and their measurement ... 10
A Cryogenic Phased Array Receiver for the Parkes Radio Telescope ... 11
First generation Cryo-PAF for Effelsberg ... 12
Preliminary Design of a Room Temperature C-band Phased Array Feed Prototype with Digital Back-end Based on RFSoC ... 13
CryoPAF Cold Front-End Design ... 14
A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures ... 15
A Vivaldi Based Cryogenic Phased Array Feed ... 16
Phased Array Feed Calibration Systems at CSIRO ... 17
Experimental Focal Plane Array Beamforming for the Expanded GMRT ... 18
The EDD Backend System ... 19
System Design for the Effelsberg CryoPAF Backend ... 20
SKA-Low Project Status ... 21
Computing embedded element patterns for SKA-Low prototype stations AAVS2 and AAVS3 ... 22
Calibration and direct validation of station embedded element patterns for SKA-Low prototype stations AAVS2 and EDA2 ... 23
Validation of the obtained mutual coupling impedance matrix from CST model of two element array ... 24
Design Challenges of Highly Integrated RF Electronics for Astronomical Receivers 25
pHEMT Characterisation and Small Signal Equivalent Circuit Extraction from 4 K to 290 K ... 26
LNAs for Highly Integrated Receivers ... 27
Automation of Low Noise Amplifier Measurements with the *CryoMe* Software Package ... 28
Building the Cryogenic Front-end for the ... 29
Advanced L-band Phased Array Camera for Astronomy ... 29
Introducing "CNIC" - Enabling SKA Low Realtime In-System Testing ... 30
Next generation digitiser for MeerKAT ... 31
Applications of an RFSOC based Digitiser to Digital Receiver Systems ... 32
The Bifrost Stream Processing Framework ... 33
The universal EDD frontend system ... 34
A combination of PAF and spherical reflector to obtain large FoV ... 35

Phased-Array adaptive beam-forming using Deep-Learning Techniques 36
Commercialising cryoPAF Technology 37
On-sky testing of the C-band cryoPAF: *Pharos2* 38
Results from the LOFAR2.0 Dwingeloo Test Station 39
An HLS-based beamformer using Xilinx Alveo Card 40
New and Future Technology development at the Arecibo Observatory 41
RFI-mitigation using a PAF 42
Mitigation of Self-Generated Interference with ASKAP PAF 43
RFI studies using the Parkes ultra-widebandwidth receiver and implications for future instruments 44
An EMI-shielded Module for the Parkes Cryo-PAF RFSoC Digitizers 45
TNRT's Receiver Development and plan for PAF 46
Phased Array Feed (PAF) Demonstrator for TNRT 47
A Real-Time Imaging Correlator for Compact Arrays 48
PAFAR2022 Dinner Cruise.. 49
Code of Conduct 50

PAFAR 2022 Workshop - Program

Tuesday, November 15, 2022		
8:30 – 9:15 AM (AEDT / UTC+11)	Registration, Tea & Coffee	
9:15 – 9:20 AM	House Keeping	Steve Barker
9:20 – 9:30 AM	Welcome	Tasso Tzioumis
Session 1:		**Chair:** Mark Bowen
*9:30 – 10:10 AM	The Development of Focal Plane Arrays in Radio Astronomy	Ekers, R.
10:10 – 10:30 AM	The LOFAR2.0 upgrade	Cappellen, W.
10:30 – 10:50 AM	ALPACA: The Advanced L-band Phased Array Camera for Astronomy	Burnett, M.
10:50 – 11:10 AM	Break	
Session 2:		**Chair:** Stephanie Smith
11:10 – 11:30 AM	Overview and outlook of space surveillance systems at Fraunhofer FHR	Froehlich, A.
11:30 – 11:50 AM	ASKAP's primary beams and their measurement	McConnell, D.
11:50 – 12:10 PM	A Cryogenic Phased Array Receiver for the Parkes Radio Telescope	Dunning, A.
12:10 – 12:30 PM	First generation Cryo-PAF for Effelsberg	Heyminck, S.
12:30 – 1:20 PM	Lunch	
Session 3:		**Chair:** Gundolf Wieching
1:20 – 1:40 PM	Preliminary Design of a Room Temperature C-band Phased Array Feed Prototype with Digital Back-end Based on RFSoC	Pisanu, T.
1:40 – 2:00 PM	CryoPAF Cold Front-End Design	Pütz, P.
2:00 – 2:20 PM	A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures	Sokołowski, M.
2:20 – 2:40 PM	A Vivaldi Based Cryogenic Phased Array Feed	McCulloch, M.
2:40 – 3:00 PM	Break	
Session 4:		**Chair:** Mitch Burnett
3:00 – 3:20 PM	Phased Array Feed Calibration Systems at CSIRO	Chippendale, A.
3:20 – 3:40 PM	Experimental Focal Plane Array Beamforming for the Expanded GMRT	Buch, K.
3:40 – 4:00 PM	The EDD Backend System	Barr, E.D.
4:00 – 4:20 PM	System Design for the Effelsberg CryoPAF Backend	Esser, N.
4:20 – 4:50 PM	Open Forum	
4:50 PM	End of Day 1 Sessions	

* Remote presentation

Wednesday, November 16, 2022		
8:30 – 9:05 AM (AEDT / UTC+11)	Tea & Coffee	
9:05 – 9:10 AM	House Keeping	Steve Barker
Session 5:	**Chair:**	Wim Van Cappellen
9:10 – 9:50 AM	SKA-Low Project Status	Angela Teale
9:50 – 10:10 AM	Computing embedded element patterns for SKA-Low prototype stations AAVS2 and AAVS3	Davidson, D.
10:10 – 10:30 AM	Calibration and direct validation of station embedded element patterns for SKA-Low prototype stations AAVS2 and EDA2	Wayth, R.
10:30 – 10:50 AM	Validation of the obtained mutual coupling impedance matrix from CST model of two element array	Mohamadzade, B.
10:50 – 11:10 AM	Break	
Session 6:	**Chair:**	Keith Grainge
11:10 – 11:30 AM	Design Challenges of Highly Integrated RF Electronics for Astronomical Receivers	Nalbach, M.
11:30 – 11:50 AM	pHEMT Characterisation and Small Signal Equivalent Circuit Extraction from 4 K to 290 K	Jiang, L.
11:50 – 12:10 PM	LNAs for Highly Integrated Receivers	McGenn, W.
12:10 – 12:30 PM	Automation of Low Noise Amplifier Measurements with the CryoMe Software Package	Franks, E.
12:30 – 1:20 PM	Lunch	
Session 7:	**Chair:**	Aaron Chippendale
1:20 – 1:40 PM *	Building the Cryogenic Front-end for the Advanced L-band Phased Array Camera for Astronomy	Vishwas, A.
1:40 – 2:00 PM	Introducing "CNIC" - Enabling SKA Low Realtime In-System Testing	Hampson, G.
2:00 – 2:20 PM	Next generation digitiser for MeerKAT	Malan, J.
2:20 – 2:40 PM	Applications of an RFSOC based Digitiser to Digital Receiver Systems	Roberts, P.
2:40 – 3:00 PM	Break	
Session 8:	**Chair:**	Tasso Tzioumis
3:00 – 3:20 PM	The Bifrost Stream Processing Framework	Price, D.
3:20 – 3:40 PM	The universal EDD frontend system	Kasemann, C.
3:40 – 4:00 PM *	A combination of PAF and spherical reflector to obtain large FoV	Chengjin, J.
4:00 – 4:20 PM	Phased-Array adaptive beam-forming using Deep-Learning Techniques	Cabras, A.
4:20 – 4:50 PM	Open Forum	
4:50 PM	End of Day 2 Sessions	
5:30 PM	Bus departs Marsfield for Workshop Dinner	
7:00 – 10:00 PM	Workshop Dinner	
10:30 PM	Bus returns to Marsfield	

* Remote presentation

Thursday, November 17, 2022		
8:30 – 9:05 AM (AEDT / UTC+11)	Tea & Coffee	
9:05 – 9:10 AM	House Keeping	Steve Barker
Session 9:	**Chair:** Ken Smart	
9:10 – 9:50 AM	Commercializing cryoPAF technology	Boers, M.
9:50 – 10:40 AM	CryoPAF/Marsfield Tour	
10:40 – 11:00 AM	Break	
Session 10:	**Chair:** Doug Hayman	
11:00 – 11:30 AM	On-sky testing of the C-band cryoPAF: Pharos2	D'Cruze, M
11:30 – 11:50 AM	Results from the LOFAR2.0 Dwingeloo Test Station	Hut, B.
11:50 – 12:10 PM	An HLS-based beamformer using Xilinx Alveo Card	Men, Y.
12:10 – 12:30 PM		
12:30 – 1:20 PM	Lunch	
Session 11:	**Chair:** Jason Van Aardt	
1:20 – 1:40 PM	RFI-mitigation using a PAF	Heyminck, S.
1:40 – 2:00 PM	Mitigation of self-generated interference with ASKAP PAF	Lourenço, L.
2:00 – 2:20 PM	RFI studies using the Parkes ultra-wide bandwidth receiver and implications for future instruments	Hobbs, G.
2:20 – 2:40 PM	An EMI-shielded Module for the Parkes Cryo-PAF RFSoC Digitizers	Roush, P.
2:40 – 3:00 PM	Break	
Session 12:	**Chair:** Alex Dunning	
3:00 – 3:20 PM	TNRT's Receiver Development and plan for PAF	Singwong, D.
3:20 – 3:40 PM	Phased Array Feed (PAF) Demonstrator for TNRT	Bandudej, K.
3:40 – 4:10 PM *	A Real-Time Imaging Correlator for Compact Arrays	Krishnan, H.
4:10 – 4:30 PM	Open Forum	
4:10 PM	Workshop Close	

* Remote presentation

The Development of Focal Plane Arrays in Radio Astronomy

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To be presented by Ron Ekers

I will discuss the scientific drivers for putting more than a single receiving element at the focus of a radio telescope. This started with multibeam systems using independent detectors (as is still the case at mm wavelengths). By the early 80s the concept of fully sampling the voltage at the focal plane of a parabolic dish was being discussed and the first rudimentary systems for radio astronomy were built in the mid-90s. Despite the challenging technology involving bandwidth and mutual coupling a number of groups were moving forward spurred on by the many additional advantages which could be foreseen. I will summarise some of these developments and future plans and also show a few of the exciting astronomical results which will have a revolutionary impact on the future of radio astronomy.

The LOFAR2.0 upgrade

Wim van Cappellen[1], Boudewijn Hut[1], André Gunst[1], Arno Schoenmakers[1], Carla Baldovin[1], and Gijs Schoonderbeek[1]
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LOFAR, the Low-Frequency ARray, is a radio telescope that observes the lowest frequencies that can be received from Earth. Its 52 antenna stations are spread out over Europe. LOFAR2.0 is a major upgrade to LOFAR. By enabling simultaneous observing of all Low Band Antennas (LBAs) and High Band Antennas, and by using new calibration techniques, LOFAR's LBA imaging sensitivity will increase by a factor of ~5, while pushing to lower frequencies (< 50 MHz) and maximizing the image fidelity.

LOFAR2.0 replaces the electronics in the station cabinets: New receivers with an increased RFI robustness are introduced, the signal processing capacity at the stations is tripled, and the station cooling is improved. The clock accuracy of the Dutch stations will be improved by the distribution of a central reference clock using White Rabbit.

The hardware design of LOFAR2.0 has been completed (see Figure 1). After successful tests of the new station processing subrack in the lab, the performance of the integrated system is tested in the Dwingeloo Test Station. In the second half of 2022 the hardware will be installed in one of the LOFAR stations for its final validation.

The new Timing Distributor subsystem has been tested in LOFAR and successfully demonstrated that the clock drift has been reduced from tens of nanoseconds to less than 1 nanosecond over a period of 8 hours.

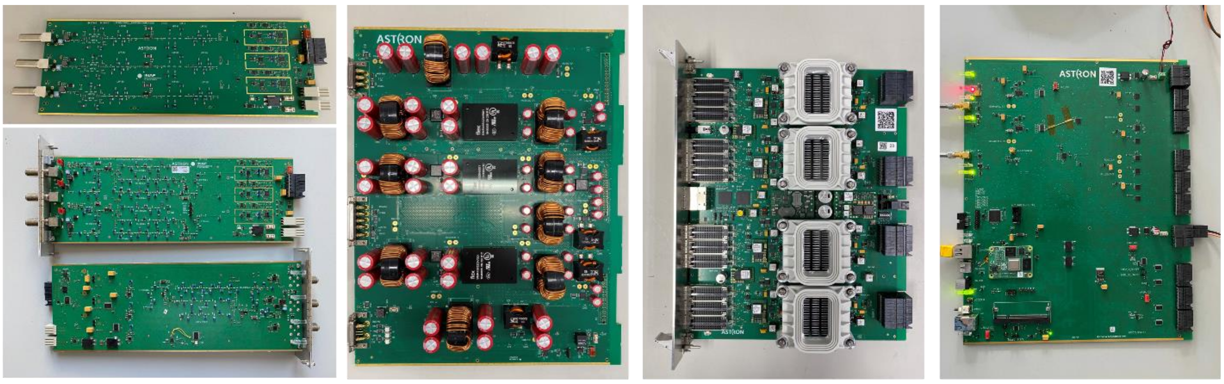

Figure 1. LOFAR2.0 station processing hardware.

ALPACA: The Advanced L-band Phased Array Camera for Astronomy

Mitchell C. Burnett[1], Karl F. Warnick[1], Brian D. Jeffs[1], Amit Vishwas[2], Stephen P. Parshley[2], George E. Gull[2], German Cortes-Medellin[2] and Donald B. Campell[2]
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[2] Cornell University, Ithaca, USA

The Advanced L-band Phased Array Camera for Astronomy (ALPACA) is a fully cryogenically cooled 69-element dual-polarized broadband dipole array with a digital signal processing back end for real-time beamforming and calibration [1]. An instantaneous processing bandwidth of 305 MHz with 40 full-Stokes beams can be tuned from 1.3-1.72 GHz. The beamformed system noise temperature design goal is 25 K. ALPACA was to be a permanent phased array feed facility instrument on the Arecibo Telescope prior to its decommissioning and collapse in December 2020. Efforts are underway for evaluation, funding, and reconfiguring ALPACA for the Green Bank Telescope (GBT). With its wide field of view, ALPACA will enable dramatically increased survey speeds for galactic and extragalactic spectral line sources (e.g., HI), pulsars, radio transients, and other high value science studies.

We will present the design and development progress of the ALPACA instrument as it nears completion. The dipole array elements and LNAs are integrated as easily replaceable cryogenic modules, housed behind an RF-transparent foam and HDPE thermal window which supports the vacuum load. Received signals are transmitted using custom RF-over-fiber transmitter and receiver links from the front end, mounted at prime focus on the GBT, over 3.5 km to the digital back-end hardware. For array calibration, output voltage correlation, channelization, beamforming, and imaging, ALPACA will use a heterogeneous architecture with Xilinx RFSoC FPGAs and a cluster of GPU processing nodes networked by a 100 GbE spine. The back end will be capable of producing 40 simultaneous dual-polarized beams with both coarse and fine frequency channelized data modes.

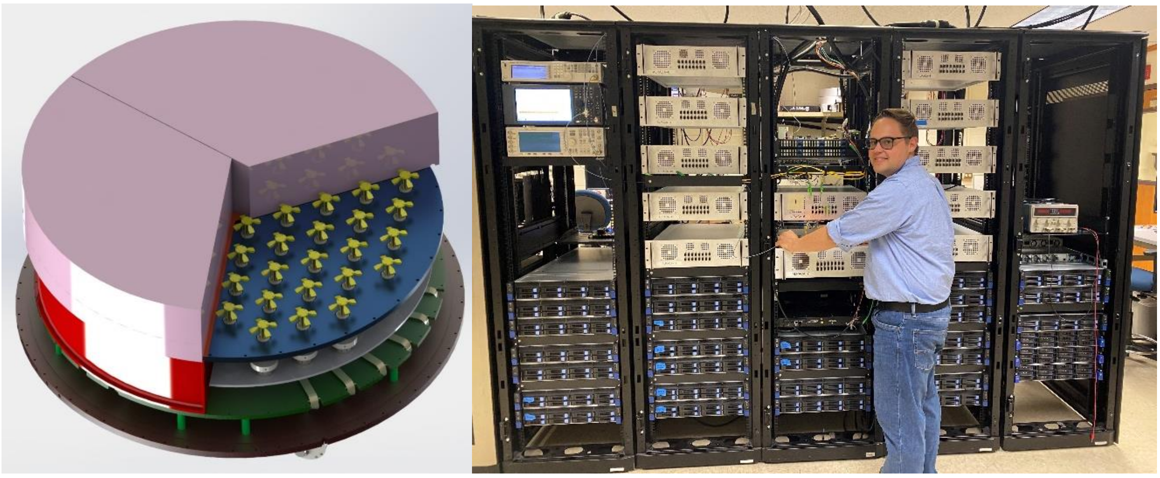

Figure 1. [Left:] ALPACA front end cryostat with the vacuum window and section of the RF clear foam removed showing the 20 K cryogenic array stage, the ground plane (blue), first 80 K stage (grey), radiation shield (red), and base plate (green). [Right:] Digital back end with 12 Xilinx ZCU216 RFSoCs, 27 HPCs, and 54 Nvidia A10 GPUs.

Table 1. Digital Back End Operational Modes

Operational Mode	Pulsar/Transient	Spectral Line	Beamformer Calibration
Output Channels	1250	96000	1250
Bandwidth (MHz)	305.2	122.1	305.2
Dump interval	64 us	100 ms	500 ms

[1] M. C. Burnett, K. F. Warnick, B. D. Jeffs, et al., "Design and development of a wide-field fully cryogenic phased array feed for Arecibo," in 2020 *XXXIIIrd General Assembly and Scientific Symposium of the International Union of Radio science (URSI GASS), 2020, pp. 1-4*

Overview and outlook of space surveillance systems at Fraunhofer FHR

A. Froehlich[1], D. Behrendt [1] A. Engel[1], M. Gilles [1], C. Kirchner[1], P. Müller [1],
O. Peters[1], C. Reising [1] and T. Eversberg [2]
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[2] German Space Agency, Germany

The number of threatening space debris particles is constantly increasing and poses a growing threat to space infrastructures such as satellites or manned spaceflight. Therefore, various sensor systems are needed for detection, trajectory determination and cataloging. With the help of this data, avoidance maneuvers can be carried out, for example.

An important parameter is the sensitivity of the systems, since even small particles with a size of 1 cm can lead to the failure of a satellite due to the high velocities. In order to ensure area-wide detection, various sensor systems are being set up around the world.

One of these sensors is the GESTRA system, which is set up at FHR since 2014 on behalf of DLR [1]. In order to continuously improve the performance and the applicability, further developments and expansion stages are carried out based on the GESTRA system, which will be presented and described in the following.

Within the scope of EUSST, the receiving system of the GESTRA receiver will be further optimized, in connection with the project "GESTRA Networking", the network capability of the systems will be analyzed for different constellations [2].

Within the scope of TX2, the transmitter of the GESTRA system will be revised, which includes an increase in performance and an increase in robustness. This will increase the sensitivity of the system in the future and allow it to deploy in different environments [3].

In parallel, the experimental system is being taken to a higher TRL level with an industrial partner, so that it can be used in different environments while complying with regional regulations and industry standards.

As an outlook, performance enhancement through the use of cryogenic receivers is being investigated. There are already developments and publications on how to build a cryogenic scalable receiver system, with initial demonstrators and a setup for a 38-element array that has been simulated thermally and electrically. [3][4]

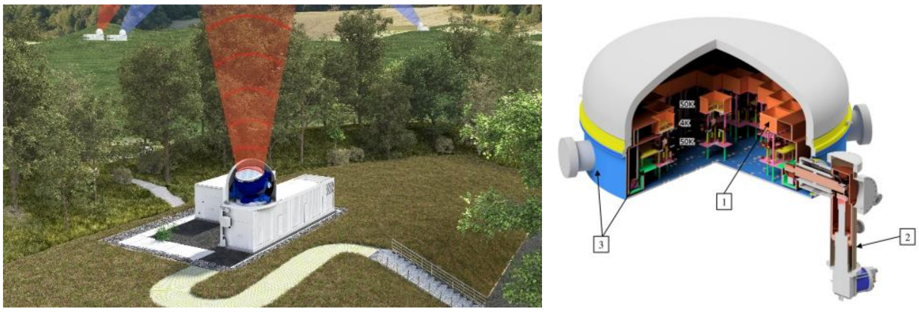

Figure 2. Left: GESTRA systems in various stages of development as distributed systems,
right: Concept of a cryogenic phased array receiver with 38 elements

[1] H. Wilden, C. Kirchner, O. Peters, N. Ben Bekhti, A. Brenner and T. Eversberg, "GESTRA — A phased-array based surveillance and tracking radar for space situational awareness," *2016 IEEE International Symposium on Phased Array Systems and Technology (PAST), 2016, pp. 1-5, doi: 10.1109/ARRAY.2016.7832621.C.A. Balanis, Antenna Theory: Analysis and Design, Wiley,* New Jersey, 2005.

[2] H. Wilden et al., "GESTRA - Recent Progress, Mode Design and Signal Processing," *2019 IEEE International Symposium on Phased Array System & Technology (PAST), 2019, pp. 1-8, doi: 10.1109/PAST43306.2019.9020744..*

[3] C. Reising et al., " GESTRA - upgrading to future distributed phased array radar networks for space surveillance," *2022 IEEE International Symposium on Phased Array System & Technology (PAST), 2022, submitted for publication*

[4] A. Froehlich et al "Conceptual design of cryostat for cryo-cooled 37 elements phased array radar system for space surveillance" *2022 IOP Conf. Ser.: Mater. Sci. Eng. 1240 012102*

N Ben Bekhti *et al* "First studies towards a cryo-cooled Phased Array Radar System for Space Surveillance" *2019 IOP Conf. Ser.: Mater. Sci. Eng. 502 012194*

ASKAP's primary beams and their measurement

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The Australian SKA Pathfinder telescope[1] is equipped with Phased Array Feeds on each of its 36 antennas, with which it forms 36 dual-polarization beams. The telescope is now largely operational and early experimental sky surveys have emphasized the need for reliable measurements of primary beam shape.

The Rapid ASKAP Continuum Survey[2] (RACS) of the whole accessible sky was designed as an advanced commissioning test of all the telescope's systems and was commenced in 2019. Images were produced using primary beams of width determined by previous holography measurement but were assumed to have gaussian shape. The image flux-density scales were set with reference to the flux-density standard PKS B1934-638, but comparisons of RACS results with published surveys (SUMSS[3], NVSS[4]) showed the RACS source flux-densities to be systematically high by 5-10%. The flux errors varied systematically with position within each field suggesting that a better account of beam shape variations was needed.

Consequently, the holography measurement process was reviewed and a number of improvements were made, including corrections to the sampling grid, the adoption of a better holography reference source and automated identification of data contaminated by RFI (radio frequency interference). The improved reliability of the measurements has allowed their routine use in ASKAP's mosaicing process that combines the 36 beam images into a single image of the full field-of-view.

I will briefly summarise RACS and describe the steps taken in processing holography data to image ASKAP's primary beam response patterns. I will also present some beam metrics derived from recent measurements, and their application to the understanding of antenna pointing errors. ASKAP's flux calibration remains imperfect, and I will discuss the likely remaining sources of error and some possible remedies.

[1] Hotan, A. W., Bunton, J. D., Chippendale, A. P., et al. "Australian square kilometre array pathfinder: I. system description", *Publications of the Astronomical Society of Australia*, vol. 38, 2021. doi:10.1017/pasa.2021.1.
[2] McConnell, D., Hale, C. L., Lenc, E., et al. "The Rapid ASKAP Continuum Survey I: Design and first results", *Publications of the Astronomical Society of Australia*, vol. 37, 2020. doi:10.1017/pasa.2020.41.
[3] Mauch, T., Murphy, T., Buttery, H. J., et al. "SUMSS: a wide-field radio imaging survey of the southern sky - II. The source catalogue", *Monthly Notices of the Royal Astronomical Society,* vol. 342, no. 4, pp. 1117–1130, 2003. doi:10.1046/j.1365-8711.2003.06605.x.
[4] Condon, J. J., Cotton, W. D., Greisen, E.W., et al. "The NRAO VLA Sky Survey", *The Astronomical Journal*, vol. 115, no. 5, pp. 1693–1716, 1998. doi:10.1086/300337.

A Cryogenic Phased Array Receiver for the Parkes Radio Telescope

A. Dunning[1] on behalf of the CSIRO cryoPAF team
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In order to enhance both the field of view and the frequency range of the Parkes Radio Telescope, a cryogenic phased array system (cryoPAF) is under development. The phased array feed will consist of a regular grid of antenna elements with 196 ports, 98 for each polarization. It will cover a frequency range of 0.7-1.9 GHz. Initially, an arbitrary 307.2 MHz band will be beamformed, however, it is expected that this will be increased to 921.6 MHz in the near future. The phased array feed, presented in fig. 1, contains three distinct element designs: central elements, edge elements and corner elements. The central elements are similar in design to the 'rocket' elements presented in [1].

Differential low noise amplifiers (LNAs) with integrated calibration noise coupling are attached directly to the base of the elements. The signals from each of these LNAs are processed in a single electronics module containing RF signal conditioning, digitization, preliminary digital signal processing and optical data transmission. The signals are then combined in a remotely located digital beamformer, implemented using Alveo FPGA cards. The beamformer will allow 72 dual polarization beams to be formed which will subsequently be processed in a GPU cluster.

The receiver is cooled with two single stage cryocoolers to approximately 30 K. The use of single stage cooling, rather than the more common two stage cooling, results in a small degradation in the noise temperature of the LNAs. However, this is offset by the elimination of a thermal transition between the receiving elements and the LNAs. Single stage cooling also results in a substantial simplification in the mechanical structure of the array and avoids the complication of interstage transitions between the large number of electrical connections.

We discuss key elements of the system architecture and design, present the expected performance from simulation and present some early results of measurement.

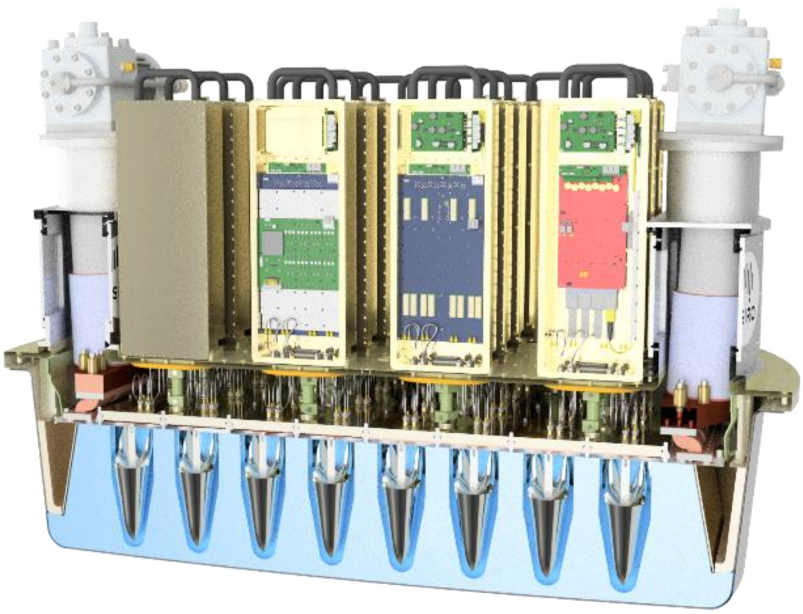

Figure 3. A rendered cross section of the cryogenic phased array receiver displaying the array elements at the base, the ambient temperature electronics modules and the two cryocoolers.

A. Dunning, M. Bowen, D. B. Hayman, K. Jeganathan, H. Kanoniuk, R. Shaw, S. severs, "The development of a wideband 'rocket' phased array feed," 2016 European Radar Conference (EuRAD), London, 5-7 Oct. 2016

First generation Cryo-PAF for Effelsberg

S. Heyminck[1], G. Wieching[1], C. Kasemann[1], P. Pütz[1], E. Barr[1], O. Polch[1], B. Klein[1], C. Leinz[1], A. Kraus[1], M. Kramer[1], Chengjin Jin[2], M. Nooroziarab[1], T. Oyedokun[1], R. Castenholz[1], M. Nalbach[1], M. Kuntschev[1], F. Schäfer[1], S. Türk[1], M. Mbeutcha[1], S. Lenz[1], A. Henseler[1], N. Esser[1], Y. Men[1], I. Krämer[1]

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[2] National Astronomical Observatories, Chinese Academy of Sciences

Embedded into the "Low Frequency Gravitational Wave Astronomy and Gravitational Physics in Space“, a joint project of CAS and MPG, a long-term development project on cryogenic PAF systems was started together with our colleagues from NAOC back in 2018. To lay the foundation stone for future PAF developments at the institutes, we established an initial 3-year phase of research, design-, and feasibility-studies. On MPIfR side the electronics division took this occasion to additionally start large investments into the development of phased array feed receiver systems. Based on the results of these design- and feasibility-studies, the design and construction of a first generation cryogenic PAF for the Effelsberg 100 m telescope was initiated in late 2021. We are aiming to install the system in late 2023 at the telescope. However, this will heavily depend on the currently rather unpredictable delivery and lead times of all commercially acquired components.

Within this work we will give an overview (see also Figure 1) on the planned system including all major sub- components, their interactions, and their embedding into the telescope structure and systems. Some of the sub- systems will be discussed in more depth, for others we just refer to dedicated contributions within this conference (see references below).

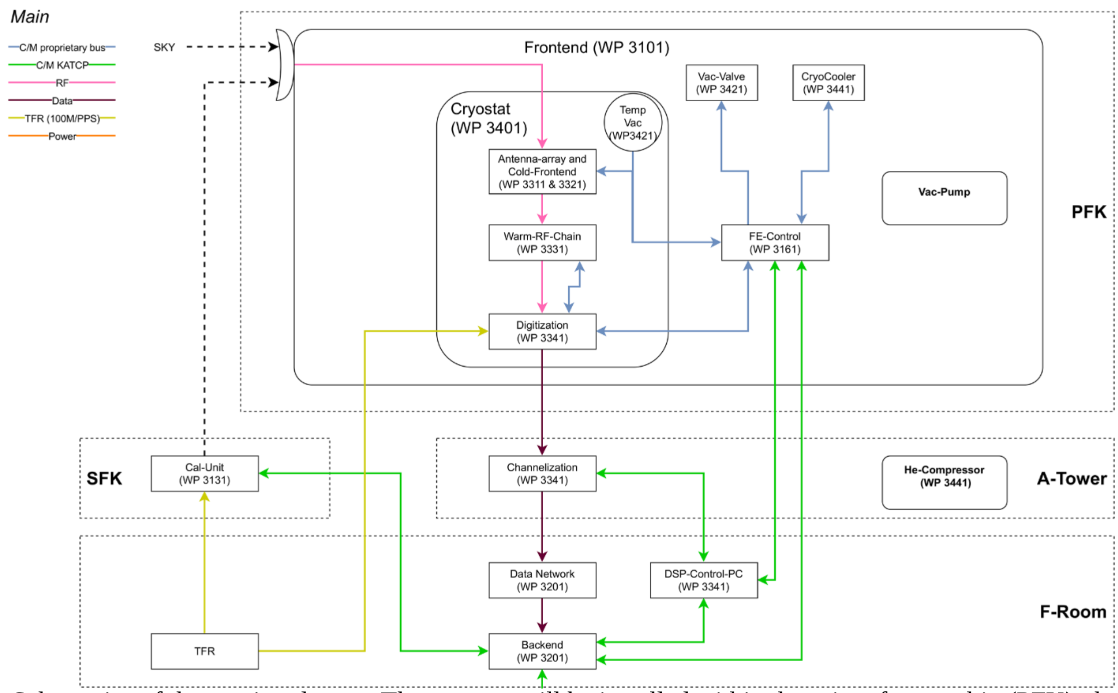

Figure 1: Schematics of the receiver layout. The cryostat will be installed within the prime focus cabin (PFK), the calibration system in the secondary focus cabin (SFK), channelization and helium compressors are located on the A-tower, and the beam-former together with the backend is placed in the Faraday room (F-room) outside the moving parts of the telescope.

[1] P. Pütz et al., “CryoPAF cold front-end design”, *Phased Array Feed & Advanced Receivers Workshop, 2022*
[2] N. Esser et al., “System Design for the Effelsberg CryoPAF Backend”, *Phased Array Feed & Advanced Receivers Workshop, 2022*
[3] Y. Men et al., “An HLS-based beamformer using Xilinx Alveo Card”, *Phased Array Feed & Advanced Receivers Workshop, 2022*
[4] S. Heyminck et al., “RFI-mitigation using a PAF”, *Phased Array Feed & Advanced Receivers Workshop, 2022*

Preliminary Design of a Room Temperature C-band Phased Array Feed Prototype with Digital Back-end Based on RFSoC

A. Navarrini[1*], A. Melis[1], G. Comoretto[2], T. Pisanu[1], R. Nesti[2], P. Marongiu[1], P. Ortu[1], P. Maxia[1], A. Ladu[1], H. Ghobadi[2], R. Concu[1], A. Cabras[1], L. Schirru[1], P. Di Ninni[2], M. Belluso[3], S. Billotta[3]
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(3) INAF (National Institute for Astrophysics)-Catania Astronomical Observatory, Catania, Italy
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We are designing a small prototype of a C-band Phased Array Feed (PAF) with RFSoC (Radio Frequency System-on-Chip) digital beam former [1]. The receiver operates at room temperature in the portion of the C- band between 4.75 and 6 GHz (Figure 1). The Front-End prototype consists of a compact module based on an 8×8 array of dual-polarization Vivaldi antennas integrated with filters and Monolithic Microwave Integrated Circuit (MMIC) Low Noise Amplifiers (LNAs) mounted on a low-loss substrate. A subset of 32 single- polarization elements is connected to the LNAs, while the remaining elements are terminated into 50 Ohm loads. The 32 active elements of the array are connected to two RFSoC boards, each accepting 16 inputs with 1.25 GHz bandwidth. These boards will perform the frequency channelization, the partial, and the final beamforming of four independent beams with 1.25 GHz instantaneous bandwidth. The PAF prototype will serve as a demonstrator for a large cryogenic PAF to be subsequently built for low-noise radio astronomy application on the Sardinia Radio Telescope (SRT, http://www.srt.inaf.it/). In our presentation, we will describe the technical requirements and the preliminary design of the room temperature prototype array and present the electromagnetic simulation results.

In parallel with the array development, a characterization of the radio frequency interferences (RFIs) scenario is necessary to determine the level of the undesired self-generated and external spurious signals from sources surrounding the SRT environment. We will present the results of two RFI measurement campaigns: one performed with the goal to study the emission of the signal from the prototype RFSoC board, for which specific mitigations will be required and applied, and the other to characterize the area surrounding the telescope. The knowledge of the self-produced RFI and of the external RFI scenario will permit us to establish the architecture of the future large-scale cryogenic array for the SRT and determine the detailed technical requirements of all its microwave components of the signal acquisition chain. (i.e. low noise amplifiers, microwave filters, attenuators, etc.).

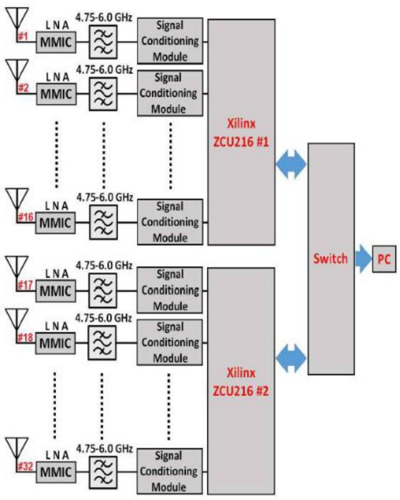

Figure 1. The architecture of the 4.75-6.00 GHz PAF shows the 32 RF signal chains and the two digital RFSoC boards connected to a 100 Gbps network switch and a PC [1].

[1] A. Navarrini *et al.*, "Architecture of C-band Phased Array Feed with RFSoC digital beamformer," *2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC)*, 2022, pp. 1-3, doi: 10.23919/AT-AP-RASC54737.2022.9814401.

CryoPAF Cold Front-End Design

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We present the design of the cryogenic signal chain for the first generation cryogenic PAF receiver, CryoPAF that is in development for the Effelsberg 100-m observatory. CryoPAF is the first cryogenic phased-array feed receiver being developed at the MPIfR. It will feature 250 antenna elements in total with first-light planned for the end of 2023. CryoPAF is considered a first-generation instrument and development of suitable front-end hardware is driven by evaluation of scalable technology for future, significantly larger receivers.

We will discuss the design considerations to accomplish the goal of maximum integration and scalability. For each antenna element we combine the cryogenic front-end signal chain onto a single PCB, consisting of the dipole antenna loop, balun, bandpass filter, LNA and connectors. This not only facilitates the integration of front-end technology into high pixel count receivers but also will be an enabler for automated assembly work, in part performed by contractors.

Several topologies for arrangement of the FE signal chains were investigated, i.e. planar stacking similar to radar applications or vertical such as a typical Vivaldi element PAF. Our initial focus was set on evaluating several underlying PCB technologies for cryogenic performance. For this various prototype LNA packages have been tested all using custom MMIC mHEMT devices developed by our partners at Fraunhofer IAF. Of particular interest is a proprietary PCB laminate technology from Andus GmbH, which features mm-thick copper panels that are profiled to include flush mounted RF substrates. This allows the MMIC chips to be placed onto solid copper material plateaus that provide heat-sinking and low-impedance ground connection to the transmission lines whilst retaining a PCB card form factor. Furthermore, embedded coaxial feedthroughs realised through impedance controlled plated vias are investigated. These connect between signal layers or through the whole laminate stack.

Whilst initial results are promising for implementation into future PAF receivers, the first generation cryogenic PAF will follow a risk-reducing approach based on vertical integration of plug-in type PCB cards. We will present the pre-production design of these plug-in cards and detail RF evaluation of the cryogenic signal chain and sub-circuits including the performance of different MMIC designs.

A High-Speed All-Sky Monitor for Fast Radio Bursts and Technosignatures

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The Engineering Development Array 2 (EDA2) [1] and Aperture Array Verification System 2 (AAVS2) [2] are prototype stations of the low frequency (50 - 350 MHz) Square Kilometre Array (SKA-Low). Since 2019, these stations have been used for various tests, including verification of SKA-Low technology, station calibration, beamforming, sensitvity etc. Despite representing a small fraction of the full SKA-Low telescope, they also have enormous science potential owing to their all-sky imaging capability. Thus, we also recorded multiple long datasets (24 hours or more) of 2-second all-sky images at several frequency channels (each about 1 MHz bandwidth) distributed between 50 and 350 MHz. We used these images to perform a pilot transient survey and demonstrate potential of the stations for transient science [3]. In approximately 360 hours of data we identified episodes of very bright pulses from the pulsar PSR B0950+08, and derived upper limits on surface density of radio transients at 2-second timescale (a relatively unexplored part of the parameter space). We also measured upper limits on flux densities of a few Fast Radio Bursts (FRBs) detected by high-frequency telescopes (ASKAP and Parkes), which demonstrated that such an all-sky monitor can be extremely useful for multi-wavelength observations of FRBs or other transient phenomena (e.g. Gamma Ray Bursts, Gravitational Wave events etc.) discovered by other instruments. I will summarise these results and discuss our on-going efforts to increase the observing bandwidth of the prototype stations to approximately 30 MHz and time resolution to tens of milliseconds which will improve the sensitivity to FRBs, short transients, and technosignatures by two orders of magnitude. These efforts are leveraged by the on-going PaCER project BLINK to develop software for high-time resolution imaging (e.g. Figure 1) and FRB searches with SKA-Low precursors. Our estimates predict that the upgraded all-sky monitoring system should detect even hundreds of bright, nearby FRBs per year, and their localisations to ~arcmin precision via triggering the Murchison Widefield Array will help to understand FRB progenitors. The presented work will open very exciting avenues for early science with SKA-Low stations even in its construction phase.

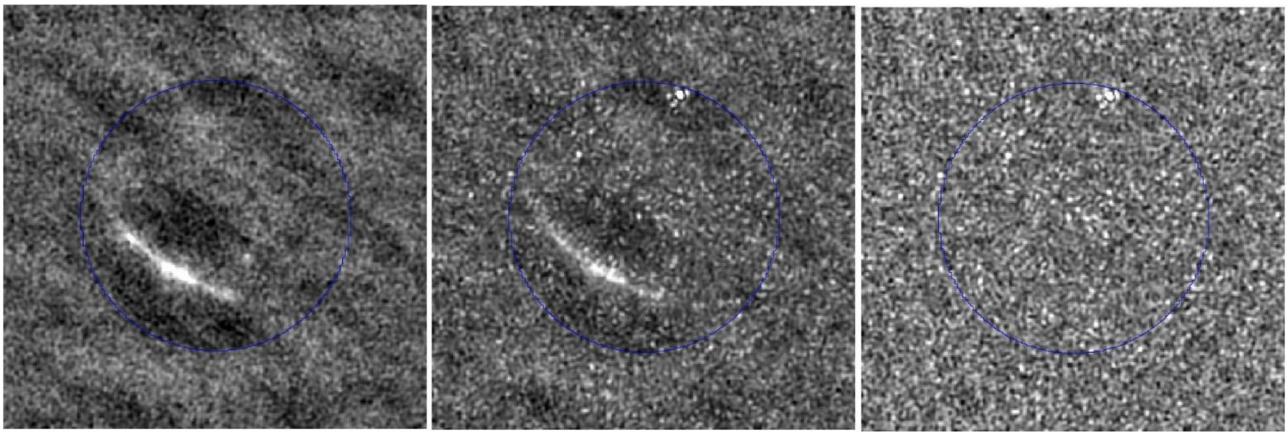

Figure 1. Example 100-ms / 28.94 kHz all-sky images from EDA2 at 241.4 MHz, which is known to be affected by radio frequency interference (RFI). Left: An all-sky image started at 11:25:31.77 UTC. Center: The next 100-ms image with a very bright short (≤ 100 ms) RFI-transient at the top of the image near the horizon (blue line). The object was not visible in the next 100-ms images. Right: The difference of the two images where the transient was automatically identified by a real time algorithm. These all-sky images were created by a version of the high-time resolution imaging software which does not have flux calibration implemented yet (hence no colour bar shown).

[1] Wayth, R., “Engineering Development Array 2: design, performance, and lessons from an SKA-Low prototype station”, JATIS, vol. 8, 2022. doi:10.1117/1.JATIS.8.1.011010.

[2] Macario, G., “Characterization of the SKA1-Low prototype station Aperture Array Verification System 2”, JATIS, vol. 8, 2022. doi:10.1117/1.JATIS.8.1.011014.

[3] Sokolowski, M., “A Southern-Hemisphere all-sky radio transient monitor for SKA-Low prototype stations“, PASA, Volume 38, article id. e023

[4] Sokolowski, M., “A High Time Resolution All-Sky Monitor for Fast Radio Bursts and Technosignatures“, 3rd URSI Atlantic and Asia Pacific Radio Science Meeting, 2022, doi: 10.23919/AT-AP-RASC54737.2022.9814380.

A Vivaldi Based Cryogenic Phased Array Feed

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At the previous PAF workshop [1] we presented our development of a prototype solid Vivaldi S-band 40 element array (Figure 1). In this presentation we will discuss the final part of project, the cryogenic ground-based testing of the array, which was carried out at the Jodrell Bank Observatory in 2021. For cryogenic testing 8 elements on a single polarization were equipped with state-of-the-art Low Noise Factory LNF_1_5_6 amplifiers, and the signals from each element were combined to form a single beam using a room temperature analogue beamformer, which was assembled from power combiners and 8 Mini-Circuits ZX60-83LN-S+ LNAs. A model of the receiver was made using Keysight's Advanced Design System, and the predicted noise temperature was approximately 11K, which was a few kelvin lower than what we measured (Figure 2). Due to the Covid pandemic we were unable to construct a dedicated cryostat for the array, so it was tested using the PHAROS 2 cryostat, and we will outline why we believe this had a negative impact on the final performance.

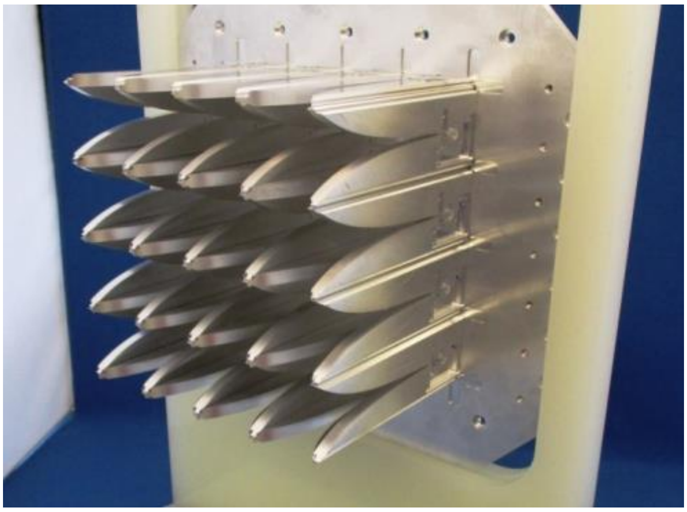

Figure 4. The front of the prototype array showing the 40 elements.

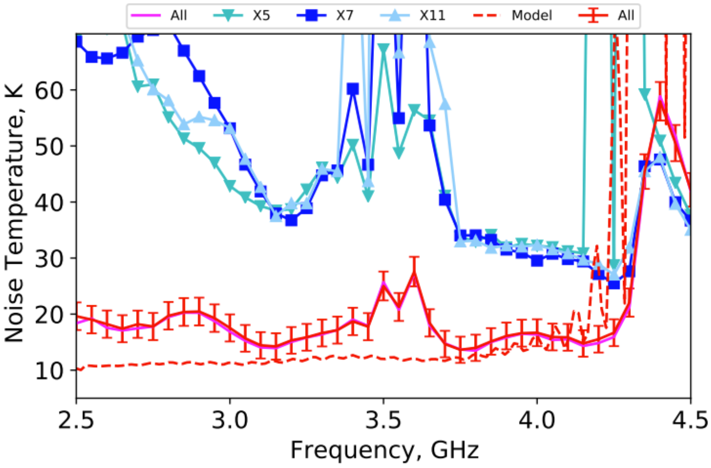

Figure 2. Noise measurements at 30K for individual elements and the combined beam.

[1] M. A. McCulloch, K. Grainge, M. Keith, et al., "Front End Technologies for an S-Band Phased Array Feed ". PAF Workshop 2019, Bonn, Germany, 2019.

Phased Array Feed Calibration Systems at CSIRO

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Phased array feeds (PAFs) allow observers to adjust beamformer weights to control telescope performance. PAF beamforming can improve instrument response for specific science goals, but also change beam properties that need calibration. Antenna beam gain, pattern, sensitivity, and polarisation all change with intentional changes to beam weights and any unwanted fluctuations in electronic gains before the beamformer.

This presentation reviews CSIRO's efforts to use noise sources to stabilise and calibrate PAF beams. The Australia Square Kilometre Array Pathfinder (ASKAP) telescope employs a calibration noise source external to the PAF, mounted at the vertex of each reflector. This on-dish calibration system is used to calibrate delay changes in the digital receiver that occur on each reset of the digitiser subsystem. With this calibration, ASKAP can refresh archived beamformer weights via an 8 min measurement of the noise source instead of having to make a one-hour observation of the Sun to calculate fresh weights. On-dish calibration is also used to calibrate the XY phase of each ASKAP beam and set it near zero by modifying beamformer weights. This allows polarisation results to be obtained from all ASKAP continuum observations without having to make regular, long measurements of astronomical sources with known polarisation properties in each beam.

More advanced applications of on-dish calibration have been challenging on ASKAP. The cavity reflection between the reflector and the PAF and its support structure causes bandpass ripples in the calibration signal. Further, multipath propagation of the calibration signal is not stable with the movement of ASKAP antennas. Measurements of the calibration noise response of the PAF while tipping the reflectors to low elevations and rotating them about their polarisation axes show significant variations, excluding the possibility of making reliable corrections to beam gain, bandpass and shape during observations. We currently make two bulk corrections at the beginning of each scientific observation: a correction to the port delays via the phase slope of the beamformer weights (at the 1 MHz resolution of the beamformer) and a single frequency-independent gain amplitude correction to each PAF port. These corrected weights are then held constant through ASKAP observations. We observe fluctuations in beam gain with temperature that could be corrected during observations if we could stabilise the calibration signal with antenna motion.

Multipath is more challenging at Parkes due to the large reflection cross-section of the focus cabin holding the CryoPAF. Therefore, we have built a calibration noise source internal to the CryoPAF. This will reduce multipath reflection via the reflector surface and dependence of the calibration signal path on antenna motion. We have reversed the calibration noise phase between groups of adjacent PAF elements to further reduce the coherence of any radiated calibration signal that leaks from the PAF and could cause multipath. After reviewing ASKAP's on-dish calibration system and its challenges, this presentation will outline the CryoPAF's internal calibration system and how we intend to use it to calibrate PAF ports and beams.

[1] A. P. Chippendale et al. "Recent Developments in Measuring Signal and Noise in Phased Array Feeds at CSIRO", *European Conf. on Antennas and Propagation (EuCAP)*, Davos, Switzerland, pp. 1-5, 2016.
[2] D. B. Hayman et al., "Gain calibration of phased array feeds," 2010 International Conference on Electromagnetics in Advanced Applications, 2010, pp. 418-421, doi: 10.1109/ICEAA.2010.5653177.
[3] A. P. Chippendale et al. "Measuring ASKAP's On-Dish Calibration Signal Level and its Impact on Beam Sensitivity," ACES Memo 18, CSIRO.
[4] A. P. Chippendale & C. Anderson "On-Dish Calibration of XY Phase for ASKAP's Phased Array Feeds," ACES Memo 19, CSIRO.
[5] Hotan et al. (2021). "Australian square kilometre array pathfinder: I. system description." *Publications of the Astronomical Society of Australia*, *38*, E009.
[6] A. P. Chippendale (2019) "Calibrating ASKAP's Phased Array Feeds with External Noise Sources," PAF Workshop 2019, Bonn.
[7] R. Beresford et al. (2018) "ASKAP on-dish calibration system." PAF Workshop 2018; Guizhou, China.

Experimental Focal Plane Array Beamforming for the Expanded GMRT

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The Expanded Giant Metrewave Radio Telescope (eGMRT) [1] proposal aims at increasing the Field-of-View (FoV) of the GMRT antennas by a factor of 25 using a Focal Plane Array (FPA) and beamforming system. As part of the initial proposal, an optimized FPGA-based prototype beamformer is designed and tested in the free-space test range located at the GMRT site. The prototype can process 32 inputs, each of 32 MHz bandwidth and with 1024 spectral channels, and can form 5 independent beams. The design was developed using the CASPER tool flow [2] and implemented on a single ROACH-1 board and 64-channel ADC. The testing was carried out through broadband radiation in the test range with the ASTRON L-band (1.1-1.4 GHz) FPA in the aperture array mode. The results will be presented from beamsteering, nulling, and optimal beamforming using the maxSNR technique.

In parallel with the prototype beamformer development, we carried out an end-to-end simulation of the beamforming system by modelling the Vivaldi antenna array, RF and analog signal processing systems, and digital beamformer using MATLAB and Simulink. We simulated free-space testing by modelling the transmitting antenna, propagation channel, and sources of interference for testing multiple beams. The simulation was carried out on the Simulink platform using multiple toolboxes for the beamformer's accurate modelling, including the antenna array, test range, and array signal processing algorithms.

The ongoing effort includes developing a wideband beamforming system that can process 300 MHz bandwidth and the feasibility of commissioning the FPA on a dish. Currently, we are implementing wideband beamforming using Xilinx RFSoC-based ZCU111evaluation board. We carried out an initial demonstration of optimal beamforming using raw voltage data from this board. Currently, we are designing a wideband spectrometer and beamformer using CASPER tool flow. As a next step in the testing, we are conducting a feasibility study for commissioning the FPA on a 15m experimental dish at the NCRA campus in Pune or one of the GMRT dishes.

[1] Patra et al., "The Expanded Giant Metrewave Telescope", MNRAS, 483, 3007-3021, 2019.
[2] Hickish et al., ""A decade of developing radio-astronomy instrumentation using CASPER open-source technology", JAI, Vol. 5, No. 4, 2016

The EDD Backend System

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Continual advances in networking, storage and data processing technologies have opened new paths for the development of modular, commodity-off-the-shelf hardware (COTS) solutions for radio astronomy signal processing. The Effelsberg Direct Digitization (EDD) backend is one such solution which aims to fulfil all the standard processing requirements of a modern radio observatory, providing a universal backend that can be deployed wherever there exists an EDD frontend. Already, instances of the EDD backend have been deployed to the Effelsberg radio telescope, the SKA-MPI observing system in South Africa and the Thai National Radio Telescope (TNRT) where they provide the capability to generate science data products for continuum, spectroscopy/spectral polarimetry, high-precision pulsar timing, pulsar and fast-transient search, and very long baseline interferometry (VLBI) use cases. Additionally the EDD backend system allows for the recording to disk of raw or channelised voltage streams for more esoteric use cases such as cyclic spectral analysis of pulsars.

While the aforementioned capabilities are not new for radio telescopes, the EDD backend excels is in its ability to bring all these capabilities together in a extensible, modular framework that runs on general purpose hardware and makes extensive use of open source, industry-standard technologies (e.g. Ansible, Redis, Icing, InfluxDB, Grafana, etc.). Using UDP multicast on high-speed Ethernet networks along with PCIe-mounted FPGAs with on-board network interfaces, the EDD solves the problem of horizontal scaling
by using polyphase filters to allow frequency multiplexing of voltage signals across heterogeneous clusters of GPU processing nodes. The ability to horizontally scale, opens the backend up to fully commensal science programs (e.g. continuum + spectroscopy + pulsar and fast transient search + pulsar timing), with commensality being further supported by the tight coupling of the EDD noise diodes to the digitization system. This allows the noise diode state to be tracked at a sampled level, enabling gating, and for the firing rate to be set higher than the maximum fluctuation frequency of interest for pulsars surveys. The ability to scale the backend also allows it to be extended to more complex observing setups such as phase array feeds (see
"System Design for the Effelsberg CryoPAF Backend" by N. Esser) and large-N interferometers.

In this work, we present an overview of the EDD backend system, looking at its underlying design, its capabilities/limitations and its future. We also highlight some of the science that is beginning to be done with the EDD backend instances deployed around the world.

System Design for the Effelsberg CryoPAF Backend

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Phased array feeds (PAFs) have been used and proven in various applications (radar, 5G, radio astronomy etc.). In particular, radio astronomy benefits from this type of receiver system, due to beamforming which allows to access the full field of view (FoV) and providing fast survey speed. In addition, spatial filtering based on digital synthesized beams is an excellent technique to suppress RFI and therewith recovers frequency bands which are blocked by interfering sources (e.g. communication services, radar) [1].

The Max-Planck Institute for Radio Astronomy is developing the CryoPAF with up to 256 receiving receptors and a bandwidth ranging from 1.3 to 2 GHz for the 100-m Effelsberg radio telescope in Germany [2].

Over the past two years, extensive research, prototyping activities and conceptual designs for the CryoPAF backend have been carried out. The CryoPAF backend processes the incoming data streams of all PAF receptors into science-ready data products in real-time. The real-time requirement of the backend is challenging, as the data rate ranges from 6.1 to 9.7 Tbit/s. This amount of data is handled and processed by powerful parallel accelerators such as FPGAs and GPUs. With the latest technologies in parallel computing, networking and storage, it has become possible to build up a backend system based on commercial-of-the-shelf (COTS) products. A key design goal of the CryoPAF backend is to cover different scientific applications simultaneously. The covered applications include pulsar timing, pulsar/FRB search, spectroscopy and VLBI. In addition, the backend is responsible for controlling and monitoring a significant part of the overall system.

In this work, we present the system design of the Effelsberg CryoPAF backend, including calibration techniques, real-time data processing (e.g. channelization, correlation and beamforming), networking and hardware infrastructure. At the heart of our backend design is the Effelsberg Direct Digitization (EDD) [3] model, which is already proven itself in various projects. The EDD backend provides hardware and software infrastructure, generates services for control and monitoring, allows the orchestration of data processing pipelines and uses communication protocols common to radio astronomy. However, the EDD has previously only been used with single-pixel feeds, whose system requirements are significantly lower compared to the CryoPAF. Therefore, new adaptations according to hardware infrastructure and software features are required to enable the operation of the CryoPAF with an EDD-like backend.

[1] S. Heyminck, G. Wieching, E. Barr, J. Wu, and N. Esser "RFI-mitigation using a PAF", *Phased Array Feed & Advanced Receivers Workshop, 15-17 November 2022, Sydney, Australia*

[2] S. Heyminck et. Al. "First Generation CryoPAF for Effelsberg", *Phased Array Feed & Advanced Receivers Workshop, 15-17 November 2022, Sydney, Australia*

[3] E. Barr et. Al. "The EDD Backend System", *Phased Array Feed & Advanced Receivers Workshop, 15-17 November 2022, Sydney, Australia*

SKA-Low Project Status

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Square Kilometre Array (SKA) Low is set to be the world's largest low frequency radio telescope. Australia will initially host more than 130,000 SKA antennas (each about 2 metres in height) covering the frequency range 30-350MHz. The project is beginning to ramp up internationally and will start construction on the CSIRO's Murchison Radio-astronomy Observatory site in Western Australia in early 2023. SKA-Low will provide an increased capability over existing infrastructure at the same frequencies, providing 25% better resolution and being 8 times more sensitive than LOFAR, the current best such instrument. Moreover, it will be able to scan the sky 135 times faster.

This discussion will provide an overview of the project's current status, a summary of the telescope as a whole, as well as the current engineering efforts that are underway.

Computing embedded element patterns for SKA-Low prototype stations AAVS2 and AAVS3

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Several SKA-Low prototype stations have been deployed on the MRO during the pre-construction and bridging programs of SKA. Known as the Aperture Array Verification System(s), the first version (AAVS1) was deployed during 2016-17, and the current version (AAVS2) in 2019. Work is currently in progress towards AAVS3. All these prototypes comprise 256 dual-polarised log-periodic dipole antennas (SKALA).

A large amount of work has gone into designing, building, modelling and evaluation of these systems [1,2,3]. A key component of this work has been the development of detailed electromagnetic models of all 256 antennas – SKALA4.1 for AAVS2. The irregular array layout precludes the use of infinite array approximations. The arrays have been simulated using the Method of Moments, accelerated by the Fast Multilevel Multipole Method running on multi-core workstations. Two commercial computational electromagnetic packages have been used in this work, viz. Altair's FEKO and IDS's Galileo-EMT. The simulations require computing embedded element patterns for each of the 256 antennas, and typically involve several million degrees of freedom. This paper will provide an overview of the modelling work undertaken, as well as a comparison between the present AAVS2 array and a proposed layout for the next station, AAVS3. The figure compares the EEP of a central element in the AAVS2 and AAVS3 arrays, at 55, 78 110, 140, 160 and 210 MHz.

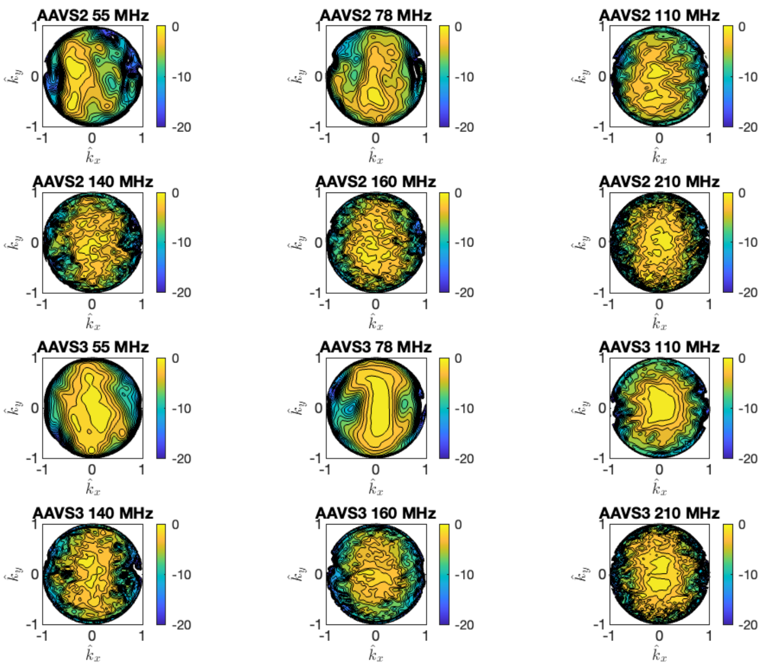

Figure 2: EEPs for AAVS2 (antenna 120) and AAV3S (antenna 1). Both antennas are centrally located in the respective stations (which are numbered differently). Results are for the X-polarisation (EW dipole arms) and show the total power pattern in dB (orthographic projection).

[1] Benthem, P., "The Aperture Array Verification System 1: System overview and early commissioning results", *A&A*, vol. 655, 2021. doi:10.1051/0004-6361/202040086.

[2] A. J. J. van Es et al., "A prototype model for evaluating SKA-LOW station calibration," Proc. SPIE 11445, Ground-based and Airborne Telescopes VIII, 1144589 (13 December 2020); doi: 10.1117/12.2562391

[3] P. Bolli, D. B. Davidson et al., "Computational electromagnetics for the SKA-Low prototype station AAVS2," J. Astron. Telesc. Instrum. Syst. 8(1) 011017 (18 January 2022) https://doi.org/10.1117/1.JATIS.8.1.011017

Calibration and direct validation of station embedded element patterns for SKA-Low prototype stations AAVS2 and EDA2

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Beginning with the first SKA-Low prototype station, AAVS1 [1], substantial effort has gone into understanding and quantifying the calibration accuracy and calibration stability of the stations. Going hand-in-hand with this effort have been steady improvements in simulation of the station radiation patterns. The current generation of prototypes are well enough understood to have had their sensitivity measured directly from astronomical observations [2,3].

I will give an overview of the work to date on quantifying the SKA-Low station prototype performance, and the ongoing work to verify the detailed simulations of antenna embedded element patterns (EEPs) from astronomical observations. Using tracked observations of the sun as a direct probe of the EEPs, I show that the simulated EEPs are in very good agreement with observations, and by using the EEPs as part of station calibration, systematic phase errors are typically reduced to ~5 degrees.

Finally, using data and simulations across the main frequency bands for SKA-Low, I quantify the statistical phase error over the entire station due to EEP beam variations, which informs the most effective way to reliable station calibration for SKA-Low.

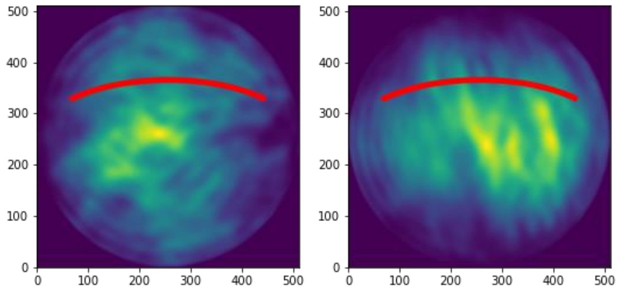

Figure 3: Example EEP power patterns formed over the sky between two antennas in AAVS2 at 110 MHz (orthographic projection). Left: the east-west oriented antennas, right the north-south. The red line shows the track taken by the sun through the AAVS2 beam.

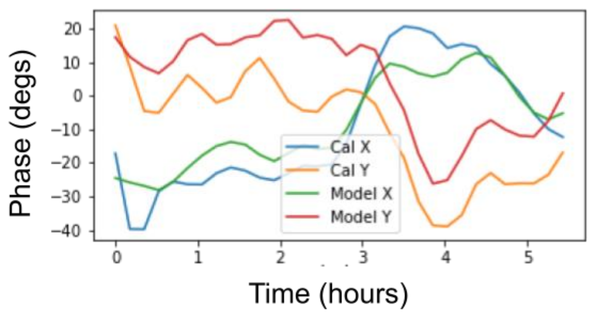

Figure 4: Plot of measured versus simulated calibration phase for an antenna in AAVS2 at 110 MHz.

[1] Benthem, P., "The Aperture Array Verification System 1: System overview and early commissioning results", *A&A*, vol. 655, 2021. doi:10.1051/0004-6361/202040086.
[2] Macario, G., "Characterization of the SKA1-Low prototype station Aperture Array Verification System 2", JATIS, vol. 8, 2022. doi:10.1117/1.JATIS.8.1.011014.
[3] Wayth, R., "Engineering Development Array 2: design, performance, and lessons from an SKA-Low prototype station", JATIS, vol. 8, 2022. doi:10.1117/1.JATIS.8.1.011010.

Validation of the obtained mutual coupling impedance matrix from CST model of two element array

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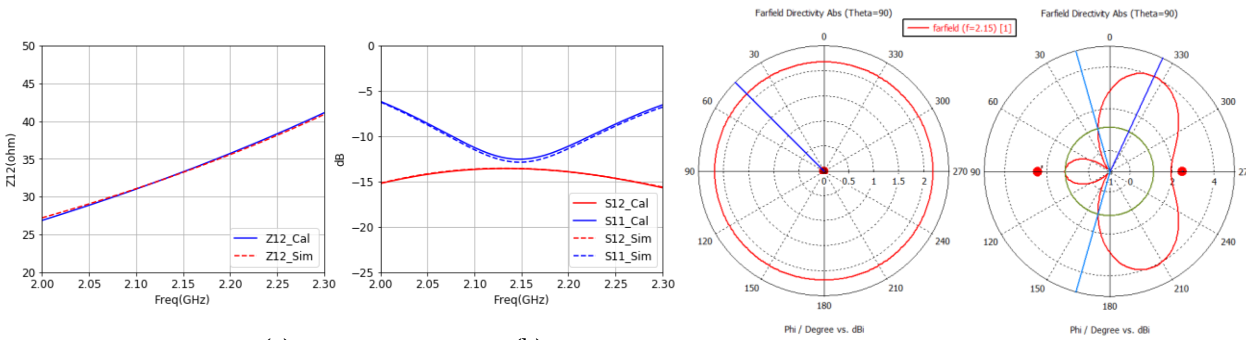
One of the important considerations in designing highly sensitive receiving phased array antennas in the field of radio astronomy is mutual coupling effects between the array elements. To include the effects of mutual coupling on the antenna parameters including reflection coefficient, input impedance and radiation characteristics, the embedded pattern of the array elements, and the mutual impedance or the S-parameter matrix needs to be obtained for further analyses [1], [2]. Therefore, an accurate model of a phased array is required, typically with a computational electromagnetics (CEM) tool.

In this work a simple two element half wave dipole array is analysed, to ensure our correct use of the CEM tool to obtain the mutual impedance matrix and the embedded element patterns, and by avoiding the complexity of modelling of a large, phased array antenna. The simulation of this chosen model is very fast, and its analytical model is available [3]. Two parallel half-wavelength dipoles at 2.15 GHz, placed at the distance of $\lambda_c/2$, are modelled in CST MICROWAVE STUDIO. As Fig. 1 shows, the simulated mutual impedance, scattering parameters and embedded pattern that has been changed by mutual coupling between two elements. To validate the use of CST for obtaining and exporting these required data, an analytical approximation of the mutual coupling impedance and scattering parameters are also calculated from Eq.1 and shown along with simulated results from CST in Fig. 1 (a) and (b).

$$Z_{12} = \frac{jZ_0}{4\pi(\sin k_0 l)^2}\int_{-l}^{+l}\left(\frac{e^{-jk_0 m}}{m} + \frac{e^{-jk_0 n}}{n} - (2\cos k_0)l * \frac{e^{-jk_0 q}}{q}\right)(\sin k_0(l - |l_m|)dl_m \qquad (1)$$

$$m = \sqrt{[(l-l_m)^2 + s^2]}, \qquad n = \sqrt{[(l+l_m)^2 + s^2]}, \qquad q = \sqrt{[(l_m)^2 + s^2]}$$



(a) (b) (c) (d)

Figure 1. Results of two half-wavelength dipoles at a distance of $\lambda_c/2$: (a) simulated and calculated mutual impedance, (b) simulated and calculated reflection and transmission coefficients, (c) pattern of isolated dipole antenna, and (d) simulated embedded patterns of one dipole in the array for all *phi* at *theta*:90 deg

This validation gives us the confidence to proceed with the CEM model of larger phased arrays, including the incorporation of LNAs and noise analysis using scattering parameters, or the model presented in [4].

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Design Challenges of Highly Integrated RF Electronics for Astronomical Receivers

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The digitizing and processing capabilities of modern radio astronomical observatories has increased significantly over the last couple of years and is still on the rising. This also leads to an increase analogue bandwidth, either by an expanded RF bandwidth and/or multiple observing pixels used within Focal Plane arrays or PAFs. Classical RF component integration, such as integration of single RF components on a bread board, are not feasible anymore due to space, weight and budget constraints.

This presentation will give a short overview of the development challenges of highly integrated RF analogue and mixed-signal components within the MPIfR EDD [1] project using the example of a downconverter.

The development has started at the MPIfR with the design of the MeerKAT S-band receivers to be compact, modular, with a high integration density, and digitization of the data directly in the receiver box. This approach has been consistently pursued at other projects as well. In addition to the MeerKAT system several extensions to the modular concept have been developed so far. One of the most prominent examples here is a downconverter unit, allowing to observe higher RF frequency bands. This units use the same form factor, signal, power, and control as the rest of the technology.

After discussing different implementation concepts, it has been decided to develop a single printed circuit board. The generation of a high-frequency LO signal from a telescope reference signal, the distribution to two polarisations, and subsequent mixing with the sky signal are realised on it. This very compact design and the spatial proximity of pure high frequency and down-converted signals together with digital controls on one board naturally also entails difficulties such as cross-talk or spectral purity that must be countered in a suitable manner. However, it became clear that a careful selection of components results in a module which is used in various receivers and telescopes.

[1] C. Kasemann, et al., "The universal EDD frontend system", *Phased Array Feed & Advanced Receivers Workshop, 2022*

pHEMT Characterisation and Small Signal Equivalent Circuit Extraction from 4 K to 290 K

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Pseudomorphic High Electron Mobility Transistors (pHEMT) are widely used as the active component for LNAs that are designed for to provide low noise and high gain performance for use in radio astronomy receivers. Small Signal Equivalent Circuit (SSEC) of these transistors are required for designing these LNAs, however these are almost exclusively based on the results of room temperature transistor measurements. In order to improve the performance of our LNAs at cryogenic temperatures it is necessary to generate models of the transistors based on measurements at cryogenic temperatures. In addition to providing transistor models, these cryogenic measurements also provide key information for understanding the physics of these devices and offer insights into how we can further improve the cryogenic noise performance of these pHEMT transistors [1].

In this work, we will introduce the cryogenic on-chip measurement system at the University of Manchester, which is capable of characterizing devices and producing the small signal equivalent circuit models at room temperature and at cryogenic temperatures down to 4K, and at frequencies up to 67 GHz. We have used this system to characterize the Win Semiconductors 100nm gate length Gallium Arsenide pHEMT technology [2] and the Diramics 100nm gate length Indium Phosphide technology [3]. The Win semiconductors technology is a large scale, high degree of process maturity and commercially available technology which exhibits high microwave performance with F_t greater than 135 GHz and F_{max} over 185 GHz. This makes it ideal for applications such as modern radio astronomy, where large numbers of amplifier components are needed and required provide very uniform performance. This is of particular importance for phased array feed and focal plane array applications. The Diramics semiconductor technology is a proven InP pHEMT technology which shows excellent low noise and high gain in a cryogenic environment and at room temperature. The basic characteristic of a 4x20 um device at a 15 K environment exhibits 5.2 K noise temperature and 1500 mS/mm transconductance (@30 GHz), F_t great than 235 GHz and F_{max} over 800 GHz. This makes it suitable for MMIC based LNAs designed for use in receivers such as phased array feeds, focal plane arrays or other high density and highly integrated applications.

In this talk we will introduce the cryogenic probe station based measurement system that we have developed and also show our latest results developing these SSEC and their impact on future LNAs that would be designed for use in future highly integrated receiver systems. We will also talk about how these kinds of measurements can be used to understand the underlying technology of the transistors and MMICs.

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LNAs for Highly Integrated Receivers

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The Advanced Radio Instrumentation Group (ARIG) at the University of Manchester have a track record of delivering high performance LNAs at millimeter-wave frequencies, including for ALMA band 2 and most recently for a large multi pixel imaging receiver.

For more traditional radio instruments that utilize a single receiver, size of the components is often not a key concern aside from minimizing the overall mass and size of the instrument. However, in more state-of-the- art instrument architectures (such as focal plane arrays and phased array feeds, or any others that utilize multiple receivers within the same instrument) the size of components can become extremely critical due to the performance dependence on the placement of the receiving elements. In these types of architectures, the number of LNAs that are needed for the instrument is also dramatically increased, increasing the time and complexity of the project.

A good example of this the sixteen-pixel instrument operating in the 70-116GHz frequency band, that we have been involved with recently. The close placement of the feedhorns necessitated that the receiver components for each pixel would fit within the cross-sectional area of the feedhorn, so allowing all of the pixels to be assembled together with minimal gaps. In addition, each pixel was required to measure the polarization of the in coming signals, meaning a separate chain of receiver components for each of the polarizations had to fit into this cross-sectional area of the feed horn.

The consequences of this were two-fold. Firstly, due to the large number of LNAs needed for this project (and other projects) a modified cryostat to test multiple LNAs and custom measurement software (CryoMe) have been developed in order to automate the measurement and bias optimization process. Secondly, the LNA packaging is designed for one MMIC per block and we have reached the limits of how far these can be miniaturized while still using the standard waveguide flange as an interface.

In this presentation we will discuss the results of these LNAs, the systems that we have developed to measure them and how the systems can be used to measure the large numbers of LNAs that will be required for future instruments. We will also show the design of these LNAs and discuss how the design choices have affected the measurement process, and how this could inform the packaging design for future receiver instruments. This will include the consequences of moving to more integrated style of packaging, including the need for prescreening the amplifier MMICs that will be used, having ways to swap MMICs, and the need for a MMIC process that provides very uniform results between the fabricated MMICs.

Automation of Low Noise Amplifier Measurements with the *CryoMe* Software Package

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It is well known that the sensitivity of a radio receiver is inversely proportional to its overall noise temperature. From Friis' formula for noise in a multistage system, receiver sensitivity can therefore be optimised by using a high gain front-end Low Noise Amplifier (LNA) [1]. It follows that radio telescopes up to millimetre, and increasingly sub-millimetre, wavelengths typically utilise cryogenically cooled High Electron Mobility Transistor (HEMT) based LNAs as initial receiver gain blocks.

As part of radio instrumentation production, LNAs will be fabricated, assembled, and characterised to ensure the instrument performance specifications have been met. The characterisation measurements will provide, among other results, the gain and noise performance of the LNA over its operational bandwidth. Multiple measurements of each LNA will be taken under different bias conditions (i.e. different drain voltages and currents), allowing for optimum performance biases to be established. Using this information, it can be ensured that only the best performing amplifiers are selected for integration into the receiver. Modern radio astronomy projects, such as large-scale telescope arrays, focal plane arrays, and phased array feeds, require dramatically more LNAs than ever before. Due to this increase in LNA demand, testing can become a very time-consuming part of a project.

In order to speed up the LNA testing process we have developed a new open-source software package named *CryoMe* which allows us to automate the process of measuring LNAs. The software can perform fully automated cryogenic Y-Factor measurements. The instrumentation is controlled to bias an LNA, maintain requested ambient/load temperatures, and perform power measurements over the required frequency bandwidth. The software performs analysis of the output data providing, among other results, the calibrated noise and gain measurements of an LNA under test. The system is also designed to perform automated sweeps of bias conditions, using a safe adaptive drain current seeking algorithm, and store results in a convenient file format. *CryoMe* enables a comprehensive optimisation process to be performed more quickly and reliably than it could be done manually.

We are currently working on several projects that require many LNAs in the 67-116 GHz frequency range. In order to further increase the throughput of LNA measurements we have also built a cryostat that can contain three independent chains of LNAs. The measurement system has a computer-controlled waveguide switch at the output allowing for automation of chain selection by the *CryoMe* software. A single cooling cycle therefore allows three LNAs to be fully characterised overnight.

The analysis of the measurement data is automated with outputs including, heat maps of noise and gain performance plotted against the set bias conditions, allowing optimum bias points to be quickly and easily identified. As *CryoMe* works on chains of LNAs as well as single LNAs, with analysis automated for either case, it can be used to tune amplifiers independently when they are in situ in a receiver. Furthermore, analysis can be requested of sub-bandwidths, and reprocessed in the future with different calibrations easily. *CryoMe* automation software has provided significant time saving, and data volume/analysis improvements.

In this presentation I will provide an overview of cryostat setup; discuss *CryoMe* capabilities and features; outline the benefits of *CryoMe* in time saving, throughput, and utility; and show sample outputs from a set of tested LNAs. I will also explain how this software package and automated testing approach is applicable for future radio instrumentation that requires large number of LNAs.

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[5]

Building the Cryogenic Front-end for the Advanced L-band Phased Array Camera for Astronomy

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Dense focal-plane phased arrays can capture the entire field-of-view (FoV) of a single-dish telescope instantaneously and provide significant improvement over feedhorn arrays that sparsely sample the FoV. The Advanced L-band Phased Array Camera for Astronomy (ALPACA) will be a fully cryogenic phased array feed instrument providing an unmatched combination of sensitivity (goal T_{sys} = 27K), wide bandwidth (BW = 305 MHz tunable within a 1.3-1.72 GHz band), and continuous coverage over a large field of view by digitally forming 40 dual-pol beams simultaneously on the sky. The instrument was originally targeted for installation at the Arecibo Radio Telescope but the tragic loss of the Gregorian platform on Dec 1, 2020 and decommissioning of Arecibo has led to a proposal to deploy ALPACA at the prime focus of the Green Bank Telescope. On the GBT, ALPACA would provide an instantaneous FoV of 1250 arc-min^2 making it a transformational instrument for discovery across several science use cases.

Here, we will report on the design, development, and progress with assembly of the ALPACA front-end. A large, welded HDPE 'top hat', backed by a RF transparent foam provides a durable vacuum tight structure while allowing the antenna array to have an unobstructed 2-pi steradian view. The array features 69 dual-pol, antenna elements and low-noise amplifiers that are cryogenically cooled by three CTI-1020 cold heads. We employ multi-channel flexible RF striplines to carry signals and bias through the cryostat and feed the signals to a custom designed RF-over-fiber link for transport to the digital back end (described in detail by Burnett et al. at this conference). This novel, mixed material, RF-transparent, cryogenic vacuum vessel is designed to satisfy strict structural, thermal, and electro-magnetic requirements (see Figure 1) needed for operation at the GBT prime focus.

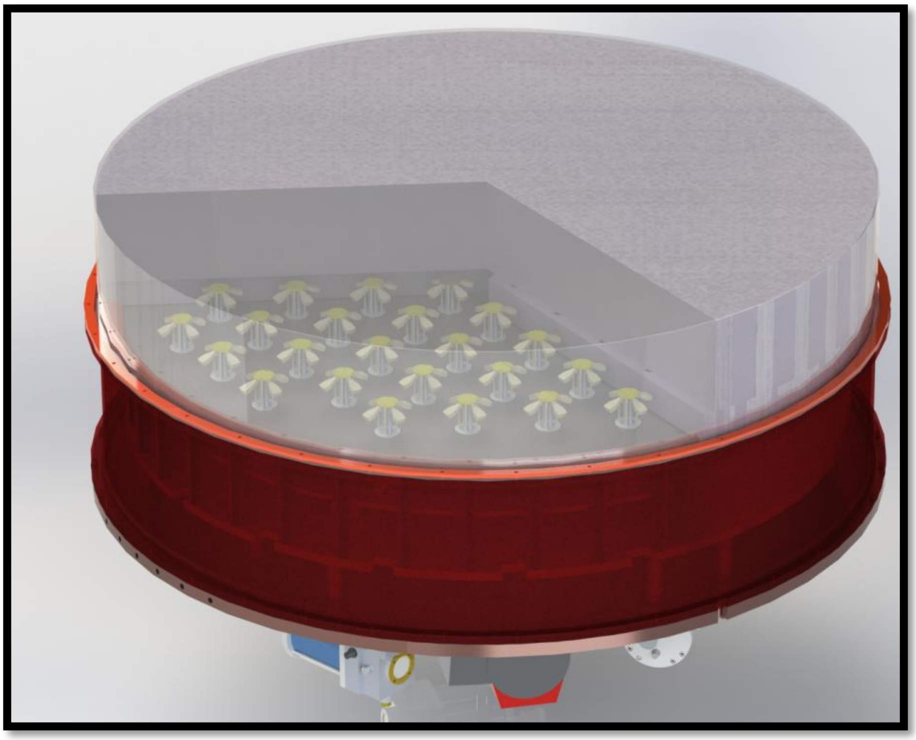

Figure 5. A CAD rendering illustrating the design of the ALPACA cryogenic front-end. Internal temperature stages are designed to follow a 3X cyclic symmetry, each connected to a cold head.

Introducing "CNIC" - Enabling SKA Low Realtime In-System Testing

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At the core of the Square Kilometre Array (SKA) Low Correlator and Beamformer (CBF) is a signal processing system based on Xilinx Alveo cards and P4 programmable network switches (see Figure 1.) A majority of the communication links are based on multiple 100GbE links entering (e.g., SKA Low station receiver data has 86 links) and leaving (e.g., Visibility outputs require 72 links) which sets the magnitude of the real time testing capabilities required. As astronomical instrumentation grows in size it becomes more challenging to create and devise testing systems with matching capabilities [1]. Test systems can be difficult in that they require extra space, need to operate in real-time, are an additional construction cost, and require integration with the real system under test.

Each of the Alveo FPGA cards in the CBF system can be individually programmed with a particular personality for the required signal processing function (e.g., correlator or beamformer) [2]. Fortunately, most of the functions of a test system are in common with the signal processing functions. In this manner, when the CBF system is being tested a number of Alveo can be reprogrammed with what CBF calls the "CNIC", or the 100% Network Interface Card (NIC). Typically, NICs operate in a software environment and can struggle to achieve real time data flow. However, the Alveo CNIC can sustain 100Gbps data rates, although the Alveo memory is finite. The Alveo timing is accurately controlled (<50ns) with PTP time stamps.

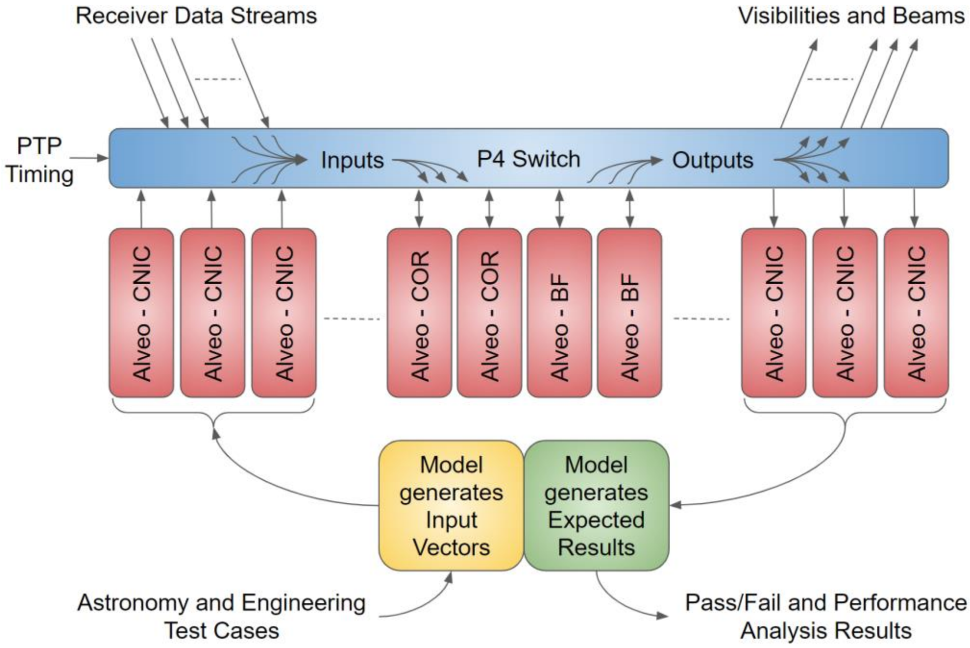

Figure 1. Overall view of the SKA Low Correlator and Beamformer in-system testing.

Using the CNIC results in a system that can be scaled with testing requirements, as well as being an integral part of the system requiring no physical modifications. The only additional costs are for Alveo firmware and software development (which are in general, common with signal processing development). Key to testing is a golden signal processing model that can generate test data based on astronomy or engineering use cases (or even using pre-recorded data from the receivers.) The second key function of the model is to calculate the expected outcome of the system under test and compare that with the measured outcomes of the CBF system which leads to a pass/fail testing outcome. Further details of CNIC will be discussed at the Workshop.

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Next generation digitiser for MeerKAT

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Since the deployment of the first MeerKAT digitiser in 2014, a number of groundbreaking observations have been made using the MeerKAT telescope. More than 150 papers have been published since first light in 2016 **Error! Reference source not found.**. In 2019, funding was received to increase the number of antennas by a pproximately 16 to form a new extended MeerKAT array **Error! Reference source not found.**. Initially the plan was to re-use the L-band digitiser from MeerKAT on the extension project. This was however not possible due to obsolescence of critical components. Engineers were forced to update the design using present day available technology. Additionally, the upgrade provided the opportunity to update the design based on lessons learned from MeerKAT. One of the major design changes was to integrate the FPGA and ADCs on one module which receives conditioned RF signal and outputs packetized digitized data on 40 or 100GbE.

The key specifications of this new digitiser module are summarized in **Error! Reference source not found.**:

Table 2. Key digitiser module specification.

Parameter	Specification
Frequency range	10 – 6400 MHz
Gain stability [1]	$\leq 0.7\%$
Phase stability **Error! Bookmark not defined.**	$\leq 1.6\ ^{\circ}$ rms
SFDR **Error! Bookmark not defined.**	≥ 60 dB
ENOB **Error! Bookmark not defined.**	≥ 7.6
IMD_3 **Error! Bookmark not defined.**	≥ 60 dBc

The physical view of the digitiser module is shown in **Error! Reference source not found.**.

Figure 5. MeerKAT extension digitizer module.

This paper presents some of the key design aspects considered for this updated design. The latest available measurement data will also be presented.

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[1] Measured at L-band frequency

[5] MPIfR, 16 September 202, The MeerKAT Extension Project, Available at: https://www.mpifr-bonn.mpg.de/pressreleases/2020/9 (accessed: 30 September 2022)

Applications of an RFSOC based Digitiser to Digital Receiver Systems

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CSIRO Space and Astronomy have recently developed a custom single board digitizer platform for use in radio astronomy and other general purpose digital receivers. This system is based around programmable RF System on Chip technology (RFSOC) and offers up to 8 simultaneous digitized channels with a sampling rate up to 5 GS/s per channel and RF usable frequency range up to 6 GHz. A large quantity of programmable signal processing is also available for further data conditioning, and output data is distributed optically on 3 x 100 Gb/s ethernet ports. All timing and control signals are supplied optically, and the system was co-designed with a matching RFI shielding and heat management enclosure, resulting in a very compact, low emission system suited for at-focus applications.

This talk will focus on the design and features of this platform and describe its application to several digital receiver systems currently under development targeted to various applications, including a cryogenic PAF receiver.

The Bifrost Stream Processing Framework

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Bifrost is a stream processing framework, created to ease the development of high-throughput processing CPU/GPU pipelines. It is specifically designed for digital signal processing (DSP) applications within radio astronomy. A portable C API is provided, along with C++ and Python wrappers. The heart of bifrost is a flexible *ring* buffer implementation that allows different signal processing '*blocks*' to be connected to form a *pipeline*. Each block may be assigned to a CPU core, and the ring buffers are used to transport data to and from blocks. Processing blocks may be run on either the CPU or GPU, and the ring buffer will take care of memory copies between the CPU and GPU spaces. Bifrost comes with a library of reconfigurable blocks designed for radio astronomy application. In this talk, I will give an overview of Bifrost and will detail how it is being used for correlation, beamforming, high-speed imaging, and Fast Radio Burst searches. An example of porting the Tensor-Core Correlator [2] code to a Bifrost plugin will also be given. Bifrost is available online at https://github.com/ledatelescope/bifrost.

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The universal EDD frontend system

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The universal EDD (Effelsberg Direct Digitization) frontend system stands for an innovative concept to control and access all data created from a radio-astronomical receiver system. It defines the link between all analog parts of the receiver frontend and the digital data analysis system (EDD backend). The main innovation is to establish an only digital link directly at the frontend without additional analog intermediate wiring. This means all communication to and from the frontend, including the RF-data-streams, are handled in digital format right at the cryostat.

One of the main design difficulties was to mitigate RFI-emission from the EDD electronics as far as possible to avoid self-RFI contamination. This was especially important to be able to use the system within MeerKAT, where it had to comply with the very stringent SKA and MeerKAT RFI requirements. Based on a modular concept, using building blocks for all individual control and monitoring tasks, the concept can simply be adapted to nearly all existing and upcoming receiver systems including the first generation Cryo-PAF [1]. The concept is already in use for the MeerKAT S-band systems, and is currently being implemented into most of the Effelsberg receivers available.

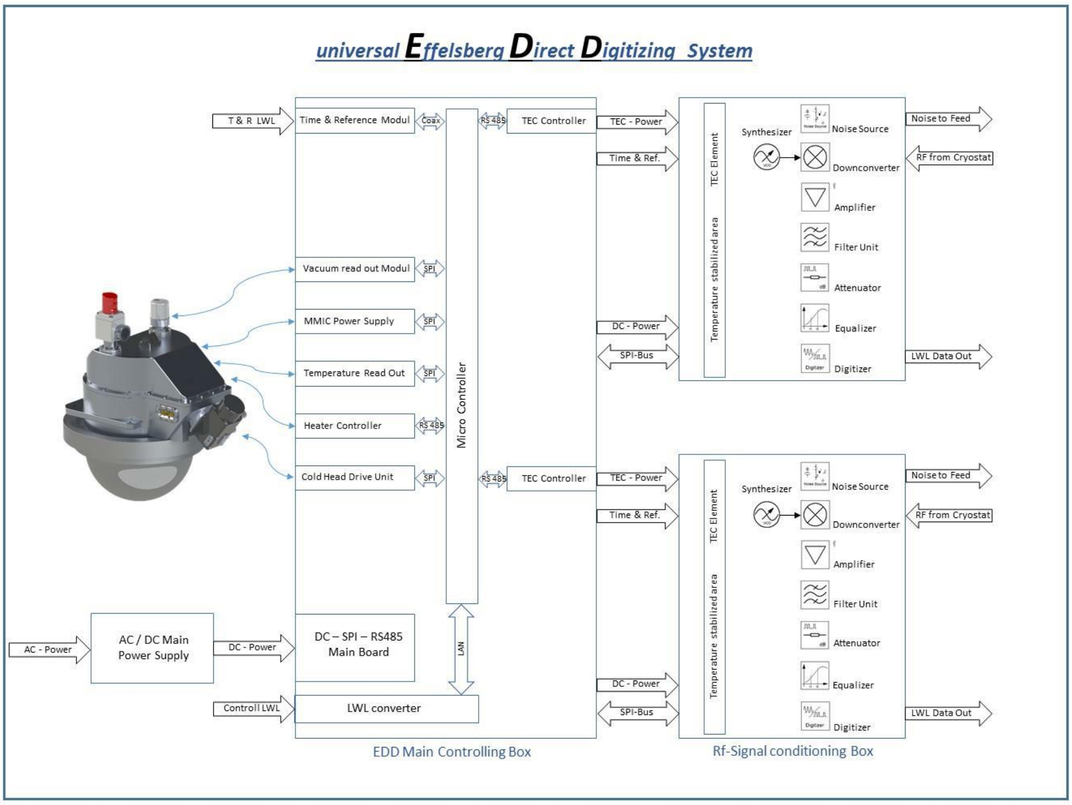

Figure 1. Schematics of the EDD frontend setup, showing the main receiver components and their data and control links. The full system is located directly at the cryostat.

[1] N. Esser et al., “System Design for the Effelsberg CryoPAF Backend”, *Phased Array Feed & Advanced Receivers Workshop, 2022*

A combination of PAF and spherical reflector to obtain large FoV

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We present a proposal for the application of a large Phased Array Feed (PAF) on a large aperture spherical reflector [1][3]. The optics is shown in

Figure **6**. The large spherical reflector will be fixed on the ground. The PAF will be hung in the air. A focus cabin suspension system similar to that used at the FAST telescope will be used [2]. Simulation indicates that by using a 10m x 10m PAF on the neutral spherical surface of the FAST telescope, an efficiency of 80% of a 300m aperture and a much wider FoV could be obtained. Compared with the FAST telescope, the spherical main reflector fixed on the ground will be much less expensive. But to build the large PAF will a cost-effective way is still very challenging.

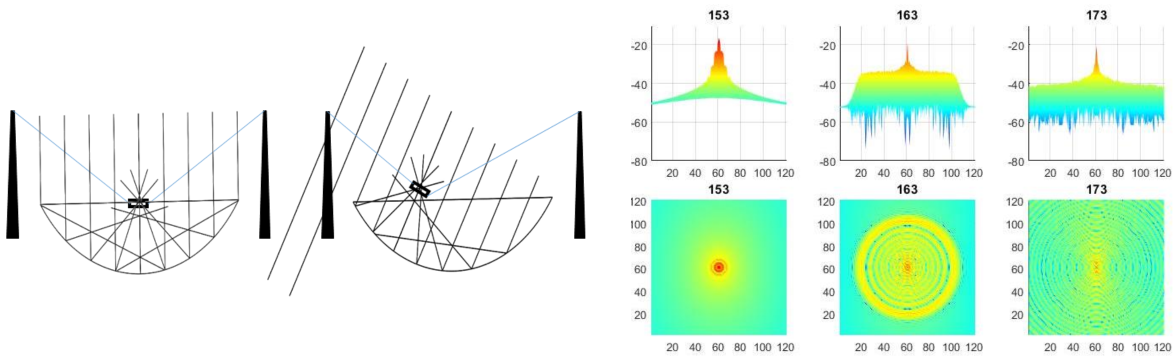

Figure 6 The optics of the combination of a PAF and a spherical reflector(left), and the field distribution of the reflected wave at various distance below the center of the spherical surface(right).

Given the inherent property of the spherical shape of the main reflector, the required sizes of the PAF at various frequencies are more or less the same. This imply that the number of the elements of the PAF will be proportional to the relative frequency squared. We will present the simulation results at several frequencies. In the meantime, we will also give a discussion on the relative virtues of this proposal compared with the FAST telescope.

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Phased-Array adaptive beam-forming using Deep-Learning Techniques

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This work, inspired by [1], proposes a method to speed up the beam-forming of an array of antennas using Deep Learning (DL). Pattern-synthesis algorithms based on traditionally used optimization techniques are very flexible, but they show speed and local-minima-trap problems to converge to the optimum and to find the needed weights, especially for large arrays. We aim to compare these techniques with different architectures based on a Convolutional Neural Network trained using images of the desired beam pattern and the corresponding ground truth arrays of weights to assign to the antennas. For the model training a very varied dataset of images is used, in part synthesized using a simulator and in part obtained from [2], with interference coming from different directions, to allow the network to generalize the procedure. This study also proposes a comparison between different DL models to identify which network performs better in terms of computation time, directivity loss and interference suppression to mitigate, with the updated pattern, the effects of the interfering disturbances in quasi real-time.
Figure 1 illustrates the pipeline of the entire process as described before, after the training the model is tested using new patterns and comparing the image obtained using the calculated weights applied to the antennas with the starting image.

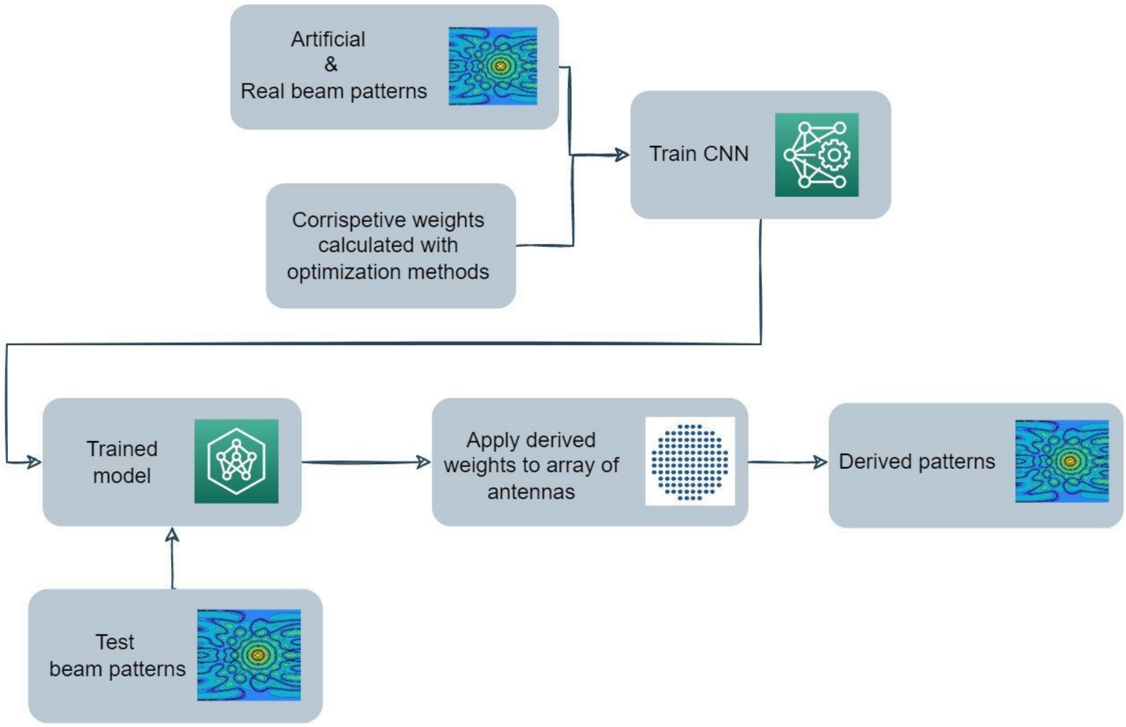

Figure 1. Main scheme

[1] S. Bianco, P. Napoletano, A. Raimondi, M. Feo, G. Petraglia and P. Vinetti, "AESA Adaptive Beamforming Using Deep Learning," 2020 IEEE Radar Conference (RadarConf20), 2020.

[2] A. Navarrini et al, "The Warm Receiver Section and the Digital Backend of the PHAROS2 Phased Array Feed," IEEE Int. Symp. on Phased Array Systems and Technologies (PAST), Waltham, MA, USA, Oct. 15-18, 2019.

Commercialising cryoPAF Technology

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Quasar is a start-up developing phased array satellite ground stations based on CSIRO cryoPAF technology. With the increase in satellites in low earth orbit, multi-beam phased arrays enable a single aperture to simultaneously connect with multiple satellites.

In this talk we will describe how CSIRO and Quasar are working together to develop cryogenic phased arrays for satellite ground stations.

On-sky testing of the C-band cryoPAF: *Pharos2*

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In early 2020, the upgraded C-band cryoPAF *Pharos2*[1] receiver finally achieved "on-sky" testing using the 25m Pickmere Radio Telescope, situated ~10km from Jodrell Bank Observatory (UK) and which is nominally an element of eMERLIN and VLBI. Pharos2 is the result of a long-running international collaboration between Jodrell Bank Observatory (UK), INAF (IT), Chalmers University of Technology (SE), and ASTRON (NL). The upgraded receiver comprises a 220-element Vivaldi array (24 of which were utilised), 2~3K LNAs, and an SKA prototype digital beamformer [2]. It was developed and is presented here to establish a development path for similar devices to be deployed on large-scale future telescopes such as SKA.

Ground testing in 2019 yielded encouraging results using the original *Pharos* analogue beamformer, with TRx~15K established. Following delivery of the signal transport and digital beamforming systems from INAF later in the year, a period of on-sky telescope time was granted by eMERLIN. Following an extensive set of diagnostic and verification tests, including focussing, a programme of beamforming and sensitivity tests began.

Beam weights are calculated first by observing a "strong" sky source such as Cygnus A by recording raw voltages on-source and off-source using a single frequency channel. Correlating the visiblities, we were then able to weight the 24 elements in that frequency channel using the TSysMin and SNRMax methods, weights that were then uploaded to the digital beamformer. Sensitivity tests were then carried out by sweeping the telescope across a selection of "classic" 3C and NGC calibrator sources covering a wide range of flux densities.

In this presentation, I will discuss the procedures and challenges we faced in conducting these observations, as well as noting the lower-than-expected instrumental sensitivity of SEFD~500Jy (exp. ~250Jy). We explored a variety of methods for forming weights, including testing whether weights could be interpolated across a number of frequency channels, substantially reducing the telescope time required to observe the source required to calculate the weights. The beam shapes we observed were considerably more Gaussian than expected, and far more so than other reported PAFs although these were typically operating at L-band. Although we were not able to follow-up these observations largely due to the COVID-19 pandemic, we suspect an unfortunate combination of element spacing, cross-coupling noise, and antenna shape has contributed to forcing the weight-calculating algorithms to unfavourably focus on the central element(s). This would cause insufficient rejection of ground spill, reducing sensitivity.

I will also present a variety of other observations including tests of the weighted receiver's stability, and a number of spectral line observations that required detailed study of the noise quality across tens of minutes in order to establish the observed lines' parameters; from this we draw conclusions regarding the quality of the observations that must be carried out in order to calculate high-quality weights for such science observations

[1] S. Melhuish, M. D'Cruze, K. Grainge, et al., "Pharos2 – Upgraded C-band PAF". PAF Workshop 2019, Bonn, Germany, 2019.
[2] A. Navarrini et al., The Warm Receiver Section and the Digital Backend of the PHAROS2 Phased Array Feed, IEEE Int. Symposium on Phased Array Systems and Technology, Waltham, MA, USA, Oct. 15-18, 2019.

Results from the LOFAR2.0 Dwingeloo Test Station

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Thousands of antennas are spread across the European continent in 52 antenna stations, forming the Low-Frequency Array, LOFAR. For over ten years, their signals are combined to observe astronomical phenomena at the lowest frequencies possible from the Earth's surface. To increase LOFAR sensitivity and instantaneous bandwidth, the antenna stations will be upgraded to LOFAR2.0. LOFAR2.0 will enable simultaneous observing with all antennas.

The designs of the new hardware products (Figure 1) for the LOFAR2.0 station have been validated in the lab. After integrating the hardware with monitoring and control software and processing firmware into the Dwingeloo Test Station (DTS; Figure 2), the verification and validation phase of the station started. This test station is a small LOFAR2 station with 9 Low Band Antennas and 3 High Band Tiles and operates independently of the operational LOFAR telescope. It is set up on the Astron premises in Dwingeloo and that location provides a more realistic operation environment in terms of weather and radio-frequency interference.

The Dwingeloo Test Station is used for a series of tests, amongst others

- Simultaneous observing in the low and high-frequency bands.
- Validation of the RF performance and linearity of the receiver chain.
- Validation of the improved thermal design, in which the LOFAR2.0 hardware can dissipate more heat, while also remaining fully in operation during the warmest days.
- Interface validation, such as time reference distribution, power distribution, mechanical, optical and monitoring and control.
- Gain experience on failure modes and how to act on them.

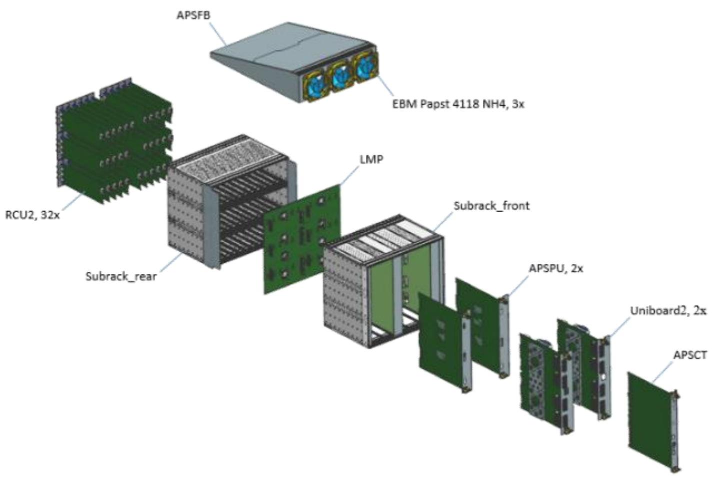

Figure 6. Exploded view of the hardware in the Antenna Processing Subrack (APS)

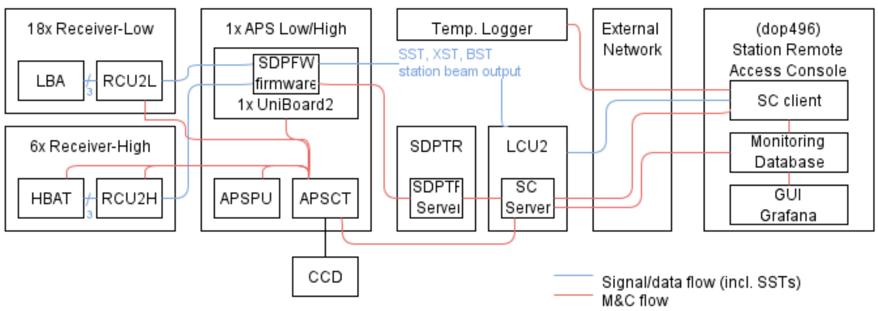

Figure 2. Schematic of the Dwingeloo Test Station.

An HLS-based beamformer using Xilinx Alveo Card

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High-level synthesis (HLS) provides an abstraction layer for the development of FPGA firmware that allows algorithmic descriptions to be written in high-level languages such as C/C++. It can significantly improve development efficiency and enable developers to quickly modify designs with only a limited number of revised parameters. Thus, it's a perfect tool for developing a modern FPGA-based beamformer.

In our work, as part of the MPIfR CryoPAF project, we are building a 128-beam prototype beamformer on Xilinx Aveo U55C cards using HLS. The beamformer is composed of several Xilinx Vitis kernels, as shown in Fig. 1: 1) beamforming kernel, which performs the complex multiplication between the raw data from all elements and the input weights; 2) SPEAD kernel, which packs and unpacks the SPEAD format packets; 3) reorder kernel, which reorders the packets from all elements to the canonical order; 4) corner turner kernel, which transforms the data to element grouped shape; 5) udp kernel, which packs and unpacks data in udp format.

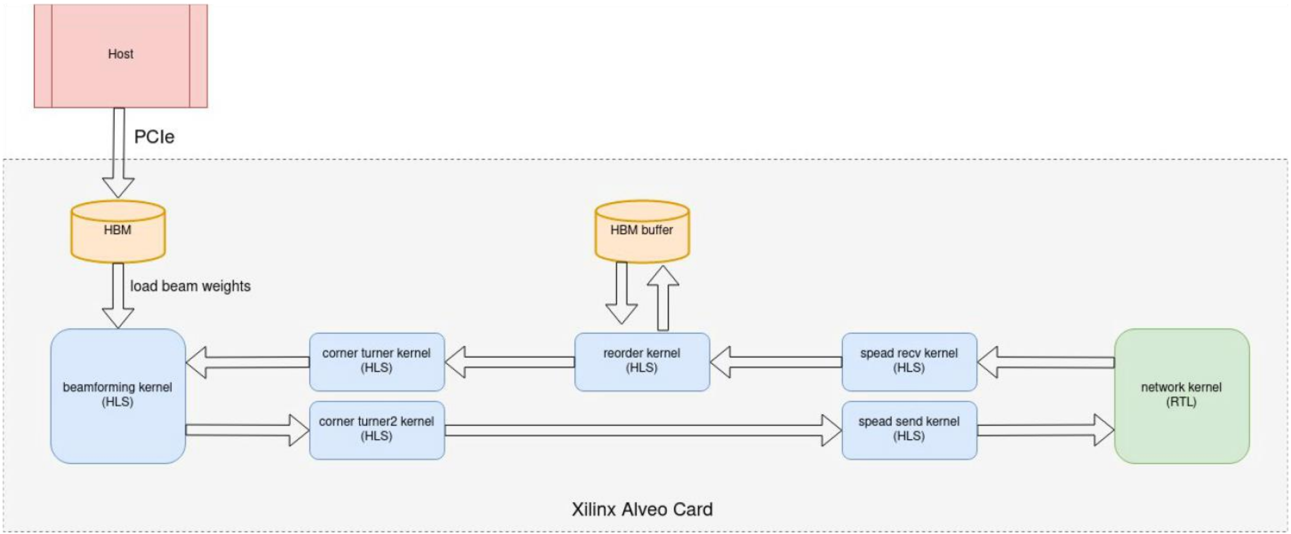

Figure 1. Top design diagram of the FPGA beamformer.

In our design, the purpose is to perform beamforming on the 8bit complex data stream of 16 frequency channels, 2 polarization and 128 elements on each Alveo U55C card. In total, we need about 32 to 64 cards to handle the whole data rate of 4Tb/s. The number of cards used will be determined on the resource usage and timing closure constraint. The power consumption would be less than 100 W per card.

New and Future Technology development at the Arecibo Observatory

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I present here some exciting new instrumentation projects currently underway at the Arecibo Observatory (AO). These projects fall into two categories. (1) Upgrading existing research facilities and developing techniques to improve the performance of these and other radio astronomy telescopes. (2) Novel technology development for a next-generation facility instrument at Arecibo.

In the first category, significant advancement has been made on three fronts. (1) AO has a 12m telescope located within the observatory campus. This telescope was originally commissioned to aid the 305m telescope for phase referencing for VLBI observations. The telescope was equipped with room temperature receivers operating at X (8.1-9.2 GHz) and S (2.21-2.34 GHz) bands. We integrated these receivers with the legacy 305m telescope backends and observations were restarted at AO in early 2022. Further, a wideband (2.5-14 GHz), cryogenic receiver is being developed and will be commissioned by the end of 2022. (2) Efforts to develop a real-time FRB detection system for the 12m telescope are underway. (3) AO also started a new collaboration with the Center for Advanced Research in Science and Engineering (CARSE) [1], University of Puerto Rico, Mayaguez. This collaboration aims to develop cutting-edge RFI mitigation techniques and demonstrate the use of these techniques for sensitive radio astronomy observations. For this purpose, we plan to build an experimental setup, which incorporates the 12m telescope, for both developments of RFI mitigation techniques and their application to real radio astronomy observations.

While the above development projects have relatively short-term goals, we have also started technology development for a next-generation observatory instrument at Arecibo. The ultimate goal is to develop a competitive facility instrument to satisfy the long-term research objectives of the three groups at AO viz. the radio astronomy, planetary science, and space & atmospheric science groups. One of the possibilities we are considering is a compact array of dishes in a tiltable plate, widely referred to as the Next Generation Arecibo Telescope (NGAT) [2]. I will present the NGAT concept and other technologies we are considering for the next-generation facility instrument.

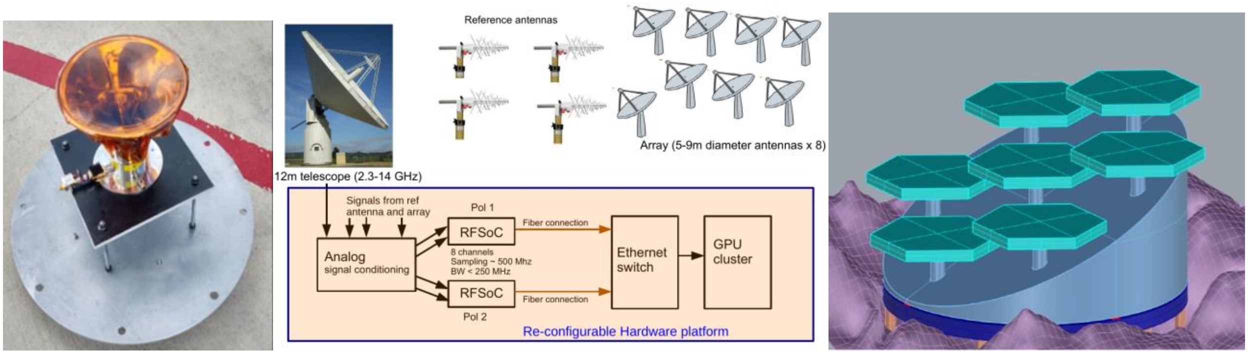

Figure 1. (Left)The Quadruple-Ridged Flared Horn (QRFH) that is being developed for the 12m telescope. The cryogenic receiver will cover the frequency range of 2.5 to 14 GHz. (Middle) Schematic of an experimental setup at Arecibo for the development of RFI mitigation techniques. (Right) Conceptual diagram showing the Next Generation Arecibo Telescope (NGAT).

[1] R. R. Solis (PI), F. Cordova, S. Hunt, M. Jimenez, Center for Advanced Radio Sciences and Engineering (CARSE), 2022, NSF award AST-2132229
[2] D. Anish Roshi, N. Aponte, E. Araya, H. Arce, L. A. Baker, W. Baan, et al., The Future Of The Arecibo Observatory: The Next Generation Arecibo Telescope, 2021, arXiv:2103.01367

RFI-mitigation using a PAF

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Within this work, we present the techniques and first astronomical results from our RFI-mitigation process in use with the modified ASKAP PAF at the Effelsberg 100m telescope. The telescope is located close to one of the densest populated areas in central Europe. Therefore, a huge fraction of the RF-band accessible with the telescope instrumentation suffers from massive human made radio frequency interference (RFI) or is even completely unusable for astronomy. PAF systems, due to their capability of special filtering within the beam- forming process, in principle allow blanking a large fraction of these signals and hence have the possibility to open up the sky (partly) in the polluted frequency areas. This of course only works as long as the RFI is not saturating the signal chains of the receiver.
As demonstrated in 2017 by Chippendale and Hellbourg [1], this works well for the modified ASKAP PAF we are using at Effelsberg. Within the RFI environment at Effelsberg the classical beamforming process using a maximum SNR algorithm based on an on- and off-source array covariance matrix (ACM) does not produce usable beam-weights for large fractions of the band (see also figure below). Hence, even in absence of the RFI during the following science operations, all frequency bins without valid beam-weights are unusable.

Since 2021, we are using a combination of eigenvalue decomposition of the on- and off-source ACM in combination with attenuating RFI-signals ("intensity filtering") and a special filtering of the maximum SNR solution space from $\boldsymbol{R}_{off}^{-1}\boldsymbol{R}_{on}\boldsymbol{w}_{msnr} = \lambda_{max}\boldsymbol{w}_{msnr}$ to identify and reduce RFI. In addition, we use an interpolation algorithm to fill remaining gaps with useful beam-weights. With these algorithms in place, we can significantly boost the SNR of pulsar observations and therewith increase the system performance in FRB-search, the main science driver for the receiver. This is also seen as a first step towards an online RFI-mitigation process, which will adapt the beam-weights during the observations to the permanent changing RFI conditions. The Cryo-PAF system as planned for Effelsberg [2] will have the hardware and software capabilities build into the backend to host and operate such a system.

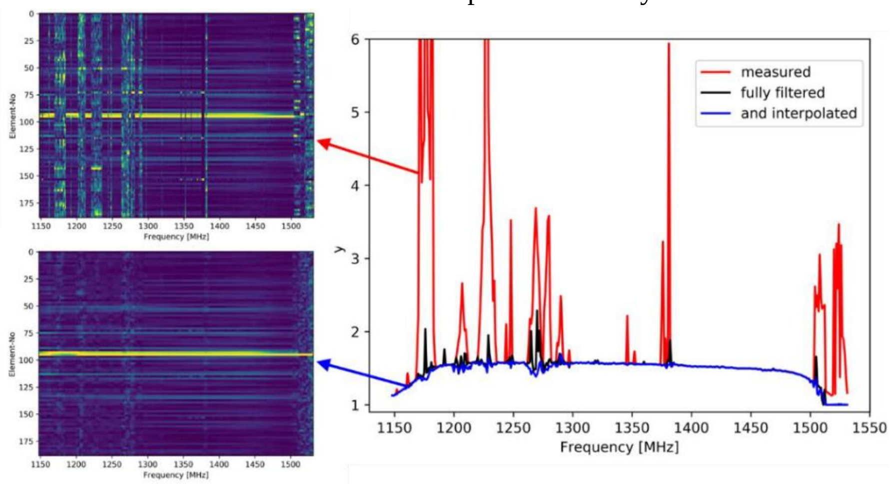

Figure 1: Top left figure shows the raw amplitudes of the beam-weights and with it, the RFI present in the simple max. SNR solutions (30s integration per ACM). The lower left plot shows the same after applying the filtering (special and intensity) followed by an interpolation on the remaining open areas. The righthand side plot shows the corresponding y-factor vs. frequency (the raw y-factor from max. SNR (red), the y-factor of the fully filtered beam-weights (black), and the y-factor on the interpolated beam-weights). Y-factors better than expected by the Rx-performance indicate that the beam-weights are pointing towards an RFI source stronger than the on-source observed during the on-measurement.

[1] A. P. Chippendale, G. Hellbourg, "Interference mitigation with a modified ASKAP Phased Array Feed on the 64m Parkes Radio Telescope", https://doi.org/10.1109/ICEAA.2017.8065413
[2] N. Esser et al., "System Design for the Effelsberg CryoPAF Backend", *Phased Array Feed & Advanced Receivers Workshop, 2022*

Mitigation of Self-Generated Interference with ASKAP PAF

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For astronomers to embrace active radio frequency Interference (RFI) mitigation techniques, we must help them understand the impact of mitigation on the astronomical response and calibration of a telescope. Therefore, we will present mitigation of an unwanted signal to the noise floor (36 dB suppression) whilst observing a flux reference (Virgo A) with an ASKAP antenna. Figure 1 shows a mean increase of 1.5% or 1.2K in sensitivity (Tsys/η) of the 1 MHz channel containing the unwanted signal. This was achieved by using a spatial nulling algorithm (oblique projection) to calculate modified weights for the phased array feed (PAF) beamformer.

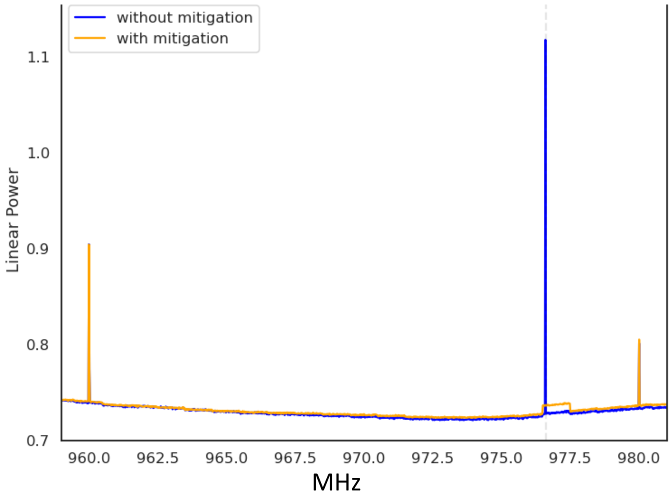

Figure 7. Single antenna total-power spectrum, including unwanted self-generated interference with and without mitigation (orange and blue, respectively), showing mitigation of the unwanted signal to the noise floor (36 dB) while observing a flux reference (Virgo-A). After mitigation, an average increase in system temperature of 1.5% or 1.2K is introduced in the coarse 1 MHz channel containing the signal.

The mitigated signal originates from ASKAP's digital receiver and remains static throughout an astronomical observation. It can be suppressed at the beginning of the observation, at the time of beamformer weight calibration. This static use case is a logical intermediary step before implementing the dynamic case - adjusting beam weights continuously throughout the observation - as is required to mitigate RFI from moving sources, e.g., signals from satellites and aircraft.
Despite promising progress in interference mitigation algorithms in radio astronomy, much work remains to implement these algorithms as part of a holistic strategy in routine, large-scale telescope operations. Mitigating self-generated interference, internal to an astronomy receiver, is a practical initial use case of ASKAP's RFI mitigation capabilities via PAF beamforming that could readily be made operational.

CSIRO's ASKAP radio telescope is the first synthesis imaging array designed explicitly from its outset to use phased array feed (PAF) technology. The beampattern of each digitally formed PAF beam is the linear combination of each PAF element response. Varying beamformer weights allows for the optimisation of beam shape and sidelobes. In addition, by adjusting beamformer weights, a near-zero (or null) response of the resulting beam in the direction of the RFI source can be obtained.

[1] A. P. Chippendale and G. Hellbourg, "Interference mitigation with a modified ASKAP phased array feed on the 64m parkes radio telescope," 2017 International Conference on Electromagnetics in Advanced Applications (ICEAA), 2017, pp. 948-951, doi: 10.1109/ICEAA.2017.8065413.
[2] L. Lourenco and A. P. Chippendale, "Radio frequency interference mitigation for astronomy with phased array feeds" URSI RFI2022, 2022
[3] L. Lourenco and A. P. Chippendale, "*Active Mitigation of self-generated interference with ASKAP's phased array feeds*" AT-AP-RASC 2022, 2022

RFI studies using the Parkes ultra-widebandwidth receiver and implications for future instruments

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The Parkes Ultra-wide-bandwidth receiver operates between 704 and 4032 MHz. It has now been used for astronomical studies for more than three years in a challenging RFI environment. In this paper we will report on the different types of non-astronomical signals in our data, issues relating to wide-band digitisers and impulsive RFI and early attempts to mitigate some of the RFI. We will report on a test suite of data that can be used for more in-depth RFI studies or to develop and test mitigation algorithms.

We will discuss the implications of our results for future wide-band receivers and also for the next generation of receiver systems (such as the cryogenically-cooled PAF) at Parkes.

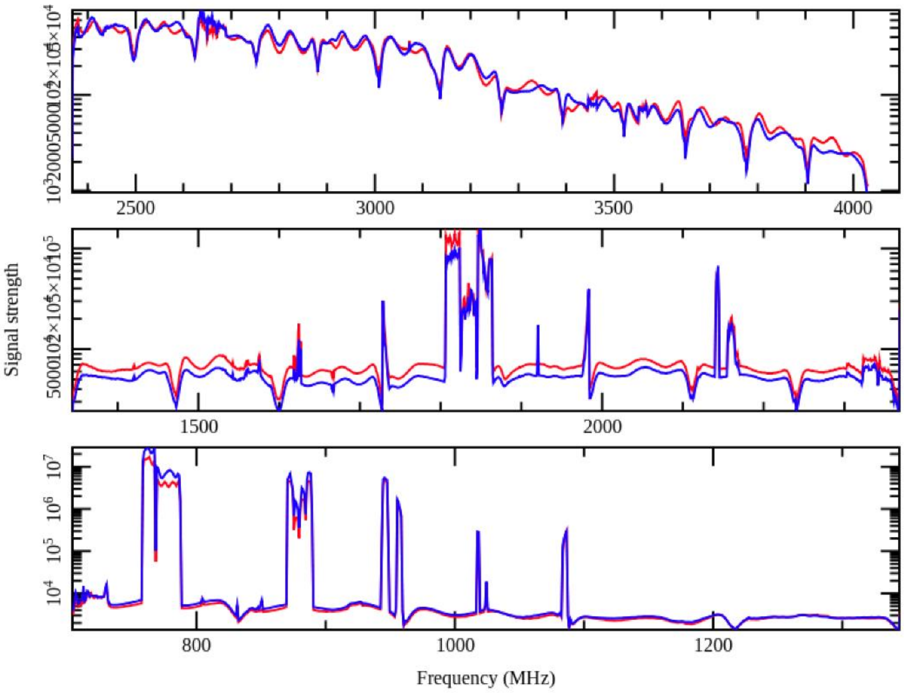

Figure 8. Typical wideband spectrum as recorded through the Parkes wide-bandwidth receiver system. The signals include mobile transmission towers, mobile handsets, aircraft and satellite signals, and WiFi as well as digitizer aliasing effects.

An EMI-shielded Module for the Parkes Cryo-PAF RFSoC Digitizers

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Requirements for high dynamic range, high bandwidth, and high channel counts in PAFs for radio astronomy have driven a trend for cutting-edge digitizers such as the Xilinx RF System-on-Chip (RFSoC) to be integrated into the receiver package. Digitizing close to the focus allows fiber optics to replace long coaxial cables, with dynamic range improvements over previous RF over Fiber (RFoF) designs. The catch is increased power consumption and the potential for broadband self-generated electromagnetic interference (EMI). Careful filtering, shielding and printed circuit design are necessary to maintain receiver sensitivity while taking advantage of the capabilities of the RFSoC.

Building on development from the ASKAP PAFs and Parkes Ultra-Wideband receiver, a tightly integrated, shielded "Warm Electronics Module" has been developed for the Parkes Cryogenic L-Band PAF (Cryo-PAF). This module contains the 'Jimble', an RFSoC digitizer board capable of digitizing 8 × 12-bit 4 GS/s channels simultaneously, channelizing them with a polyphase filterbank, and transmitting the data on 3 × 100 Gb/s ethernet data streams. The module also contains RF amplifiers, bandpass filters, and power for the cryogenic LNAs. The Jimble is housed in a shielded compartment, isolated from the analogue circuitry, which is then shielded again. Reference signals, data streams, and ethernet communications for monitoring and control are all transported into the module on a single 12-fiber ribbon.

The module is powered from an external isolated 48 V DC supply. Internal power rails are generated by a custom shielded switched-mode power supply. All external and internal power rails are filtered with high-performance 10 GHz feedthrough filters. An external fan provides cooling for over 130 W of internal power dissipation. The machined aluminum enclosure minimizes weight to fit within a limited overall mass budget while maintaining thermal performance and shielding effectiveness; the module is 154 × 408 × 82 mm and weighs only 4.3 kg when fully populated.

Testing of the conducted and radiated EMI has shown that the enclosure effectively shields the Jimble digitizer and other electronics. With only the internal shielding in place (Figure 1 inset), radiated EMI fell below the noise floor of the EMI test system, which is more than 20 dB below pre-compliance MIL-461F RE102 at 100 kHz resolution bandwidth.

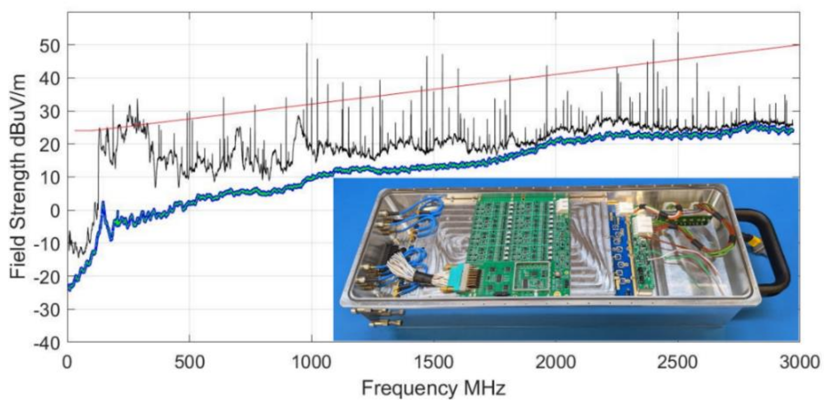

Figure 9. Radiated EMI measurement (100 kHz resolution bandwidth), showing the MIL-461F RE102 limit (red), without shielding (black), with shielding (green), and a baseline 'empty room' measurement (blue).
Inset: Cryo-PAF Warm Electronics Module test unit.

TNRT's Receiver Development and plan for PAF

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The 40-meter Thai National Radio Telescope (40m TNRT) by National Astronomical Research Institute of Thailand (NARIT) has completed its construction phase in early 2022. With the dual focus design, TNRT's compatible with a wide range of receivers and observing frequency, such as L-band, K-band, C-band, Q-Band, W-band, Multibeam and Phased Array Feed (PAF). The L-band and K-band receivers, developed under the collaboration with MPIfR, have been installed and being commissioned and prepared for performance tests of the antenna. The CXKu-band and Q-band receivers are under the development. Here, we present an update on receiver development and preliminary plan for an L-band PAF for TNRT in the future.

Phased Array Feed (PAF) Demonstrator for TNRT

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Abstract

This new project presents the development plan of initial state of Phase Array Feed (PAF) demonstration prototype project for 40-meter single dish Thai National Radio Telescope in Thailand. PAF will be used for Sun observation, operated at room temperature, the operation frequency is 1.37GHz to 1.47GHz. System architecture consists of RF front end located on focal plane and backend located in backend room. RF front end consists of 16 channels direct sampling with 12bit ADC 4GSPs for each channel. The hardware used COTs or EVB of Quad-MxFE Board interface with FPGA (Xilinx Virtex UltraScale+ VCU118 EVB) via FMC and FMC+. It serves to digitizes and packetizes of received signal of all 16 channels then transmit data to another FPGA via 2xQSFP (100GbE SR4) in backend room.

Beamforming will be performed process in offline. Backend FPGA stores raw data to NVMe storage, more than 1 Hour recording time. PC with MATLAB query data from NVMe storage to perform the offline data processing. In the first phase of this project emphasis on software core development to evaluate adaptive beamforming algorithm in offline mode for software implementation, concept design, before refining hardware implementation in the second phase with compacted hardware design.

A Real-Time Imaging Correlator for Compact Arrays

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Modern radio interferometers typically consist of hundreds to thousands of antenna elements and employ substantial digital signal processing to handle large operating bandwidths of a few tens to hundreds of MHz. Conventionally, FX correlators [1] are used as the primary signal processing unit of the interferometer and these become computationally complex and inefficient for large-N (>1000) arrays. For this reason a generic fast imaging back-end called the E-field Parallel Imaging Correlator (EPIC) [2] was recently deployed on the Long Wavelength Array station at the Sevilleta National Wildlife Refuge (LWA-SV) [3] in New Mexico. EPIC uses a novel architecture that has the capability to produce electric field or intensity images of the sky at the angular resolution of the array with full or partial polarization and spectral resolution of the channelizer at a very high cadence–on the order of tens of milliseconds. By eliminating the intermediate cross-correlation data products, the computational costs are significantly lowered in comparison to a conventional FX or XF correlator from $\sim N^2_{ant}$ to $\sim N_{ant} \log N_{ant}$ for large and dense, but otherwise arbitrary array layouts. This substantially lowers the output data rates while yielding two-dimensional polarimetric image products for science analysis. EPIC is now implemented on a GPU-accelerated hardware and commissioned, at the Long Wavelength Array station [4, 5, 6] located at the Seviletta National Refuge (LWA-SV) in New Mexico (USA), as a commensal transient imaging back-end that can potentially detect and localize sources of impulsive radio emission on millisecond timescales. In this talk, I will discuss the architecture of EPIC and its GPU implementation. I will present the initial validations from commissioning observations of EPIC and simultaneous beam-formed observations of bright sources in the field.

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[4] Kent J., Dowell J., Beardsley A., Thyagarajan N., Taylor G., Bowman J., 2019, Monthly Notices of the Royal Astronomical Society, 486, 5052.

[5] Krishnan H., Kent J., Dowell J., Bearsdley A. P., Bowman J. D., Taylor G. B., Thyagarajan N., Jacobs D., 2020, in 2020 IEEE USNC-CNC-URSI North American Radio Science Meeting (Joint with AP-S Symposium). pp 169–170, doi:10.23919/USNC/URSI49741.2020.9321611

[6] Krishnan H., Beardsley A., Bowman J., Dowell J., Taylor G., Kolopanis M., Thyagarajan N., 2022, Monthly Notices of the Royal Astronomical Society (submitted).

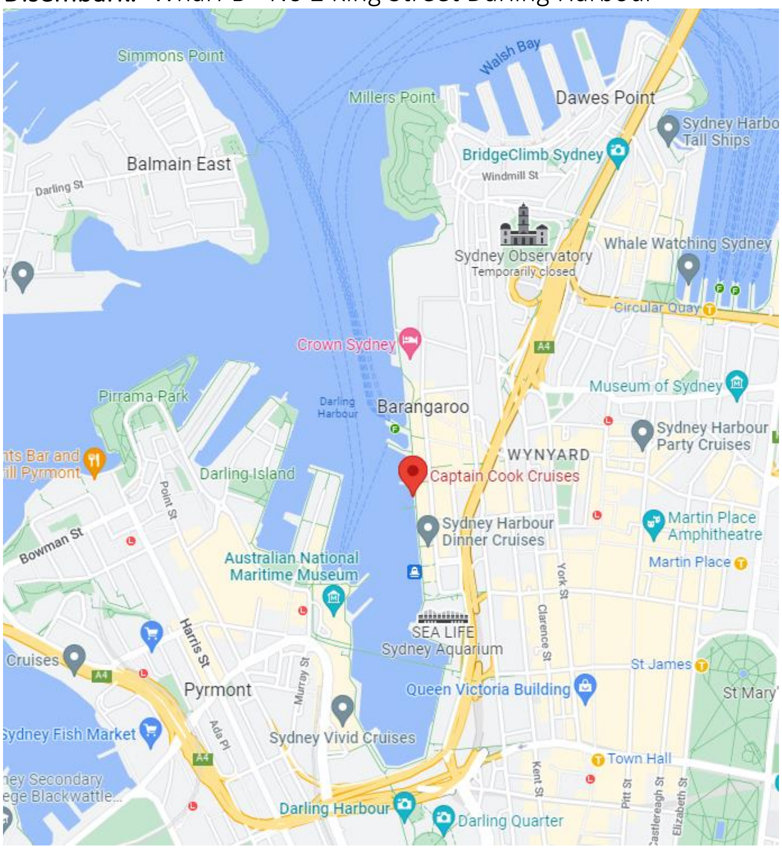
PAFAR2022 Dinner Cruise

The PAFAR2022 Workshop Dinner will be a stunning harbour cruise with three-course dinner.

A bus has been arranged to transport attendees, departing CSIRO's Radiophysics laboratory in Marsfield at 5:30pm and will return to Marsfield after the dinner cruise, departing King Street Wharf at 10:30pm.

The wharf is easy walking distance from Wynyard railway station and other public transport options, and the vessel is wheelchair accessible.

Date: Wednesday 16 November 2022
Time: 7:00 pm – 10.00 pm
Embark: Wharf A - No 2 King Street Darling Harbour
Disembark: Wharf B - No 2 King Street Darling Harbour



Code of Conduct

The Chair and Organising Committees of PAFAR2022 value your attendance and are dedicated to providing a discrimination- and harassment-free workshop experience for all delegates, regardless of gender, gender identity or expression, age, sexual orientation, ability, physical appearance, race, ethnicity, religious affiliation, or technology choice.

Harassment includes: offensive or exclusionary comments, jokes or images, sustained disruption of talks or other events, inappropriate physical contact, unwelcome sexual attention or innuendo, deliberate intimidation, stalking and photography or recording of an individual without consent.

By registering for PAFAR2022 you are agreeing to abide by this Code of Conduct:

- We ask that you behave professionally at all times.
- Harassment or discrimination is not appropriate in any conference venue, including talks, workshops, social events and online media.
- All communication should be appropriate for an audience that includes people of many different backgrounds
- Please be considerate and respectful of fellow delegates and Conference organisers. Do not insult people or put them down and ensure that you critique ideas rather than individuals.

Individuals found to be in violation of this Code of Conduct, or of making allegations in bad faith, will be subject to disciplinary action. Such action may include: a verbal warning, expulsion from the conference without refund, or reporting of inappropriate behaviour to an employer.

If you are being harassed, notice that someone else is being harassed, or have any concerns relating to harassment or discrimination, please contact a conference organiser.

Conference organisers are happy to help participants contact hotel/venue security or local law enforcement, provide escorts, or otherwise assist those experiencing harassment to feel safe.

We expect participants to follow these rules at workshop venues and conference-related social events.

Local Organising Committee: Steve Barker, Stephanie Smith, Ken Smart, Carmel Hartmann

Technical Committee: Alex Dunning, Gundolf Wieching, Karl Warnick, Jin Chengjin