THE COLLABORATION FOR ASTRONOMY SIGNAL PROCESSING AND ELECTRONICS RESEARCH

CASPER

http://casper.berkeley.edu

Dan Werthimer - University of California, Berkeley
Don Backer - University of California, Berkeley *(deceased)*
Mandana Amiri - University of British Columbia
Marin Anderson - University of California, Berkeley
Matthew Bailes - Swinburne University of Technology
William Barott - Embry Riddle Aeronautical University
Marco Bartolini - Medicina radiotelescopes (INAF - IRA)
Etienne Bauermeister - MeerKAT / SKA South Africa
Geoff Bower - University of California, Berkeley
Kaushal Buch - GMRT, National Centre for Radio Astrophysics, India

Sandeep Chaudhari - GMRT, National Centre for Radio Astrophysics, India
Henry Chen - University of California, Los Angeles
Hong Chen - University of California, Berkeley
Jin Chengjin - National Astronomical Observatories, Chinese Academy of Sciences
Jayanth Chennamangalam - West Virginia University
Jim Cordes - Cornell University
Louis Dartez - University of Texas at Brownsville
David DeBoer - University of California, Berkeley
Matt Dexter - University of California, Berkeley
Tom Downes - California Institute of Technology
Ran Duan - California Institute of Technology
Terry Filiba - University of California, Berkeley
Ricardo Finger - University of Chile

John Ford - National Radio Astronomy Observatory
Griffin Foster - University of Oxford
Jesús García - Ingeniería y Servicios Aeroespaciales
Isabel García-Rojo - Ingeniería y Servicios Aeroespaciales
Dale Gary - New Jersey Institute of Technology
David George - MeerKAT / SKA South Africa
James Gibson - San Francisco State University
Shelton Gnanaraj - GMRT, National Centre for Radio Astrophysics, India
Suraj Gowda - University of California, Berkeley
Lincoln Greenhill - Harvard University
Yashwant Gupta - GMRT, National Centre for Radio Astrophysics, India
Irappa Halagali - GMRT, National Centre for Radio Astrophysics, India

Dave Hawkins - Owens Valley Radio Observatory
Carl Heiles - University of California, Berkeley
Jack Hickish - University of Oxford
Gilbert Hsyu - University of California, Berkeley
Homin Jiang - Academia Sinica Institute for Astronomy and Astrophysics
Glenn Jones - California Institute of Technology
Zhu Kai - National Astronomical Observatories, Chinese Academy of Sciences
Michael Kandrashoff - University of California, Berkeley
Francois Kapp - MeerKAT / SKA South Africa
Kiril Karkare - California Institute of Technology
Jonathon Kocz - Swinburne University of Technology
Tom Kuiper - Jet Propulsion Laboratory

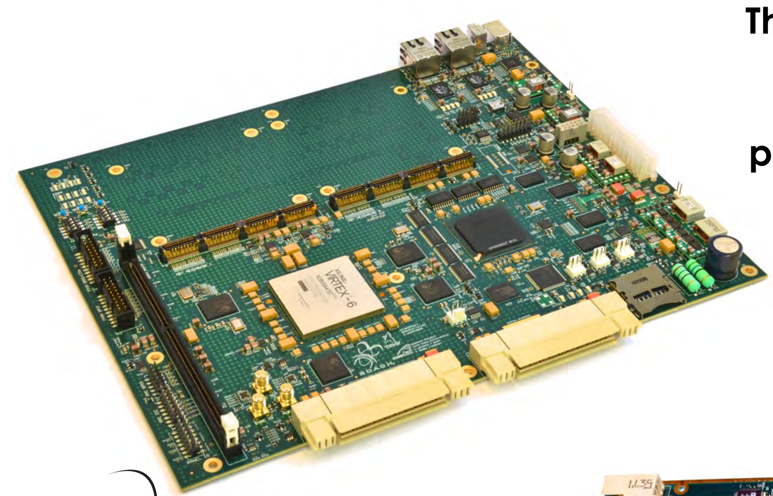
Ajith Kumar B. - GMRT, National Centre for Radio Astrophysics, India
Rich Lacasse - National Radio Astronomy Observatory
Glen Langston - National Radio Astronomy Observatory
Chao-te Li - Academia Sinica Institute for Astronomy and Astrophysics
Jon Losh - Massachusetts Institute of Technology
David MacMahon - University of California, Berkeley
Jason Manley - MeerKAT / SKA South Africa
Andrew Martens - MeerKAT / SKA South Africa
Shanly Rajan - MeerKAT / SKA South Africa
Andrea Mattana - Medicina radiotelescopes (INAF - IRA)
Ben Mazin - University of California, Santa Barbara
Sean McHugh - University of California, Santa Barbara

Peter McMahon - Stanford University
Guifré Molera Calvés - Aalto University Metsähovi RO, Finland
Mekhala Muley - GMRT, National Centre for Radio Astrophysics, India
Giovanni Naldi - Medicina radiotelescopes (INAF - IRA)
Robert Navarro - Jet Propulsion Laboratory
Wesley New - MeerKAT / SKA South Africa
Aaron Parsons - University of California, Berkeley
Danny Price - University of Oxford
Rurik Primiani - Harvard-Smithsonian CfA
Luis Quintero - National Astronomy and Ionosphere Center, Arecibo Observatory, Puerto Rico
Harshavardhan Reddy - GMRT, National Centre for Radio Astrophysics, India

Anish Roshi - National Radio Astronomy Observatory
Zac Rzesniowiecki - University of California, Berkeley
Simon Scott - University of California, Berkeley
Andrew Siemion - University of California, Berkeley
Laura Spitler - Cornell University
Melissa Soriano - Jet Propulsion Laboratory, Pasadena, CA
Matthew Stevenson - California Institute of Technology
Samuel Tun - New Jersey Institute of Technology
Joeri van Leeuwen - Netherlands Foundation for Research in Astronomy
Willem van Straten - Swinburne University of Technology
Mark Wagner - University of California, Berkeley
Melvyn Wright - University of California, Berkeley
Jonathan Weintroub - Harvard-Smithsonian CfA
Dana Whitlow - National Astronomy and Ionosphere Center, Arecibo Observatory, Puerto Rico

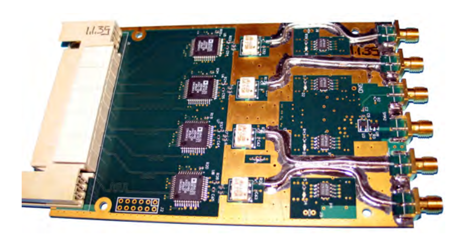
Robert Wilson - Harvard-Smithsonian CfA
Kristian Zarb-Adami, University of Oxford

Open Source Hardware and Software



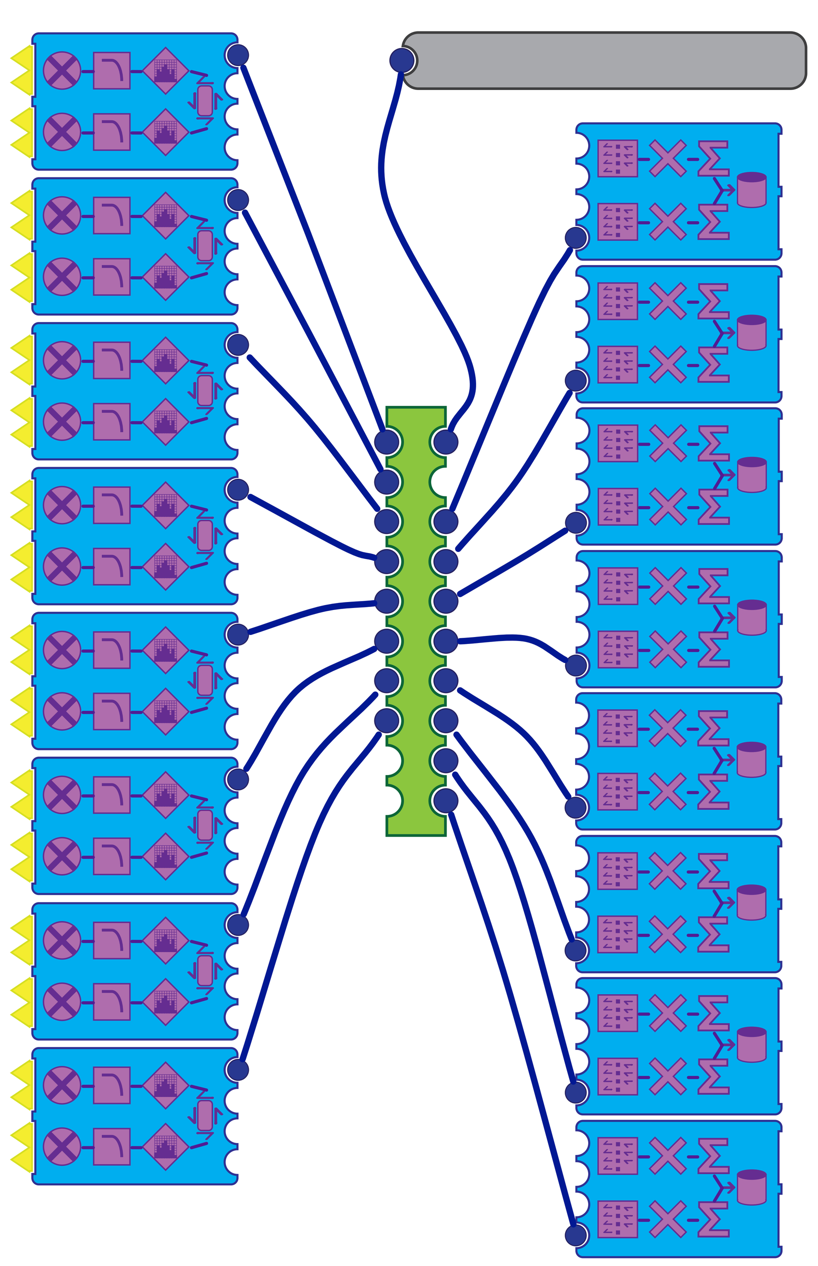
The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) is a growing community of scientists and engineers interested in developing hardware and software that enables the rapid, efficient and economical implementation of high performance digital signal processing. Although CASPER's original focus was on astronomical applications, the collaboration has now grown to include researchers tackling a variety of signal processing challenges in biotechnology, quantum computing and other fields.

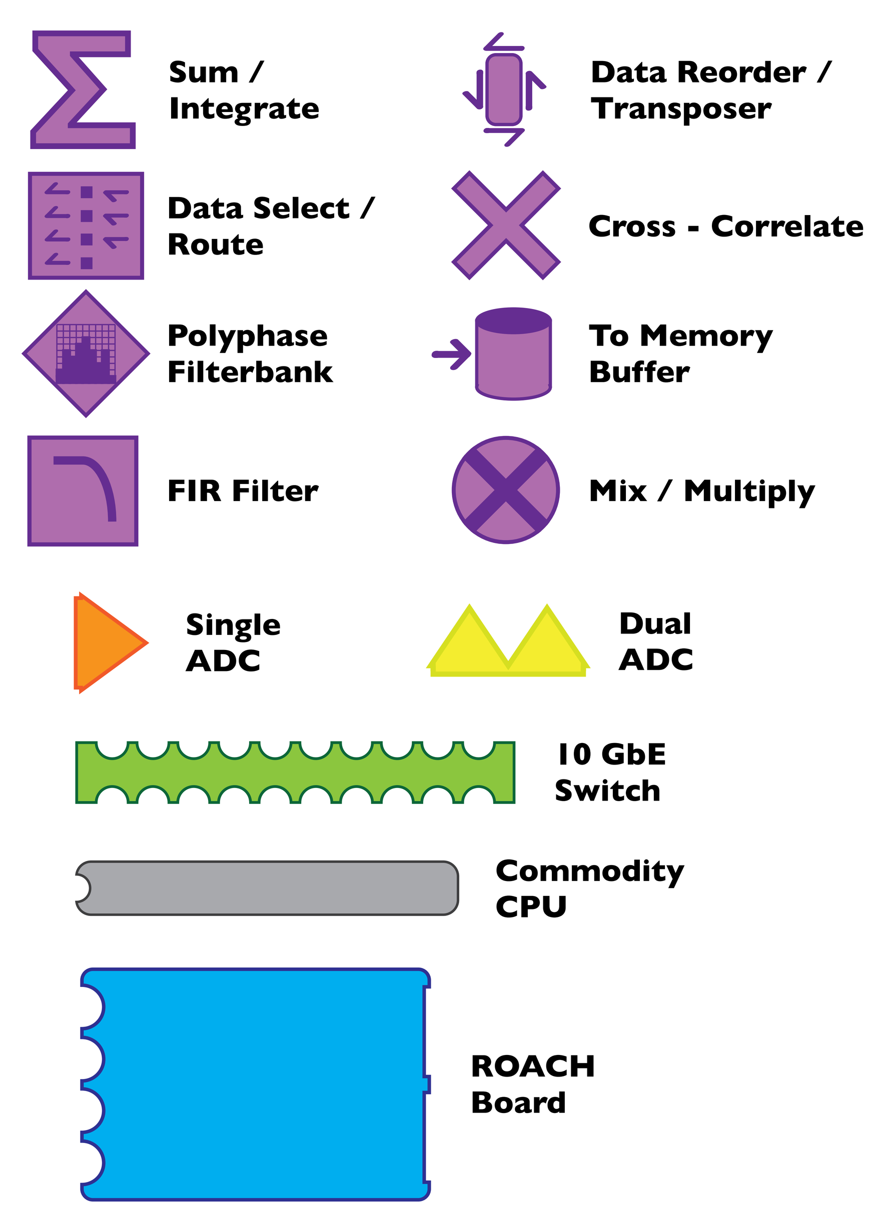
ROACH2



4 input x 250 megasample/sec analog-to-digital converter (ADC)

Pictured at left are two hardware components developed by the CASPER collaboration that represent fundamental building blocks of the CASPER approach to instrument design. The second generation Reconfigurable Open Architecture Computing board (ROACH II) is the latest of a series of field programmable gate array (FPGA)-based computing boards developed by CASPER collaborators. Though these boards are custom built, they feature common high-speed hardware interfaces and are programmed using a platform-independent graphical programming language (Simulink, see below). The 4 input analog to digital converter pictured is just one of nearly a dozen ADC and DAC boards ranging from 1 to 64 inputs and 64 megasample/sec to 6 gigasample/sec sampling rates that can be interfaced with CASPER boards. The ADC/DAC hardware interface has remained consistent from generation to generation, allowing digitization components to be reused and upgraded independently.



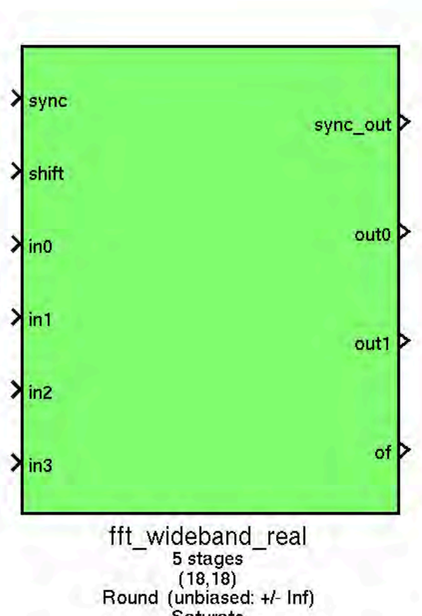


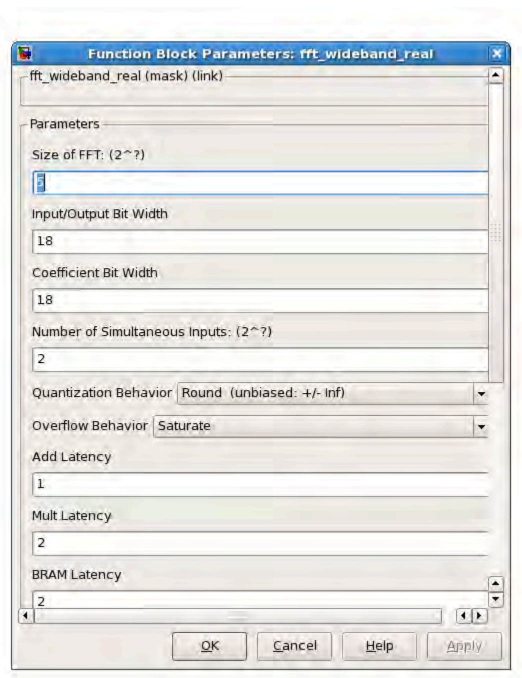
CASPER advocates a modular and scalable instrument design philosophy in which large instruments, such as the 32-input 'FX'-style correlator at left, are constructed from smaller generic building blocks. These building blocks can be dynamically programmed for a given task using a set of flexible, platform-independent 'gateware' libraries. These libraries can be used as the framework for many common signal processing applications and can be reused with little redevelopment on new generations of hardware.

Board-to-board communication is accomplished using industry standard protocols and cross-connect components, such as 10 gigabit Ethernet and commercially available Ethernet switches. Commodity compute components, such as CPUs or graphics processing units (GPUs) can be incorporated into an instrument by simply plugging them into an Ethernet network.

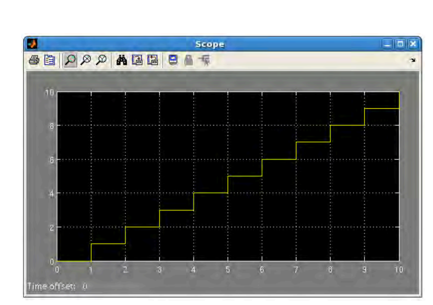
Command and control is performed through a standard Linux distribution running on each FPGA board, with FPGA memory mapped to Linux device files.

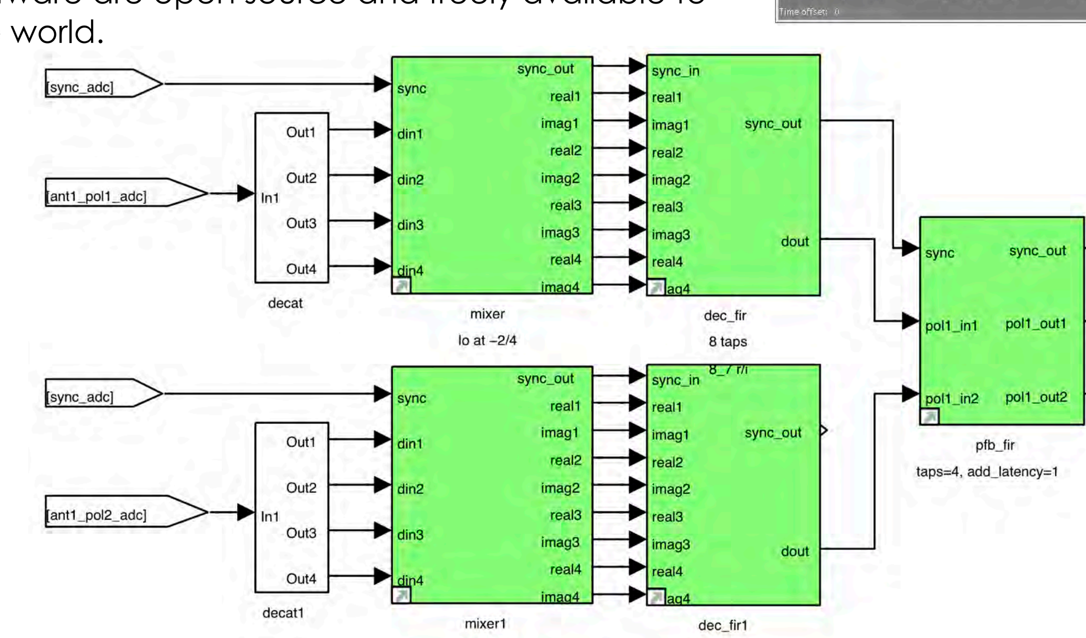
CASPER FPGA boards can be programmed using the Matlab/Simulink graphical programming environment. Complex signal processing libraries are constructed from primitive digital logic elements and are presented to an instrument developer via a high level parameterized interface. The Simulink environment also provides for clock cycle accurate simulations of hardware using simulated signal sources and software test instruments.



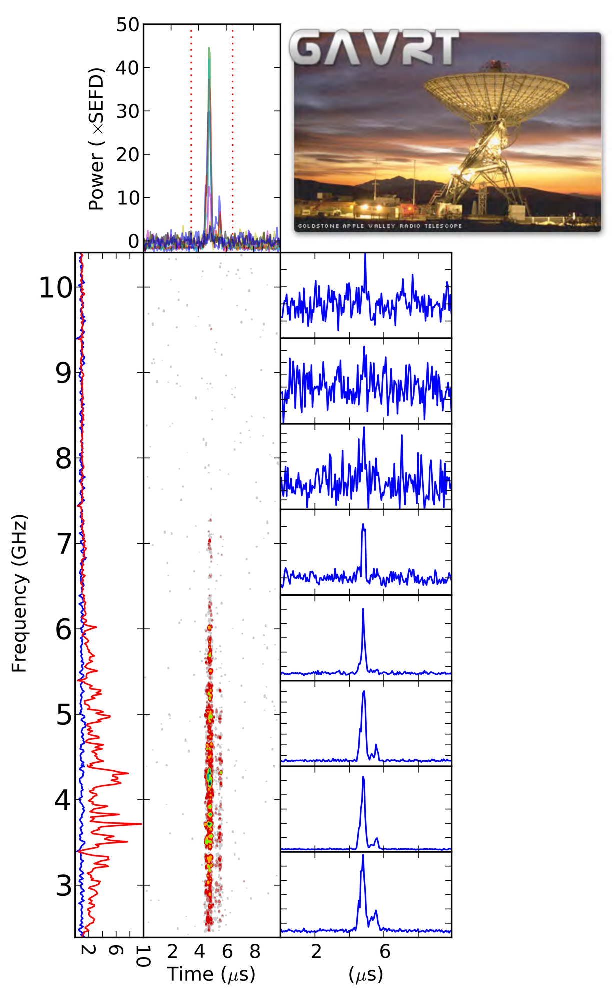


A graphical programming approach abstracts low-level hardware and opens up instrument design to non-specialists. Existing Simulink instrument designs can be shared, modified, recompiled and deployed on hardware in a matter of hours. All CASPER hardware, instrument designs and support software are open source and freely available to the world.

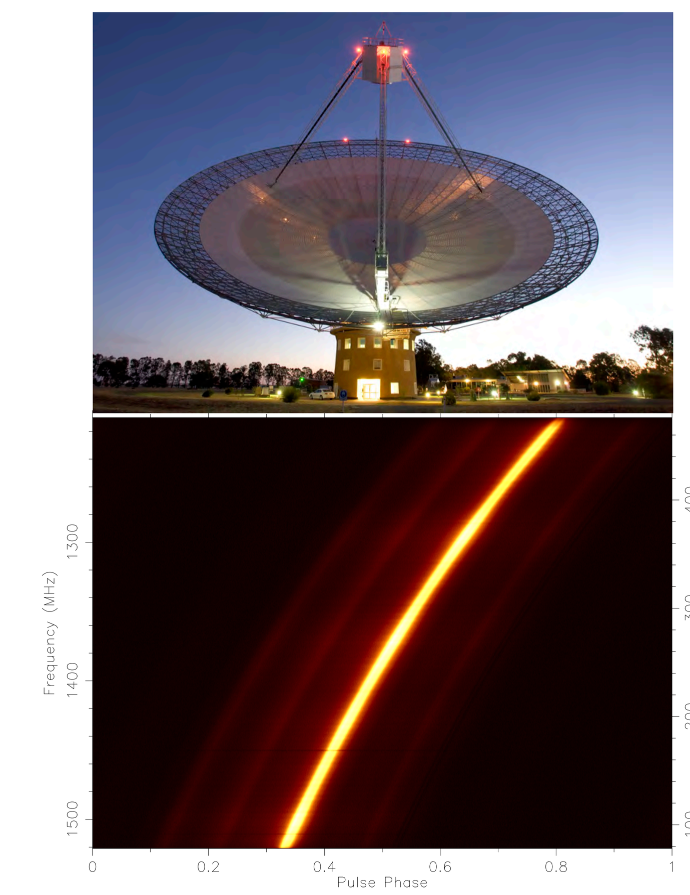




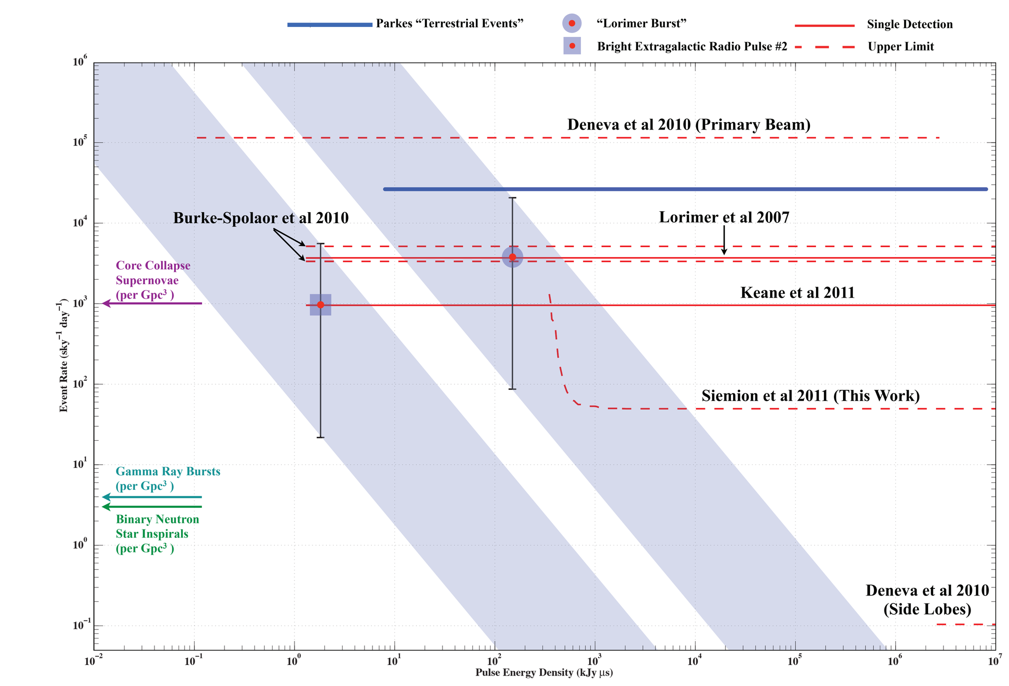
CASPER-Enabled Science



In a CASPER instrumentation effort led by Glenn Jones, the Goldstone Apple Valley Radio Telescope (GAVRT) has been equipped with a novel fast transient instrument capable of capturing snapshots of 8 GHz of instantaneous bandwidth. This system is being used to study an enigmatic source of fast transient radio emission, giant pulses from the Crab pulsar. The plot above shows a coherently dedispersed Crab giant pulse captured between 2 and 10 GHz.

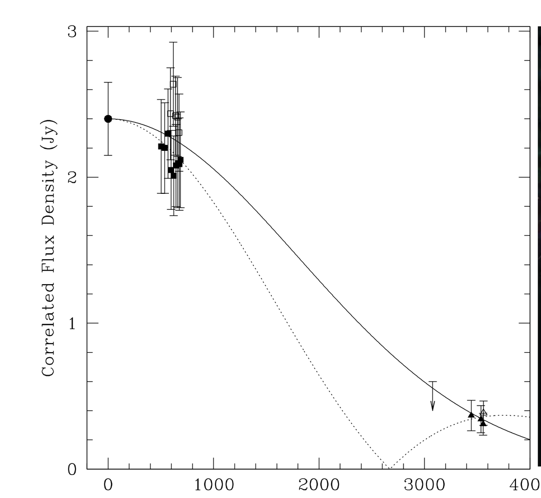


The Parkes Radio Telescope (above top) in south eastern Australia has long led the pack in the discovery of new pulsars, with more than 1000 credited so far. The current and next-generation pulsar spectrometers for the Parkes 13-beam receiver are constructed from CASPER components and incorporate a myriad of novel features, including real time interference excision. The plot above at bottom shows a folded profile of PSR J0437-4715, the brightest millisecond pulsar known, which was discovered in a Parkes pulsar survey.

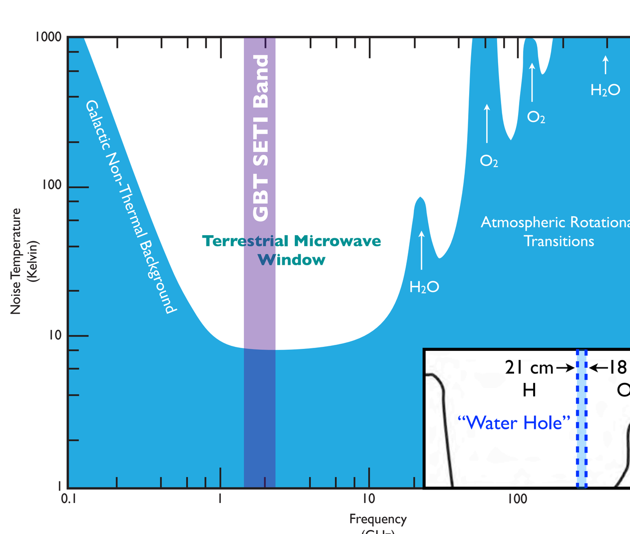


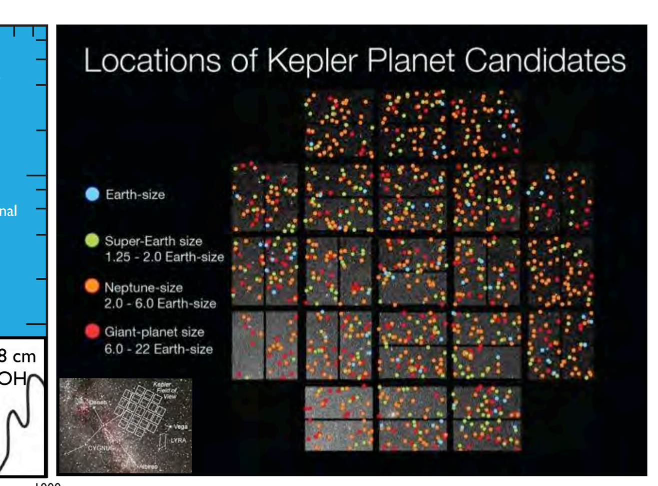
At the Allen Telescope Array (ATA), CASPER FPGA boards were used to construct the "Fly's Eye" fast transient search instrument, a 44-input spectrometer that processed signals from each ATA antenna separately. With antennas pointed independently, this mode of operation yields a total field of view of nearly 200 deg^2. The plot above shows the event rate limit for 10 ms pulses imposed by the Fly's Eye non-detection, as well as event rates for other recent single pulse surveys. Shaded bars on the Lorimer Burst and the extragalactic event described in Keane et al. (2011) represent 2 sigma confidence on a Euclidean isotropic distribution.

The seven radio dishes pictured above form the Karoo Array Telescope (KAT)-7 array, a technology demonstrator for the 64 dish MeerKAT SKA pathfinder. MeerKAT will offer an unprecedented radio surveying capability in the southern hemisphere, shedding light on a range of fundamental questions from general relativity to the nature of the most distant radio galaxies. The entire digital signal processing subsystem for both KAT-7 and MeerKAT is being constructed from modular CASPER components.

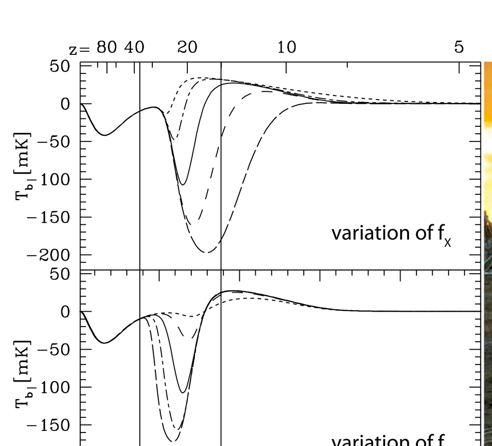


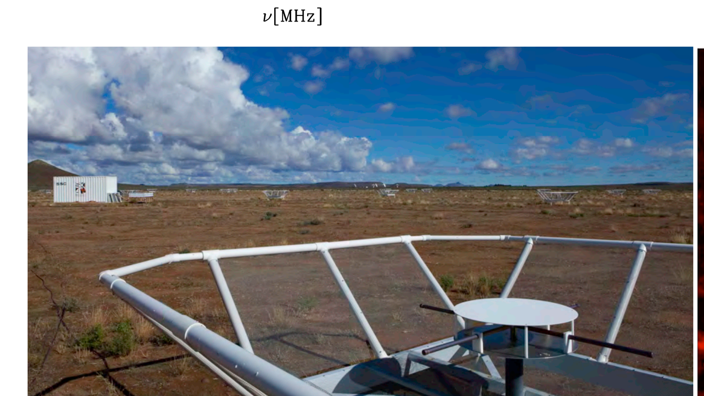
One of the richest and most active regions in our galaxy is the galactic center, home to a super massive black hole four million times the mass of the Sun. The highest angular resolution observations of the galactic center ever made use high frequency very long baseline interferometry (VLBI) employing CASPER instrumentation. In VLBI, radio telescopes from all over the world are combined (above right) to achieve an effective telescope diameter of thousands of kilometers. CASPER hardware and libraries implement the VLBI Digital Back End, which is used at each telescope to format and store 60 TB of single station data. Shown above left are correlated flux density data plotted against projected baseline length for the observations described in Doeleman, Weintroub, Rogers, et al, Nature 2008. The solid line shows the weighted least-squares best fit to a circular Gaussian brightness distribution, with FWHM size of 43.0 μas, or 37 μas compensating for smearing due to inter-stellar scattering. The dotted line shows a uniform thick-ring model with an inner diameter of 35 μas and an outer diameter of 80 μas convolved with scattering effects due to the interstellar medium. To achieve higher sensitivity, a key improvement is to phase up array telescopes locally before they are combined with other distant facilities. This 'beamforming' operation has now been implemented, also with CASPER techniques, at the Submillimeter Array (SMA) and at the Combined Array for Research in Millimeter-wave Astronomy (CARMA). See also the poster by Primiani et-al, JP1.11 Equipping the Submillimeter Array for VLBI.

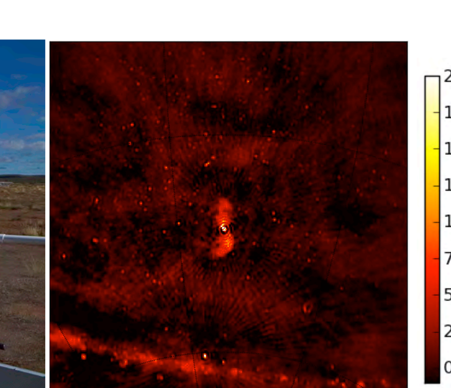




In early 2011, a group of astronomers and engineers from UC Berkeley, the SETI Institute and the National Radio Astronomy Observatory configured the Green Bank Ultimate Pulsar Processor (GUPPI) to record raw time domain data across a 800 MHz bandwidth in a search for engineered radio emission from extrasolar planets identified in the Kepler Mission. GUPPI is constructed from a combination of CASPER ADCs, FPGA boards and off the shelf GPUs. Pictured above left is the band recorded in this experiment, plotted against the so-called "terrestrial microwave window" - a range of frequencies that pass through both interstellar space and the Earth's atmosphere relatively unimpeded. Above right is a plot of the more than 1200 planet candidates identified so far by the Kepler Science Team.

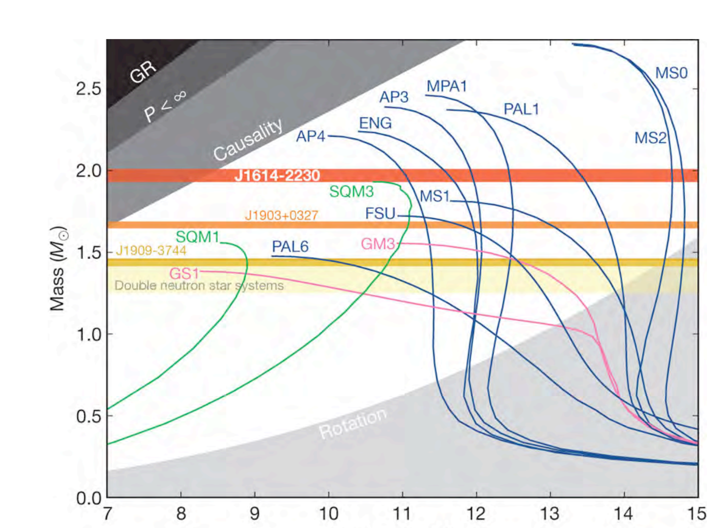






One of the most exciting forefronts in cosmology is the investigation of the very high redshift universe ($z > 7$) and especially the so-called 'dark-ages' ($6 < z < 50$) before the first stars and galaxies formed. This period is very difficult to probe, but 21 cm emission from neutral hydrogen may offer a rare glimpse in. At this moment, the race is on to detect the signature of reionization, the moment at which the cooled primordial hydrogen is ionized by the first stars. The figure in the upper left panel at left compares the expected signal assuming various theoretical models of reionization with the frequency band observed by the Large-aperture Experiment to Detect the Dark Ages (LEDA). Later investigations will push even farther back in the Universe's history. Ancillary science targets abound in the relatively unexplored low frequency regime, including solar physics, fast and slow transient events and low frequency sky mapping. The figure in the bottom right panel at left shows a 150 MHz total power map of a region surrounding the bright radio source Centaurus A produced by the Precision Array for Probing the Epoch of Reionization (PAPER) experiment.

The relatively simple appearance of the antennas used in these low frequency arrays (top right and bottom left, at left) belies the commensurate complexity in the signal processing systems required to assemble individual antenna signals into a cogent observation of the sky. The challenge of interferometrically combining signals from individual antennas scales with the square of the number of elements, which combined with the huge data rates involved (gigabytes/sec per element), rapidly necessitates very high performance hardware. Both of the experiments shown here are collaborating with CASPER to meet their signal processing challenges with modular and scalable open-source hardware and flexible, shared signal processing libraries.



Paul Demorest recently led a team of astronomers at the Narional Radio Astronomy Observatory in a measurement of the mass of a 2 solar mass neutron star - J1614-2230, the most massive neutron star known. This subtle Shapiro delay observation was made possible by the Green Bank Ultimate Pulsar Processor - a pulsar instrument made up of CASPER FPGA boards paired with off-the-shelf graphics processing units (GPUs). The plot above shows various possible equations of state for the very dense matter comprising neutron stars, indicating those models that have been ruled out based on this new observation.