CASPER / PIRE DSP Workshop and Summer School Abstracts 12-16 Aug. 2019

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1. Multibeam Digital Beamforming on 4-Element Array at 28 GHz using Xilinx RF SoC ZCU1275

Viduneth Ariyarathna, Sravan Pulipati, Udara De Silva, Najath Akram, Elias Alwan, Soumyajit Mandal, Ted Rappaport, Arjuna Madanayake

The formation of simultaneous beams across a multitude of directions is an important aspect in many areas such as radio astronomy, imaging, phased-array radar and wireless communications. Multibeam beamforming is a key enabler for emerging millimeter wave (mmW) based 5th generation (5G) communication networks. Designers of 5G (and 6G) mmW wireless systems are considering digital implementations of multibeam beamformers, despite the high complexity, because of the advantages such as high flexibility and ability to utilize the full degrees of freedom from an array. Preliminary results of a 4-element 28 GHz digital array receiver, which is the first step towards a 28 GHz fully digital 16-element array receiver will be presented. The array receiver is implemented using commercial off-the-shelf electronics to support an 800 MHz channel bandwidth targeting mmW communication systems. A 28 GHz patch antenna sub-array that performs analog beamforming is designed to increase the gain in the elevation plane. The receivers are designed to work with orthogonal frequency division modulation (OFDM) supporting ~3 Gbps data rate over the 800 MHz bandwidth and have been modeled in AWR Microwave Office using circuit models to design the optimum receiver electronics. A real-time digital signal processing (DSP) algorithm that generates 4-simultaneous beams operates on the Xilinx ZCU 1275 processing platform. The ZCU 1275 features the Xilinx Zynq UltraScale+ XCZU29DR Radio Frequency System on Chip (RFSoC). The XCZU29DR chip contains 16 12-bit ADCs (that supports sampling up to 2 GSPS) and 16 14-bit DACs (that supports sampling up to 6.4 GSPS). The details of the designed 28 GHz antenna will be presented along with the measured antenna responses. The architecture, design procedures and the electronics of the front-end receiver that can achieve 3 Gbps data rate over the 800 MHz bandwidth will be discussed. The ZCU 1275 board based digital back-end design specifics will be covered along with the architecture of the digital processing circuits and clocking mechanisms of the data converters. The initial results of the 4 simultaneous beam measurements will be presented.

2. Low-Power RF ADCs for Radio Astronomy *(poster)*

Phaneendra Bikkina, Andrew Levy

Alphacore presents its ultra-low power RF analog to digital converters (ADCs) of different sampling rate, bandwidth and resolution flavors with demonstrated measurement results that are a significant improvement over the current state-of-the-art. Some these ADCs are critical building blocks of our planned ASICs for Radio Astronomy (examples include RFI mitigation ASIC, wideband spectrometer etc.) that are currently under development. We have also successfully demonstrated some our low power "core"-architectures utilizing advanced calibration techniques. The presentation discusses how these "cores" in combination with on-chip DSP could be used to implement advanced wideband low power receivers for radio astronomy applications. We also present our road map to our future high speed wideband digitizers with both full data interface (with data rates beyond 200GB/s) and on-chip DSP for low output data rate option (low power mode).

3. CASPER meet MetaSat *(lightning talk)*

Daina Bouquin, Daniel Chivvas

The small satellite community needs comprehensive access to mission enabling information and the ability to broadly share their knowledge and experience. The MetaSat schema aims to address these needs by functioning as a common way of describing hardware, software, and data specifications across missions to improve interoperability between them. In this way MetaSat will support the radio astronomy community by improving access to information on small satellite missions that make use of RF instrumentation and CASPER-supported tools and hardware. The MetaSat team wishes to engage and work directly with the many voices of the CASPER community throughout the schema design process. This workshop is meant to begin a conversation with the CASPER community and give an overview of the MetaSat project.

4. Porting of a CASPER wideband full-stokes parameterized spectrometer to the ZCU111

Brian Bradford, Alan Wilson-Langman, Jack Hickish

This talk presents the development of a wideband full-stokes parameterized spectrometer (polarimeter) for radio astronomy applications, targeting the Xilinx Zynq RFSoC platform. In the past, progress has been limited by the cost, performance and complexity of developing such systems. CASPER has addressed this problem by developing platform independent hardware and open-source software to take advantage of developments in Field Programmable Gate Array (FPGA) and Analog to Digital Converter (ADC) technology in order to "quickly" target new platforms. This project focused on the porting of a CASPER spectrometer instrument and dependent libraries to the Xilinx ZCU111 evaluation platform. The port was based on Migen, an open-source python library for generating and building gateware, that has gained traction in the open-source community. Additionally, Xilinx released an open-source, python-based software project called PYNQ. This project enabled near-native software control of ZCU111 hardware designs via its extensive APIs exposed as python libraries. These libraries allowed for a simple pythonic interface in order to control the gateware that is automatically generated as part of the Migen build process as well as a wide-range of existing Xilinx IP cores. This talk will discuss the pros/cons and lessons learned regarding Migen and PYNQ, whether these tools would be viable for a future toolflow, or whether certain aspects should be integrated into the CASPER toolflow.

5. ALPACA Beamformer Digital Back End Development

Mitchell Burnett, Brian Jeffs, Karl Warnick, Donald Campbell, German Cortes-Medellin, Stephen Parshley, Amit Vishwas

Brigham Young University (BYU), in collaboration with Cornell University, is developing the Advanced Cryogenic L-Band Phased Array Camera for Arecibo (ALPACA) as a user provided facility instrument on the Arecibo 305 m radio telescope. The instrument will be comprised of a fully cryogenic 138 element phased array feed (PAF) and real-time digital beamformer back end capable of producing 40 simultaneous dual-polarized beams with approx. 308 MHz of instantaneous bandwidth. The digital beamformer design is a heterogenous architecture using 18 Xilinx RF System on Chip (RFSoC) ZCU111 evaluation boards for direct antenna voltage sampling and frequency channelization (F-engine) followed by 25 GPU servers (two GPUs each) for beamforming and correlation (XB-engine). The baseline XB-engine implementation will include separate coarse and fine channel spectrometer modes and an array calibration mode for beamformer weight calculations. This presentation will introduce a high-level overview of the system design architecture and introduce the ZCU111 platform and report on the current status of hardware implementations and system integration. For example, with the XB-engine providing a second-stage ‚Äòzoom' fine channel spectrometer mode, the first stage polyphase filter bank (PFB) in the F-engine cannot be a conventional critically sampled design without introducing spectral aliasing and amplitude scalloping in the second stage fine spectra. ALPACA will use an oversampled PFB fist stage spectrometer to avoid these issues. We also plan to present the status of porting the ZCU111 as a CASPER compatible board based on progress from the 2019 CASPER board porting workshop in South Africa.

6. MeerKAT GPU X-Engine

Gareth Callanan

The MeerKAT correlator X-Engines are currently running on the SKARAB platform. At SARAO we are busy designing a GPU drop in replacement for the X-Engine in order to evaluate the feasibility of such a solution. This replacement will use the existing xGPU library for performing correlation and accumulation and the SPEAD2 C++ library for handling the high bandwidth input streams. xGPU was has been integrated into PAPER and is currently being adapted for HERA. PAPER streamed data over 10GbE to the X-Engines while MeerKAT streams data over 40GbE at a rate of approximately 28Gbps(excluding overhead data). This presentation will discuss the current state of the MeerKAT X-Engine GPU prototype including the technical challenges encountered when adapting xGPU to meet MeerKAT's design requirements. The proposed and tested solutions to these challenges will also be presented. Furthermore the advancement in GPU technology over the last few years and the effect this has on xGPU processing speed will be discussed.

7. Adaptive Filter for RFI Mitigation Implemented in ROACH2

F. Curotto, R. Finger, R. Fuentes, R. Duan, L. Bronfman, D. Li

In the last decades, there has been an exponential growth in the use of wireless communication systems, both in the consumer and the industry market. This has had the side effect that many radio telescopes are affected by radio frequency interference. The level of damage by interference ranges from corrupting a small percentage of data, to completely preventing astronomical observations in certain bands.

Over the years, radio astronomers and engineers have developed several mitigation techniques to deal with this type of interference, from legislation to ban emissions near telescopes sites, to offline software tools to flag and delete the interference in astronomical data. In this work, a real-time mitigation method is developed, based on the mathematical concept of adaptive filters. In an adaptive filter setup, a second measurement of the interference is taken with a reference antenna, and the filter parameters are tuned in order to properly cancel out both interference copies. The method has the advantage of being able to remove the interference without incurring in any data loss.

The filter is implemented in ROACH2 hardware to achieve high speed and bandwidth, and then is tested, both in a laboratory setup, and with a telescope. It is shown that while the filter works very well in controlled laboratory conditions, its performance degrades significantly in the realistic scenario, specifically because the practical limitations become more prevalent in this case. Nevertheless, the filter is still able to clean astronomical data if the interference presents favorable conditions (high power, localized source, and without multipath propagation).

8. After the FPGA: Building DSP Processing Pipelines on a Non-real-time Platform *(lecture)*

Jayce Dowell

The conversion of analog radio frequency signals into digital data is only one step in building a functioning instrument. The data also need to be transported, aggregated, sorted, and processed. Instruments that require massively parallel computation now use a hybrid, scalable FPGA/GPU architectures, typically benefiting from reduced development costs. The FPGAs are used for the initial digitization of time-series, and often conversion to the frequency domain, while the GPUs are used to handle the subsequent processing.

Bifrost is an open-source modular C++/Python framework that is intended to foster growth of a "CASPER of GPUs," by making it straightforward to build reliable high-performance data capture and analysis pipelines using CPUs and GPUs. The framework uses circular memory buffers to transport data between blocks that implement particular algorithms. This framework allows arbitrary operations to be inserted into a pipeline and for pipelines to be quickly reconfigured to accommodate new analysis methods. I will provide an overview of Bifrost and its concepts. I will also discuss the Bifrost-based FPGA/GPU beamformer and correlator in use at the Sevilleta station of the Long Wavelength Array.

9. SMuRF readout electronics for microwave SQUID multiplexing *(poster)*

John M. D'Ewart, Zeeshan Ahmed, David Brown, Saptarshi Chaudhuri, Hsiao-Mei Sherry Cho, Bradley Dober, John E. Dusatko, Sofia Fatigoni, Josef C. Frisch, Mark Halpern, Shawn W. Henderson, Gene C. Hilton, Johannes Hubmayr, Kent D. Irwin, Ethan D. Karpel, Stephen E. Kuenstner, Chao-Lin Kuo, Dale Li, John A. B. Mates, Stephen R. Smith, Joel Ullom, Leila R. Vale, Daniel D. van Winkle, Cyndia Yu, Gunther Haller, Jesus Vasquez, Edward Young, Ari Cukierman, Ryan Herbst, Larry Ruckman

The SLAC Superconducting Microresonator RF electronics (SMuRF) is designed to readout over 2000 frequency multiplexed detectors between 4 and 8 GHz. SMuRF is a compact system based on the SLAC Advanced Telecommunication Computing Architecture (ATCA) common platform. SMuRF includes an FPGA, digitizers, RF front end (4-8GHz), and low frequency amplifier/detector bias control. SMuRF is targeted for microwave SQUID multiplexed TES arrays; other potential applications include MKIDS and metallic magnetic calorimeters. Major challenges for these applications include wide bandwidth, readout noise, and linearity. We present the complete SMuRF system including analog performance, firmware overview, and readout noise for a microwave SQUID multiplexed system.

10. The Arizona Radio Observatory Wideband Spectrometer

David Forbes

I will describe the Arizona Radio Observatory Wideband Spectrometer (AROWS), a new digital spectrometer built for the ARO 12-meter telescope on Kitt Peak. AROWS is a spectroscopic backend for the telescope's millimeter-wave heterodyne receivers, and was designed to match the 4 GHz usable IF bandwidth of these receivers.

The primary scientific application of this instrument is deep molecular line surveys, for which baseline discontinuities between spectral segments are problematic. This led to a requirement for 10 GSPS, 8 bit digitizers, which, as of the inception of the project in 2015 had only recently become available as COTS products from the defense industry. A combination digitizer/FPGA module called CHAMP-WB-A25G was purchased from Curtis-Wright to form the basis of the spectrometer. The vendor-provided system gateware was not compatible with the CASPER tool chain, so AROWS combines programming blocks (FFT engine, decimator) from multiple non-CASPER sources, with the rest of the gateware written in-house.

The evolution of commercial technology has opened new avenues for very-wide-bandwidth digital spectrometers, with Xilinx RFSoC products providing particularly attractive possibilities. I will also describe our incipient efforts to build a next generation of ARO backends within the CASPER framework.

11. Software Defined Radio Developments in the Argentine Institute of Radioastronomy for Pulsar and Timing Measurements.

G. Gancio, C. Lousto, J.Combi, L. Combi, F. Garcia

The Argentine Institute of Radioastronomy (IAR) is equipped with two single-dish radio telescopes capable of performing daily observations of pulsars in the south hemisphere. These radio telescopes were built in 1966 and 1980 respectively, and used mainly for the research of the hydrogen line and radio continuum at 21cm, these observations ended in the year 2001 and several scientific publication of great interest related with the mapping and radio continuum at 21cm where done. In the year 2017, a collaboration with the Rochester Institute of Technology started with one of the IAR antennas being refurbished to achieve high-quality timing observations, for it a new software defined radio back-end was developed based on the commercial Ettus SDR boards, thru the development of a custom pulsar receiver software for pulsar and timing measurements. After the successful measurement of several pulsars it was decided to upgrade the second antenna with a new receiver and an improved version of the digital backend. Also we will present the radio observatory and the technological developments that lead to improve our daily observations, focusing on the software development for the digital back end realized to the date among observations results that will be useful for pulsar science, such us the observations of the millisecond pulsar J0437-4715, and the future prospects to work with the CASPER Hardware.

12. Fourier Transforms I/II *(lecture)*

Deepthi Gorthi

Lecture.

13. FPGA Basics *(lecture)*

Kari Haworth

Discussion of what an FPGA is and when you'd want to use one. General (and brief) introduction to concepts and terminology. Review of the FPGA design flow from requirements through lab testing.

14. CASPER Hardware *(lecture)*

Jack Hickish

Lecture.

15. Enabling 100 gigabit Ethernet on the VCU118/VCU1525 for Casper

Benjamin Hlophe

The availability of 100G MAC on the Virtex UltraScale+ FPGAs has created a valuable resource for CASPER system designers to exploit. Work was done to enable the Xilinx 100G MAC core and interface it with AXI stream infrastructure on the rest of the CASPER VHDL firmware. A board support package to enable casper yellow blocks to connect to the 100G MAC is in development. In the work various architecture optimizations have been explored to enable non-blocking and high throughput interface to and from the 100G MAC.

16. The SKARAB Design: Issues Encountered and Lessons Learnt

Adam Isaacson

MeerKAT has been successfully integrated with the latest SKARAB hardware processing units and has started to yield exciting scientific results. The SKARAB performs the correlator beamformer signal processing functions needed for MeerKAT. It is currently capable of implementing a 64 antenna, 32K FFT F-engine and a 64 antenna correlator X-engine. A considerable amount of effort has been placed into getting the SKARAB firmware and hardware optimised for the signal processing functions utilised for the MeerKAT telescope. This presentation will give an overview of the issues encountered, lessons learnt and what could be done differently for the next generation CASPER hardware e.g. SKARAB2.

17. Development of A LOW COST 4-bit, 16 Giga-Samples per Second Analog-to-Digital Converter Printed Circuit Board Assembly for Radio Astronomy

Homin Jiang

In this study, a 4-bit, 16-Gsps analog-to-digital converter (ADC) printed circuit board assembly (PCBA) was designed, manufactured, and characterized for digitizing radio telescopes. For this purpose, an Adsantec ANST7123-KMA flash ADC chip was used. Because of this chip doesnot follow the JESD204 standard, a novel channel bonding method has been developed for alignment of the high-speed serial data input. The PCBA is equipped with a field-programmable gate array (FPGA) Mezzanine Card (FMC) connector. With FMC, it allows us to employ the field-programmable gate array evaluation board, VCU118, by Xilinx as the testing platform. The PCBA enables data acquisition with a wide bandwidth and simplifies the intermediate frequency section. In the current version, the PCBA and the chip exhibit an analog bandwidth of 10 GHz (3 dB loss) and 20 GHz, respectively, which facilitates second Nyquist sampling. Preliminary results of spurious-free dynamic range (SFDR), signal-to-noise and distortion ratio (SINAD) and effective number of bits (ENOB) will be presented.

18. African lessons for Astronomy

Francois Kapp

The South African Radio Astronomy Observatory (SARAO) is in the process of completing the MeerKAT telescope, while also working on the African VLBI Network and the Square Kilometre Array. In looking at these projects, some themes emerge that can be collected into guiding principles for thinking of the Acquisition of Radio Astronomy Instruments. Some of these principles are very well aligned to the CASPER philosophy, while others offer insight into buy vs build trade-offs and the differences between experiments and facilities. The constraints that are unique to Radio Astronomy, for example Radio Frequency Interference, will receive special attention. In keeping with the theme for the workshop, the material is accessible to someone who is being introduced to the field of Radio Astronomy, although basic academic knowledge of Signal Processing and Radio Communications is assumed.

19. Pulsar signal processors enabled by CASPER

Ramesh Karuppusamy, Amit Bansod

The Effelsberg 100m Radio Telescope carries out astronomical observations over a range of radio frequencies in the 50cm--3mm wavelengths. The telescope is used for pulsar observations for over ~35% of total time available for astronomical observations. Radio pulsars themselves are used as tools to t est fundamental physics and this is is best addressed by high signal-to-noise ratio pulsar observations. The achievable S/N to pulsar signals is proportional to the collecting area of the telescope and their receiver bandwidths. In order to observe pulsars with newer and wider band receivers, we have developed two generations of pulsar signal processor gateware based on hardware and toolflow developed by the CASPER community. The gateware were designed to support both baseband (up to 1ns time resolution) and spectro-polarimetric data with a programmable sample width of 16us or more. Using a distributed storage system, and high performance networking equipment, we can can now routinely support observations with a data rate of up to 2GB/s. In this talk, I will outline these systems and some recent results.

20. Direct Sampling: Real world, real time, wide band ADC and DSP design for radio astronomy applications

Henno Kriel

Technological advances made in analogue to digital convertors (ADC), real time digital signal processing (DSP) elements like field programmable gate arrays (FPGA) and multi gigabit transceivers (MGT) data links, it has become possible to acquire and process large radio frequency (RF) bandwidths. This presentation aims to give an overview of how these technological advances can be utilized to design and implement new radio astronomy receiver and processing systems. Design parameters like RF bandwidth, anti-aliasing, sampling rate, dynamic range, input/output (IO) bandwidth and DSP resources will be explored. The proposed science case drives the input requirements for the system and these parameters. As with any real world system engineering problem, it requires various trade offs between the different stages or elements to ensure the best fit for the targeted system. These trade offs can be limited due to RF interference (RFI) and physical environment, current technology available, component or system cost, design cycle period, system integration with current or legacy systems and obsolescence. All of these aspects will in some way impact the final product and ultimately determine its success.

21. Experience with Student-Constructed Telescopes for Radio Astronomy *(demonstration)*

Glen Langston, N. Patel (ed. L. Greenhill)

Glen and Nimesh have each worked with a range of students to develop portable radio-horn telescopes for HI observing, exploiting software defined radio (SDR) technology. Glen will present experiences with students in construction and use. He observes, "using software defined radios Radio Astronomy is within the reach of all high schools, colleges and hobbyists. Ideally citizen science project should be open-ended, allowing the participants to innovate and create. Radio Astronomy is ideal for citizen science as a great variety of telescopes can be created, each designed for their own science goal." During the demonstration, he will present his SDR system and early tools for spectroscopy and transient event detection. These will be matched to a radio horn and receiver built by undergraduates in Harvard's Astronomy 191 semester-long lab taught by Nimesh, who will also discuss As Glen notes, "there is much room for innovation, further software development and discovery of the radio universe."

Experience with Student-Constructed Telescopes for Radio Astronomy *(poster)*

Glen I. Langston, Sue Ann Heatherly, Sophie Knudson, Evan Smith, Richard Prestage, Eve Klopf

Our group has designed, documented construction and operated Radio Telescopes intend for use by high schools, colleges, hobbyists and other Science Aficionados. West Virginia University freshmen built two telescopes during a two-week summer program. The students operated the telescopes, which they named Alexander and Bess. Their experience was mostly successful, and we learned how to improve documents describing construction and operation. We're incorporating lessons learned into revised documentation, published on the web at https://opensourceradiotelescopes.org/wk

22. Online signal processing in Cyclotron Radiation Emission Spectroscopy for precision measurement of the tritium beta-decay spectrum *(poster)*

B. H. LaRoque, for the Project 8 Collaboration

The Project 8 experiment seeks to measure the absolute neutrino mass using tritium beta decays and a new spectroscopy technique, Cyclotron Radiation Emission Spec- troscopy (CRES). The initial phase of Project 8 demonstrated that CRES could be used to detect single-electron cyclotron radiation. In the current phase of the project, the CRES technique is applied to the tritium beta-decay spectrum for the rst time. A single analog channel is read by a data acquisition (DAQ) system based on a ROACH 2 board followed by CPU-based online processing. The next phase will demonstrate the ability to scale up the source volume of the experiment, which will increase the required complexity of the DAQ system. The new system will need to read out 30-60 analog channels and use digital beamforming for online signal processing and data reduction. We are investigating the use of SNAP and SKARAB boards for the front-end, as well as various platforms for the online signal processing. Here we present the current DAQ architecture and preliminary plans for the next-phase system.

23. Timing and Frequency Distribution over Ethernet using White Rabbit

Wei Liu, Rick Raffanti, Dan Werthimer

Most CASPER based instrumentation use a time/frequency distribution system that transmits 1 PPS (one pulse per second timing reference) as well as a reference frequency (10 MHz or an ADC sample clock) to all the digitizers in the instrument, using a bank of dedicated coax or fiber cables. Large correlators can require hundreds to thousands of cables for time and frequency transfer. White Rabbit is open source hardware and software that is used to distribute time and frequency over Gbit/second Ethernet, saving cables and complexity. Each node in a system on requires a single fiber to carry bidirectional data, monitor and control, as well as precision frequency and timing transfer. Each node uses a 1 Gbit/sec bidirectional Ethernet transceiver (one color is used to transmit, another color for receive); White Rabbit can transfer timing to 30 ps RMS accuracy with a central system reference clock (eg: a GPS disciplined hydrogen maser) and can service more than 1000 nodes and cover distances of the order of 10km. This presentation will describe how White Rabbit works, why it's useful, open source White Rabbit switches that are commercially available, how to develop White Rabbit hardware and software, and add White Rabbit capabilities to casper boards. White Rabbit PTP Core(WRPC) is a open source IP core, which can work on different platforms, such as Spartan-6, Virtex-6, Artix-7, Kintex-7 and so on. We will describe made WRPC work on PANOSETI kintex7 based quabo board, and three key technologies use in WR: PTP, layer-1 synchronization and precise phase measurements.

24. Cooling Next Generation CASPER Hardware *(poster)*

Omer Mahgoub

SKARAB2 is set to be the latest incarnation of Casper's reconfigurable processing hardware. Utilizing Xilinx Ultrascale+ FPGAs, an early power estimate using Xilinx Power Estimator has yielded power consumption figures approaching 200W per FPGA. With 4 FPGAs per board, this presents a considerable challenge in ensuring thermal integrity. The power in the latest generation of processors is fast outpacing the ability to cool them and the traditional cooling techniques employed by SKARAB2's predecessors might not be sufficient. Alternative cooling methods and techniques therefore need to be investigated.

The primary cooling methods currently used in industry are mainly comprised of air and liquid cooling with air cooling being the most common. Air cooling ranges from a variety of natural convection passive heatsink designs to forced convection active heatsink and fan combinations. Although traditionally reserved for Super Computing systems and data centers, liquid cooling is starting to become more mainstream as the necessity arises. From direct contact liquid cooling that targets specific components on your board to fully immersed cooling solutions in which boards are submerged, liquid cooling is gaining traction in thermal management.

This presentation will look at the feasibility of different cooling techniques that can be employed from PCB through to module level on future CASPER hardware.

25. Ethernet Multicast Networking for Radio Astronomy: the Good, the Bad and the Ugly *(lecture)*

Jason Manley

I will discuss the advantages and challenges of interconnecting radio astronomy instrumentation using a large-scale multicast ethernet network, and some of the pitfalls of equipment selection, network architectures, protocols and configuration, and external equipment connections.

MeerKAT has been successfully operating at full scale for over a year now, leveraging a multicast ethernet L3 network to distribute data between processing elements.

Until recently, all of these components have been under internal control (designed and developed in-house). However, we are now in the process of deploying and commissioning the first User Supplied Equipment, which integrates into the existing network.

This 3rd-party equipment is not under our control. We provide an Interface Control Document to explain the network's limitations and how to use it correctly and fairly. However, it is difficult to accurately document all possible use-cases and it is possible, under certain conditions, for these users to detrimentally affect streams to other equipment. Care needs to be taken to ensure proper operation of the network.

26. Radio Astronomy & Interferometry Principles *(lecture)*

Dan Marrone

PART 1
Introduction to Radio Astronomy
+ Characteristics of Radio Astronomy
- Frequency/Wavelength ranges
  - Atmospheric and ionospheric bounds
- Special characteristics
  - Long wavelengths, diffraction, single-mode
  - Coherent detection, field sensing
- Early radio astronomy history
- Radiation processes and science motivations
- Radio telescope morphologies
  - Low/high frequency
  - Single-aperture and interferometry
  - Phased arrays
- Detection Methods
  - Coherent detection
  - Mixing and Amplification
  - Incoherent detection

+ Radiation and Detection
- Brightness, Flux density
- Blackbody, RJ limit, and brightness temperature
- Thermal noise in circuits, equivalent temperature
- Square-law detection of voltage
- Radiometer equation

PART 2
Introduction to Interferometry
+ Telescopes
 - Illumination and primary beam

+ Why Interferometry

+ Two-element Analysis
 - Response of multiplying interferometer
 - Effect of bandwidth

+ Interferometric Measurement
 - Fourier Transform response (van Cittert-Zernike)
 - FT relationships in interferometric imaging

27. DSP on FPGAs *(lecture)*

Andrew Martens

Digital Signal Processing is required in many fields. Certain types of DSP, given certain priorities, are best solved using FPGAs. Using FPGAs for DSP comes with unique challenges including; designing to take advantage of parallelism, ensuring linearity and sufficient dynamic range, resource management, timing closure, and debugging. The push to larger, higher performance systems comes with its own challenges including scaling existing systems, timing and synchronisation, and data transport. Certain design methodologies, tools, hardware and software, like those found in CASPER, can make life easier.

28. Distilled Essence of the PFB

Jim Moran (improvised by L. Greenhill)

The PFB,
Oft used,
As oft misunderstood.

29. Finite Precision Arithmetic in Polyphase Filterbank Implementations

Talon Myburgh

Radio wave readings are often most useful to scientists when presented as a spectrum. For this reason, most radio telescopes have a back-end spectrometer which transforms the incoming data from the time to frequency domain. In radio astronomy, the preferred way of doing this is through the use of a Polyphase Filterbank (PFB). The efficiency of the PFB is sensitive to its implementation, parameters, and input signal type. In my MSc, I've explored the effect of these variables, by developing both a fixed-point and floating point simulator that is widely generic. This approach allows a user to explore a range of implementation options when prototyping/testing. The fixed-point simulator was tested against a CASPER implemented PFB hosted on an FPGA and was largely in agreement therewith. My research thus far has outlined potential ways of mitigating the quantisation error present in the CASPER PFB, while further exploring floating point and posit number system implementations. A by-product of this rigorous understanding of the PFB and its essential components (documented in my thesis), has induced study into further topics such as post-channelising, shift register populating and how the PFB affects the overall accuracy and precision of the correlator. In my presentation, I look to introduce the PFB, detail the MeerKAT implementation thereof, introduce the developed simulator and report on some of the hypothesis made and results obtained.

30. Introduction to Red Pitaya and support in the CASPER toolflow *(lecture)*

Wesley New

Recently support for the Red Pitaya Platform has been added to the CASPER toolflow. It is the first really low cost board to be supported by the flow. It will allow easier access to CASPER supported hardware and aid in growing the collaboration. This presentation will cover the Zynq FPGA architecture and how support was added to the CASPER toolflow.

31. Incorporating Partial Reconfiguration into the CASPER Toolflow

Amish Patel

As the size and complexity of FPGAs increase, so do compile times; the current CASPER tools recompile a design in its entirety for each call of the build process. Partial reconfiguration can be leveraged to exclusively compile the dynamic parts of the design. That is, those resources which change between modes of implementation for a given firmware base. In the case of CASPER, this allows the board support package of the target hardware to be precompiled and only the DSP be recompiled when generating a bitstream. This has the added benefit of reduced upload and configuration times due to smaller bitstream files and persistent communication interfaces, e.g. Ethernet, PCIe. SARAO is in the process of incorporating Partial Reconfiguration into the CASPER toolflow, with development targeted at the Ultrascale+ platforms including the VCU118 and VCU1525. This presentation aims to update the CASPER community on developments on this task and involve a wider audience in the discussion around its implementation.

32. Cosmic Ray detection firmware for the upgraded OVRO-LWA

Kathryn Plant, Jonathon Kocz, Gregg Hallinan, Andres Romero-Wolf, Ryan Monroe, Anna Nelles, Marin Anderson, Michael Eastwood, Larry Daddario, David Woody, James Lamb, Washington Carvalho Jr., Konstantin Belov

High energy cosmic rays interacting with the atmosphere produce showers of radio emission, and detecting these cosmic rays from the radio showers alone (without relying on particle detector triggers) allows larger samples of events for new population composition studies. Air showers are detected as impul- sive events (tens of nanoseconds duration) arriving across an array of antennas. Event detection as well as initial RFI flagging must occur on the FPGAs, in order to save raw time series data. The Owens Valley Long Wavelength Ar- ray made self-triggered radio detections of cosmic-ray air showers (Monroe et al. 2019 in prep) using 256 irregularly-spaced dipole antennas with ,à°60 MHz bandwidth centered around 55 MHz and maximum baselines of 1.5 km. Over the next two years, an upgrade to 352 antennas with up to 2.6 km baselines and new signal processing infrastructure will expand the capabilities of the array, including the development of a new observing mode for detecting cosmic ray air showers commensally alongside the other science operations. I will present the preliminary digital signal processing design for the upgraded cosmic ray detection system.

33. Building a high performance DSP framework for GPUs and x86 hardware: A look at the design of the CHIME X-engine and beamformer *(lecture)*

Andre Renard obo The CHIME Collaboration

We will present an open source C++14 framework used to build GPU based soft-real-time pipelines for digital signal processing, and discuss some of the performance issues encountered with software based DSPs and how to mitigate them. This framework, called kotekan, is currently used on the CHIME telescope and as a capture system for the ARO 46m and DRAO 26m telescopes. In CHIME, using a cluster of 256 servers with 1024 GPUs, the framework supports the processing of over 6.4 Tb/s of 4+4-bit radiometric data from the instrument's 2048 analog inputs over 400MHz of bandwidth. Supported GPU processing operations for CHIME include the full N^2 correlation, FFT power-beamforming, a 10-beam dynamically steerable voltage beamformer, and high cadence RFI excision. The framework has been designed to leverage GPU co-processors via the OpenCL and low-level HSA APIs. The talk will cover details of the network packet capture from the FPGAs over Ethernet with the DPDK library and userspace network drivers; in lab tests this has been shown to achieve packet capture rates of over 200Gb/s on dual-socket systems. Some of the other performance related topics covered will be: thread management, memory management best practices, ring buffer design, using cache-aware memory operations, using AVX intrinsics, and system performance debugging and monitoring. We will also cover some of the design choices in the kotekan framework, such as: pipeline composing via YAML files, HTTP based APIs for external control, APIs for exporting Prometheus metrics, and network transportable buffers. The talk will conclude with some thoughts on newly released and upcoming hardware, and the future of GPU based DSP systems.

34. Design and Implementation of 100Gb/s Ethernet on VCU118 Evaluation Board

Arash Roshanineshat, Kari Haworth

The next generation of radio telescopes need ultra-wideband signal processing digital backends. Higher signal processing and recording bandwidths require higher transmission rates. The current transmission rate used typically in telescope instruments is 40Gb/s. However 100Gb/s is becoming the standard in high performance ethernet adapters. In this project, we use the Xilinx VCU118 FPGA evaluation board to communicate to a processing system equipped with 100 Gb/s Mellanox adapters to test the throughput and validate the transmitted data. The system designed in this project uses a custom controller unit to configure the required registers of the 100 GbE subsystem using AXI-lite protocol. We aim to build a system will be flexible and reliable, providing up to 100Gbps usable bandwidth. This presentation will describe the protocol under development, and provide an update on porting the design to a block in the CASPER toolflow.

35. User support and debugging tools for the MeerKAT correlator/beamformer

A. Rust

The MeerKAT correlator/beamformer subsystem (CBF) consists of high speed networking infrastructure, servers and frequency, correlation and beam-forming engines running on SKARAB hardware. A server (CMC) runs software for control and monitoring of various CBF instruments. At the user interface level MeerKAT employs a CAM (control and monitoring) subsystem to start the CBF in specified modes as well as schedule and run observations in these modes. During operations the CBF subsystem may experience various faults and errors. These may include network errors such as excessive dropped packets and link overloads, hardware faults, memory faults and signal chain errors (e.g. numerical overflows). When these errors occur it is very difficult to effectively pinpoint and correct the fault. CBF support infrastructure is needed to perform this task. This talk will focus on the support infrastructure which consists of tools for displaying and debugging the current state of the CBF subsystem as well as sensors and snapshot blocks built into the CBF signal chain. Sensors and snapshot blocks useful for qualification and functional testing of a correlator beamformer subsystem will also be discussed.

36. Haystack VLBI Geodetic Observing System (VGOS) ROACH2 Backend

C. Ruszczyk, R. Wilcox

The next generation VLBI Observing System (VGOS)-compliant backend, of 1024-MHz bandwidth processing, is currently transitioning from the lab to standard operations at the NASA stations as well as various geodetic sites worldwide. The VGOS backend builds around the ROACH2 firmware and software architecture. We will present the VGOS requirements as relate to this development.

37. FPGA platforms and the toolflow

Lin Shu, Jie Hao, Qiuxiang Fan, Liangtian Zhao, Yafang Song, Hui Feng

This talk will introduce the FPGA platforms we developed, including SNAP2 and two kintex 7 platforms. All of them have been ported to casper toolflow. Three kinds of ADC yellow blocks (E2V_5G, HMCAD1520 and ADS5407) are also built. Besides, experiences in multi-clock design will be shared, which is important to optimize timing especially when resource utilization is very high.

38. RFSoC Firmware Development of a Frequency Multiplexed readout for Superconducting Arrays

Adrian Sinclair, Jonathan Hoh, Ryan Stephenson, Eric Weeks, Phil Mauskopf

We describe the development of a frequency multiplexed readout system for superconducting arrays using the Xilinx Radio Frequency System on a Chip (RFSoC). This system is an upgrade to the ROACH-2 based readout system we have developed for a number of balloon-borne and ground-based instruments including BLAST-TNG, OLIMPO, MUSCAT, Superspec and Toltec. Specifically our development has targeted the RFSoC ZCU111 evaluation board. The size (30x20x.27 cm), weight (.8 kg), power (< 30W), and instantaneous bandwidth (8x 4GSPS) of the RFSoC ZCU111 have made it an attractive candidate for future balloon-borne or even space-based astronomical instruments. Additionally, the RFSoC has an open source python interface, which allows for users to interact with data and update firmware settings while running. We also describe the design and performance of an IF board for up-converting and down-converting the output of the ZCU111 into the 4-8 GHz band. Applications for the new readout system focus primarily on: frequency multiplexed superconducting nanowires single-photon detectors (SNSPD), Kinetic inductance detectors (KID), and Transition Edge Sensors (TES). The overall firmware architecture for these three detector technologies are fundamentally the same. The firmware design can be divided into three separate parts: the modulator, demodulator, and tone tracking. We will also present preliminary measurements of both KIDs and SNSPDs with the readout system.

39. Single-dish backend for African VLBI Network using CASPER hardware

James Smith

The African VLBI Network (AVN) project aims to build radio astronomy competence in African partner countries in preparation for the SKA, but also to improve UV coverage by combining with the European VLBI Network (EVN) to close the gap between Europe and Hartebeesthoek.

The first AVN telescope in Kuntunse, Ghana, was inaugurated in August 2017, and currently supports radio astronomy education by providing a platform for students from African countries to perform simple methanol maser observations at 6.7 GHz. Fringe-tests with EVN telescopes have been successfully performed, though the site requires the addition of timing-and-frequency reference hardware before it can contribute regularly to VLBI observations.

The single-dish backend (SDB) deployed at Kuntunse is based on ROACH hardware, loosely borrowing from KAT-7's F-engines, and the ingest software interfaces with the station's control and monitoring system to collect all the observation metadata required in order to create neatly packaged observation data files in HDF5 format, to be used with software tools developed at SARAO.

A planned upgrade would replace the ROACH with ROACH2, sampling the incoming signal at 1024 MHz, to coincide with the band used by the proprietary DBBC for VLBI, allowing for a great deal of simplification in the receiver. Commensal single-dish observations during VLBI may not be scientifically useful, but it would allow the operator to view the live RF feed in a similar way to single-dish observations, which capability is typically not possible with standard VLBI tools.

40. An RFSOC Readout System for MKIDs

Jenny Smith

Microwave Kinetic Inductance Detectors (MKIDs) are poised to overtake the more established Charge Coupled Device (CCD) technology because they they are easy to multiplex into large arrays, can deliver a time resolution of 2 microseconds, and are capable of single photon counting without read noise or dark counts with energy resolution across the ultraviolet, visible, and infrared (UVOIR) spectrum. Currently, MKID arrays require large, complex, power-intensive readout electronics which present a major obstacle to MKID deployment in space. We plan to address this limitation by designing a new readout system incorporating CASPER blocks and the newly released Xilinx programmable computing chip: the Zynq UltraScale+ RFSoC. Successful implementation will decrease the readout system weight by 85% and volume by 85% all while using 1/20th the power. This upgrade will further increase the feasibility of utilizing MKID technology for a wide variety of astronomy research.

41. Radio interferometer observations of fast processes in thunderstorms

Julia N. Tilles, Ningyu Liu, Mark A. Stanley, Paul R. Krehbie), William Rison, Joseph R. Dwyer, Robert Brown,, Jennifer Wilson

Though ubiquitous, thunderstorms conceal much of their electrical activity deep within thousands of cubic kilometers of cloud water and ice, limiting optical observations of processes in the cloud. However, lightning spends most of its time inside the cloud, where it initiates and propagates, discharging the cloud charge regions, and also where it sometimes triggers great bursts of gamma rays -- terrestrial gamma-ray flashes (TGFs) -- that can travel hundreds of kilometers to be registered by spacecraft. Lightning initiation and TGF production are two of the great mysteries in the field of atmospheric electricity, and radio signatures associated with both [Rison et al., 2016, doi:10.1038/ncomms10721][Dwyer and Cummer, 2013, doi:10.1002/jgra.50188] allow for ground-based radio investigations. Here we present results from a sparse (three-receiver) 20-80 MHz, 100-meter-baseline radio interferometer that we deployed at Kennedy Space Center, Florida from 2016 to 2017. The results reveal new and surprising electrical processes, some of which currently defy explanation [Tilles et al., 2019, doi:10.1038/s41467-019-09621-z].

42. A gentle introduction to casperfpga *(lecture)*

Tyrone van Balla

The casperfpga Python library is used to interact with CASPER Hardware over various communication interfaces. Its core functionality allows for the reconfiguration of firmware and reading and writing of registers. To date, SARAO/SKA SA has used casperfpga to interact with the ROACH1 and ROACH2 hardware platforms, and, most recently, the new SKARAB hardware platform. This talk presents a gentle introduction to the casperfpga library and offers a guided tutorial on adding support for new hardware platforms.

The first part of this talk aims to introduce and present the current landscape of casperfpga, as used by SARAO, by providing a general overview of the main functionality, discussing the structure of the library and the casperfpga class, highlighting additional features and capabilities and by sharing various lessons learnt through integrating support for three hardware platforms (ROACH1, ROACH2, and SKARAB) into casperfpga.

The second part of this talk shifts to be of a more 'tutorial-style', where the focus is on how to add support for new hardware platforms into casperfpga . The Red Pitaya hardware platform is used as an example and this tutorial offers a walkthrough on essentially making the Red Pitaya 'a casperfpga '. The underlying transport protocol used for the Red Pitaya, KATCP, is first briefly discussed before delving into implementing the required classes, methods and logic to enable interaction with the Red Pitaya.

43. LINUX Introduction *(lecture)*

Vereese van Tonder

Abstract
$ man intro.

44. Control Software for the Red Pitaya Zynq ARM Processor *(lecture)*

Vereese van Tonder

The ROACH2 high performance processing board is fitted with an external Power PC for controlling the FPGA. Its successor, the SKARAB board, uses the softcore microblaze for controlling and communicating with the FPGA fabric. The new educational Red Pitaya board is fitted with a Zynq FPGA, which combines an ARM hardcore processor with the FPGA fabric. In the true CASPER spirit we looked at reusing and extending existing software. TcpBorphServer is control software which supports the KATCP protocol and has been extensively used for controlling and communicating to CASPER hardware. Therefore it has been chosen as the control software for the Red Pitaya.

This presentation will introduce the TcpBorphServer and explain why it is ideal to work with the ARM processor. It will cover the changes required to the software and explain what is involved in porting the TcpBorphServer Software to the ARM processor on the Red Pitaya. The memory mapping changes required for the programming of the FPGA fabric and the reading/writing of the registers will be discussed. This presentation will cover the core functionalities required to control the Red Pitaya. Finally, the future developments to the TcpBorphServer will be discussed e.g. extended support for a slower data transfer rate via the 1 GB interface.

45. SKARAB Embedded Software Challenges and Insights *(poster)*

Robin van Wyk

The Meerkat Telescope, currently being commissioned, has 250+ SKARABSs deployed as part of it's digital signal processing infrastructure. This network of SKARABs has highlighted some interesting challenges during the deployment, scaling and integration phases. This presentation will discuss some of these challenges, from the perspective of the SKARAB embedded software, and the lessons learnt while dealing with these challenges. It will also highlight the software features and fixes employed to overcome these challenges.

46. Taking a Narrow View: Diving deeper into the design of a narrowband correlator

Andrew van der Byl

The MeerKAT radio telescope is commissioned to be a multi-mode instrument. Initial modes include a wideband correlator-beamformer and pulsar search instrument. The current correlator-beamformer is focused on wideband channelisation performed by an FEngine prior to cross multiplication in the XEngine to form a correlation instrument. The wideband correlator-beamformer operates in L-Band with an instantaneous bandwidth of 856 MHz with future bands including UHF and S-Band. An additional narrowband channelisation mode is under development and is currently being tested prior to inclusion with the growing collection of modes to expand the scientific capabilities of the MeerKAT radio telescope. The initial narrowband mode operates in L-Band and has a bandwidth of 107 MHz selectable over the full wideband 856 MHz range with a band centre resolution of ~100Hz. To achieve band selection a mixing stage with digital down-conversion and filtering is required. The channeliser decomposes the band into into 32k channels operating on dual polarisation with a spectral resolution of ~3.265 kHz per channel offering an 8x improvement in frequency resolution. This presentation will discuss the development of the processing stages using the CASPER toolflow with focus on the digital down-conversion and decimation stage as well as the changes to the Polyphase Filter Bank and channeliser. Consideration will also be given to additional modifications required to realise a narrowband correlator - both in FEngine and XEngine designs. The presentation will include design considerations and constraints and will provide operational results.

47. ROACH-2-based Radio Astronomy Spectrometer for NASA's Deep Space Network *(poster)*

Kristen Virkler, Melissa Soriano, Jonathon Kocz, Jorge Pineda

The Deep Space Network (DSN) enables NASA to communicate with its deep space spacecraft. By virtue of its large antennas, the DSN can be used as a powerful instrument for radio astronomy. In particular, Deep Space Station-43, the 70 m antenna at the Canberra Deep Space Communications Complex has a radio astronomy system covering a 400 MHz bandwidth centered at 8 GHz and 10 GHz bandwidth at 17 to 27 GHz. Examples of the kinds of radio astronomical observations that could be conducted with this system include surveys for various spectral lines, including water, hydrogen radio recombination lines, and ammonia.

A new high-resolution spectrometer comprised of four Reconfigurable Open Architecture Computing Hardware (ROACH)-2 boards was recently implemented to enable spectroscopic capabilities. Each ROACH-2 can process up to four, 1GHz inputs, resulting in a total bandwidth of 16 GHz. Such a large total bandwidth enables the simultaneous observations of a large number of RRLs, which can be combined together to significantly improve the sensitivity of these observations.

The system has two different firmware modes: 1) Using a 64k-pt FFT to provide 32,768 spectral channels at ~30.5 kHz (0.5 km/s velocity resolution) and 2) Using a 16k-pt polyphase filterbank (PFB) to provide 16,384 spectral channels with ~122 kHz resolution.

Once deployed in the Canberra DSN site, the ROACH-2 spectrometer will automatically query the observing schedule for radio astronomy tracks. A user provided list of targets will then be automatically scheduled to run during these times. The integration time for each target is variable, with a minimum of 2 seconds (FFT mode) and 1 second (PFB mode), respectively. The output is recorded as binary data, then converted to FITS format for storage.

The results of this project can help future radio spectrometers or other DSN radio astronomy projects. Another possible application for this spectrometer system being explored is an extremely high spectral resolution 1M-pt FFT mode for commensal observations.

48. Radio Astronomy Signal Processing Instrumentation and CASPER *(lecture)*

Dan Werthimer

Why do radio astronomers need spectrometers, correlators, beamformers, and pulsar/frb/seti machines ? How do they work? What architectures and technologies are useful ? How can you design and build these instruments ? The CASPER collaboration has developed open source hardware, software, GPUware, FPGA gateware, and architectures for radio astronomy instrumentation. CASPER instrumentation is utilized mostly for radio astronomy, but also for physics, medicine, genomics, and engineering. Dan will review CASPER hardware and libraries, and discuss architectures for flexible general purpose scalable and upgradable instruments. Dan will also speculate on what kind of instruments the radio astronomy community could build in 10 and 20 years. Open source hardware, software, libraries, tools, tutorials, training videos, reference designs, and information on how to join the collaboration are available at http://casper.berkeley.edu

49. Pivotal Discoveries in Radio Astronomy, at Bell Labs. [INVITED]

Robert W. Wilson

In the late 1920's Bell Labs started establishing field stations in New Jersey to get away from the electrical noise of New York City and do radio research. They were eventually consolidated in Holmdel, NJ with a charter to improve long distance telephony. I will tell the story of how, with the Bell Labs culture of following up on interesting leads, this industrial lab doing somewhat directed research made three major discoveries in Radio Astronomy.

50. 40 MHz Level-1 Trigger Scouting for CMS *(poster)*

A. bin Zahid

CMS will be upgraded for operation at the High-Luminosity LHC which will start in 2027, to maintain and extend its optimal physics performance under extreme pileup conditions (~140-200 interactions per bunch crossing). These "Phase-2" upgrades will include an entirely new tracking system, supplemented by a track trigger processor capable of providing tracks to the Level-1 (L1) trigger, as well as a high-granularity calorimeter in the endcap region. Furthermore, the rate of event selected by L1 trigger (L1 accept budget) will increase from 100 KHz to 750 KHz. The upgraded Level-1 processors, based on powerful FPGAs, will be able to carry out sophisticated feature searches, while keeping pileup effects under control. In this paper, we discuss the feasibility of a system capturing Level-1 intermediate data at the beam-crossing rate of 40 MHz and carrying out online analysis. This 40 MHz scouting system would provide fast and virtually unlimited statistics for detector diagnostics, alternative luminosity measurements and, in some cases, calibrations. It has the potential to enable the study of otherwise inaccessible signatures, either too common to fit in the L1 accept budget, or with requirements orthogonal to "mainstream" physics, such as long-lived particles (LLPs) in the search for dark matter. To realize such a system, data from the L1 trigger is collected over optical links by active or passive splitting, preprocessed with powerful FPGAs, before being transferred into the memory of compute nodes for further processing and potential storage. We also discuss our plans for implementing suitable machine learning algorithms using high level languages for synthesis to translate the Neural Network model into HDL firmware; or by hardware inference engine solutions and other technologies. Finally, we describe the implementation and operation of a demonstrator used at the end of last CMS run (Run-2) by collecting data from CMS Global Muon Trigger.

51. The applications based on SNAP2

Liangtian Zhao, Lin Shu, Jie Hao, Yafang Song, Qiuxiang Fan, Hui Feng

SNAP2 has been used as backends for many telescope Arrays and single telescope,such as FAST telescope spectrometer,pulsar engine, Tianlai telescope Array correlator, beamformer, pulsar engine, Chinese Spectral Radio Heliograph（correlator, beamformer), 21CMA (beamformer). Architectures of these instruments, experiences and lessons will be shared.