Development of an 'all-digital' IF chain

Contact person: David Woody (dwoody@caltech.edu, 760-938-2075x111)
Caltech Owens Valley Radio Observatory, Big Pine, CA 93513

David Hawkins (OVRO), Don Backer (UCB), Dan Werthimer (UCB), John Carpenter (CIT), Nick Scoville (CIT), Phil Jewell (NRAO) and Paul Goldsmith (JPL)

1. Summary

Radio telescopes operate with high efficiency over many octaves of bandwidth and a reasonable goal over the next decade is to exploit this capability by developing receiver systems that can simultaneously receive and process the full width of the atmospheric transmission windows from 1 GHz up into the sub-millimeter bands. While current low noise frontend amplifiers and heterodyne receivers have ten GHz or more of instantaneous bandwidth, the conversion of the analog signal into bits for digital processing is a severe bottleneck in the signal and data path. We propose that future telescope receiver IF (intermediate frequency) systems will be 'all-digital', by which we mean that receiver analog signal processing will be minimized in favor of digital processing. Minimization of the analog processing can be achieved by using one or more ultra-wideband (high clock-rate) samplers to convert the entire receiver bandwidth to digital data streams. Network switches can be used to distribute the all-digital IF signal to multiple backend instruments for commensal observations supporting a variety of science projects.

Most observations through the radio, millimeter, sub-millimeter and even infrared bands that utilize coherent receivers can benefit from wider bandwidth samplers. Single aperture telescopes would be able to support wider bandwidth for each pixel in an imaging array and with multiplexed receivers simultaneously cover the full frequency range over which the telescope can operate. The continuum sensitivity and instantaneous spectral range for interferometer arrays would also be greatly increased. The initial development of a 5-10 GHz bandwidth sampler will immediately improve the productivity of many radio astronomy facilities and enable new observations that are not currently feasible. Subsequent development of even wider bandwidth samplers would match the projected increase in frontend bandwidth and backend digital signal processing over the next decade.

A large range of science becomes feasible when the processed bandwidth increases beyond ten GHz. The wider bandwidth improves both the continuum sensitivity and the spectral range. The wide instantaneous frequency coverage enables blind searches for redshifted lines, wide searches for new lines, simultaneous measurement of many lines and the determination of spectral indices using a single receiver tuning. The improved continuum sensitivity obviously improves continuum observations such as measurement of the SZ effect and mapping of small angular extent thermal sources.

Fortunately commercial companies have taken the lead in developing the chip sets necessary to digitally sample many 10s of GHz of analog signals with 8-bits of dynamic range. From the astronomy perspective the main development task is working with these companies to turn these chip sets into astronomically useful modules. In particular the modules need to incorporate large fast FPGAs to take in the continuous data at a rate of ~160 Gbps and deliver manageable data streams to the following signal processing units.

2. New science and instruments

SCIENCE

Here we highlights of a few science applications enabled by implementing all digital IFs utilizing ultra wideband samplers on existing instruments:

- *Formation of galaxies*
  Conventional redshift estimators from optical emission lines such as Lyα and Hα become increasingly inaccessible at z>7 (before the universe was re-ionized) from the intervening neutral intergalactic material and dust obscuration upon entering the cosmic "dark ages". Fortunately, at *z*=7–10, bright far-infrared atomic fine structure lines from [CII], [NII], [OI], and [OIII], are redshifted into the 1 mm observing window. Even with such bright lines, it is not possible to perform "blind" redshift searches to identify these distant systems since the limited bandwidth of current millimeter-wave receivers (on the order of 2 GHz) corresponds to only Δz/z=0.03–0.05 at *z*=7 for the 158 um [CII] line. Blind redshift surveys with a wideband correlator will become vital once future far-infrared to (sub)millimeter bolometers identify candidates galaxies at *z*>7 in large numbers.

- *Molecular evolution of galaxies*
  Multiple molecular line tracers are essential to understanding the physical properties (such as gas masses, densities, and temperatures) and chemical composition of star forming regions. With the current bandwidth of millimeter-wave receivers, it is already possible to detect two molecular lines within one correlator setup. Fig. 1 shows a model spectrum for a *z*=3.91 galaxy that demonstrates that a single frequency setup can detect ~ 30 lines simultaneously, even for galaxies at *z*>4, with a wideband (10 GHz per sideband) correlator. Such broad-band millimeter observations would bring studies of galaxies out to high-z from single line detections to the degree of complexity that is currently only possible in few, bright regions within our own galaxy.

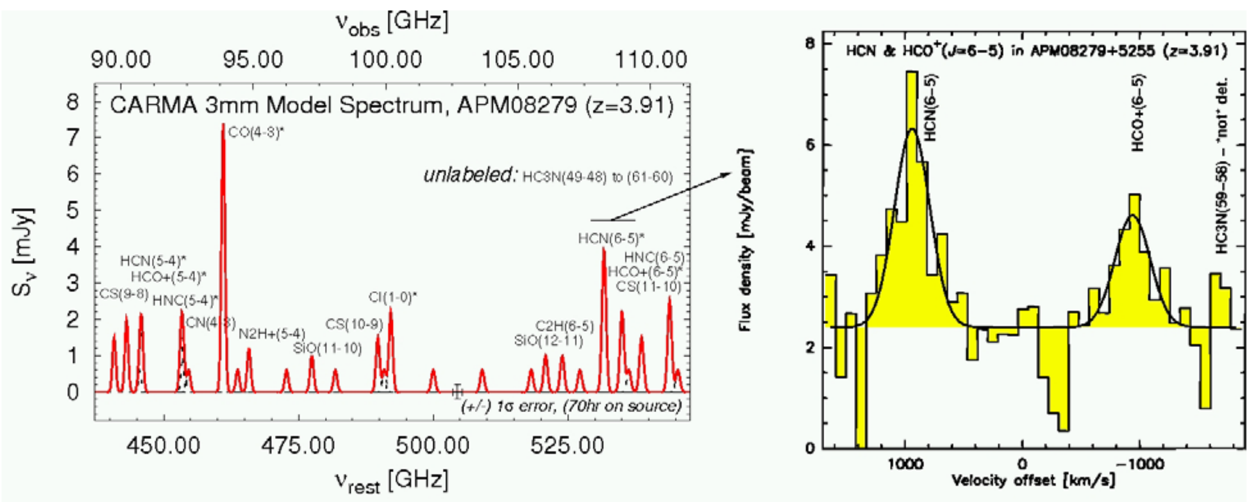

Figure 1: CARMA observations (right) and broadband model spectrum (left) of the *z*=3.91 galaxy APM 08279+5255. The model spectrum is over a 20 GHz region as obtained with 70 hr on source with CARMA. For the potentially bright molecules, 28 transitions fall into the band shown—ideal for a molecular line survey. The right panel shows a portion of this spectrum as observed with CARMA. The HCN and HCO+ J=6-5 lines are clearly detected (Riechers 2009).

- *Origin of the stellar Initial Mass Function*
  Stars form in dense ($n > 10^5$ cm^{-3}), cold ($T < 15$ K) and compact (radius ~ 0.1 pc) cores in nearby molecular clouds. The stellar initial mass function (IMF) that emerges from these cores has a characteristic shape (Salpeter 1955, Miller & Scalo 1979) that holds over a wide range of metallicities and stellar densities (Kroupa 2002). Establishing the underlying physical processes that cause the IMF to be invariant with environment, at least in the local universe, is a crucial step in the quest to understand the formation of stars. A test of the possible link between the core and stellar masses is to determine if the core mass function continues to decline into the brown-dwarf mass range (< 0.08 $M_\odot$) as does the stellar IMF. Sensitive, high-resolution, interferometric imaging is essential to isolate such low mass cores and extend the clump mass function to the brown-dwarf limit (see Fig. 2). Digitizing and processing the full 16 GHz (8 GHz in each sideband) available from the current receivers on the CARMA spectrometer will enable CARMA to achieve the necessary sensitivity to measure the core IMF in nearby molecular clouds below the hydrogen burning limit.

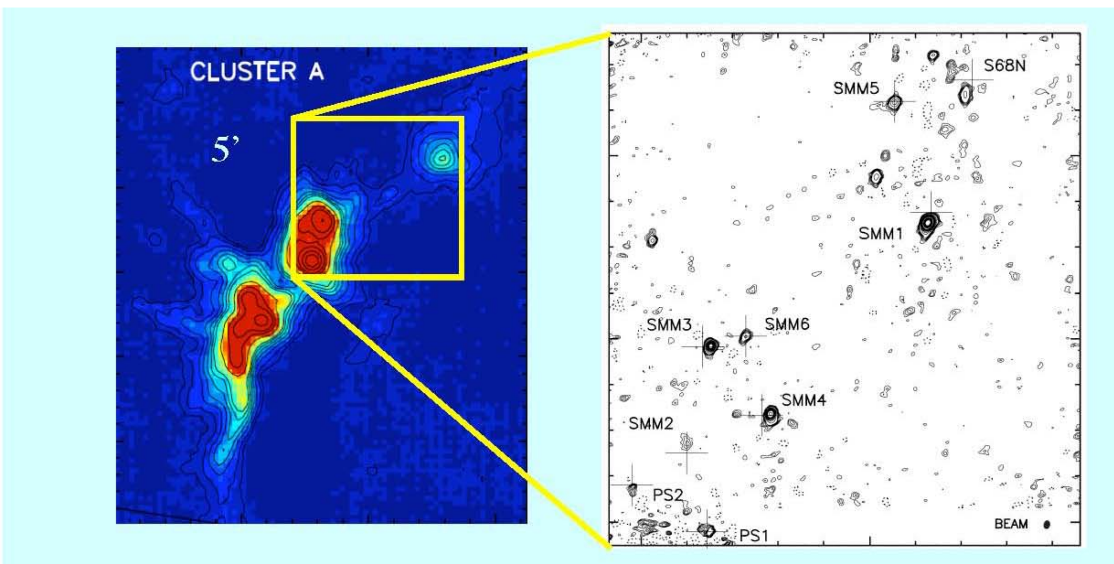

Figure 2: Continuum images of the Serpens cloud core, which contains a dense cluster of protostars. The left panel shows a λ1.3 mm continuum image at 35" resolution (Enoch et al. 2007), and the right panel is a λ3mm continuum mosaic (5' x 5' in size) at 5" resolution observed with the OVRO interferometer (Testi & Sargent 1998). High-resolution observations with CARMA, combined with the wide continuum bandwidth, will enable the mass function of dense cores to masses below the hydrogen burning limit.

- *Particle growth in circumstellar disks around young stars*
  The slope of the millimeter spectral energy distribution is a sensitive diagnostic of dust grain size. Observations of circumstellar disks around young stars suggest that dust grains have grown to centimeter-sized particles (Rodmann et al. 2006), a necessary step in the planet formation process. However, spatially unresolved data cannot disentangle grain growth and variations in the dust opacity (e.g. Beckwith et al. 1991). High resolution continuum images with interferometers such as CARMA, EVLA, and ALMA over broad bandwidths will yield accurate measurements of the continuum slope as a function of disk radius in circumstellar disks around stars spanning a range of ages. These observations will reveal the timescales for particle growth and the radial behavior of growth within circumstellar disks.

INSTRUMENTS

Ultra-wideband samplers will enable the development of new radio astronomy instruments. For example, while it is very attractive to exploit the stability of interferometry to probe the first instants of the universe by fully characterizing the polarization of the cosmic microwave background (the polarization was first detected with the DASI interferometer), an interferometer employing hundreds if not thousands of elements and processing tens of GHz of bandwidth would be required. The interferometer elements are small and could be reproduced, but the N^2 increase in correlation power has been prohibitive. An ultra-wideband sampler followed by wide-channel FPGA based correlators would make such large interferometers possible [see Astro2010 technical white paper on “Digital signal processing”]. The large fractional bandwidth for interferometers very effectively fills in the UV-plane sampling for continuum observations on small and modest sized arrays which greatly improves the image fidelity and dynamic range.

Other non-CMB future developments include simultaneous multi-beam correlators for interferometers, as well as broadband, inexpensive spectrometers for large format focal plane arrays on single dish telescopes such as the Greenbank Telescope [see Astro2010 technical white paper on “Coherent Detector Arrays for Millimeter and Submillimeter Astronomy” by Paul F. Goldsmith]. Single aperture correlation receivers can also be improved by digitizing the signal after the “magic tee” and parallel amplifiers and digitally recombining the two signals to form the desired difference or correlation signal. This greatly reduces the difficulty in achieving matched circuitry over wide bandwidths.

The improved continuum sensitivity also pays off in improved data quality since pointing and calibration will be possible using weaker sources closer to your science target. The increased continuum sensitivity resulting from larger bandwidths also makes if feasible to use a parallel array of paired antennas to continuously measure and correct for the atmospheric delays fluctuations over an interferometer array [see Astro2010 technical white paper on “Atmospheric delay correction”].

Successful development of a continuous sampling wide bandwidth module could also change how other disciplines collect and analyze their data. Instead of using oscilloscopes with triggers that cost upwards of $100k and capture a very small fraction of the data, a more affordable module that captures all of the data and provides a platform for custom processing will enable entirely new measurements. The test and measurement equipment field is moving towards a model of making instruments based “general purpose” wideband sampler modules followed by specialized signal processing software to produce spectrum analyzers, oscilloscopes, vector signal analyzers, etc. (Hunter 2009). The kinds of fields that may be affected are transient chemical reactions studies using time resolved spectral analysis, cosmic ray showers, single photon detection studies, etc.

The multiple pixel readouts for the next generation of bolometer detectors that utilize frequency multiplexing to read many pixels using only one analog readout channel should also benefit. With enough sampled bits and oversampling the large array of analog and digital processing cards could be replaced with a single sampler module and embedded software. Even narrower band signal analysis benefits from wideband samplers because of the increased dynamic range available when the analog signals are over-sampled.

3. Current capabilities

The instantaneous bandwidth available from low noise coherent detectors used for high-resolution spectroscopy and by interferometers has steadily increased over the years. Broadband low-noise MMIC amplifiers are now available with more than 20 GHz of bandwidth from 500 MHz to above 100 GHz (Grundbacher et al. 2002). The MMIC amplifiers currently used for observations in the 3 mm band cover 75 to 115 GHz with 40 GHz of bandwidth (Erickson et al. 1999, Muchovej et al. 2007). At higher frequencies SIS heterodyne mixers provide the best performance. The instantaneous sky, or radio-frequency (RF), bandwidth of these mixers can be nearly half an octave in frequency while the receiver output, or intermediate frequency (IF), bandwidth is ~10 GHz when wideband MMIC amplifiers are used for the IF (Lamb & Plambeck 2008, Pan et al. 2004, Padin et al. 1996). In addition radio astronomy receivers often receive both polarizations, doubling the bandwidth to be processed. Single aperture telescopes easily support arrays of receivers such as the 32-pixel SEQUOIA focal plane array (Erickson et al. 1999) further increasing the needed processing bandwidth. The developments that produced these excellent receivers are likely to continue and even more bandwidth will be available for processing.

Existing systems utilize samplers with ~2GHz of bandwidth or less. CARMA baseband is 0.5-1.0 GHz sampled using ~1 GHz bandwidth samplers. ALMA and the EVLA sample 2 GHz of bandwidth using samplers clocked at 4 GHz. There are many systems operating with much narrower bandwidth samplers.

Larger processed bandwidths are implemented using multiple downconverters to convert the wideband signals to baseband. Although this approach has been successful, systems with bandwidth greater than ~10 GHz are not practical because of the complexity and cost of the analog downconversion components of the system. The band to band calibration and spectral shape effects are also worse when multiple samplers are used for the downconverted bands.

Special purpose instruments have exploited the wide bandwidth from the frontends using analog detectors for total power detection, coarse analog lag spectrometer [Harris et al. 2007] and analog cross-multipliers [Padin et al. 1991, 2001]. These systems have also been successful for their particular projects but they are not general purpose techniques.

One area where the capability steadily increases without the necessity of making fundamental breakthroughs is the digital logic. The processing power of digital chips continues to follow Moore's law. The I/O bandwidth and logic density of the new generation of FPGAs (field programmable gate-arrays) can now handle the huge data rate generated by an 8-bit 20-GSps sampler. The spectrometer and correlator backend capability will correspondingly increase with each new generation of digital electronics. The CASPER group has been very successful at exploiting these advances for use by a wide range of astronomy teams [see Astro2010 technical white paper on "Digital signal processing"].

4. Development tasks

Two developments make a new generation 10-GHz or wider bandwidth samplers viable for radio astronomy application. One is a new generation of commercially available Track-and-Hold amplifiers (T/Hs) that can sample multi-Gigahertz wide signals. Several T/Hs and slower ADCs can be combined (phased) to produce a much wider bandwidth ADC. This is the technique used to achieve the very large bandwidth in high performance oscilloscopes and test equipment. Sampling of a 10-GHz bandwidth signal using an 8-bit 20-GSps ADC generates a data stream of 160 Gbps. The other development is the availability of very large FPGAs that can accept and process these large data rates.

The most efficient approach for developing wideband samplers is to work with the commercial test instrument companies to adapt their ADC chip sets to the stringent astronomical requirements. These companies have already undertaken the expensive and difficult task of developing the chips and several companies have already expressed interest in working on this project.

Exploiting the full capabilities of these front ends requires that the full instantaneous bandwidth be processed. Commercial companies such as Agilent, Tektronix and LeCroy continue to increase the sampling bandwidth of their test and measurement equipment well beyond 10 GHz bandwidth. The special chip sets these companies have developed for their test equipment have the capabilities needed for astronomy applications but significant effort is required to combine the sampler chip sets with the largest and fastest FPGAs to produce a sampler module that can be used in astronomical systems. There is an "engineering effort" Moore's law that goes along with the Moore's law for the increase in capability that has moved the magnitude of the development effort beyond what can be accomplished in the typical small instrumentation group. A focused development effort is required that can then be shared with the whole astronomical community.

Astronomical applications require continuous sampling and processing of the huge bandwidths whereas the normal commercial applications only collect, display and analyze short bursts of data. This requirement imposes severe constraints on the system architecture and the first level of digital filtering and processing. Processing these data directly into final spectra or cross-correlation in a single or few FPGAs is prohibitive. A promising technique is to filter the wider bandwidth signal into multiple sub-bands, and then send the sub-band data to identical band processing sub-systems similar to the technique used for the 2-GHz wide signals processed by the Wideband Interferometric Digital Architecture (WIDAR) correlator being built for the EVLA (Carlson & Dewdney 2000). This reduces the data rate seen by each sub-band.

There are other unique requirements for astronomical use of the fast ADCs. The timing issues for use in interferometers are also more severe than required for commercial test equipment. Weak signal detection also requires extremely low spurious signal levels and special modes to achieve radiometer noise limited noise floors after many hours or even days of integration. The demultiplexed data from the samplers will be fed to several parallel signal processing boards. The envisioned astronomical systems will utilize many, maybe even hundreds, of these wideband sampler modules so the packaging, power supplies and signal distribution must be designed so that many sampler modules will fit in a crate and many crates will fit into a rack.

The goal for the development effort should be to provide essentially generic sampler hardware with FPGAs that can be reconfigured for use for many different observatories and projects.

5. Effort required

The development effort required to keep up with the commercial developments of state of the art digitizer chip sets and produce sampler module satisfying the stringent astronomical requirements is relatively modest. **A team of three or four top quality engineers** with expertise in the fields of analog electronics, high-speed digital design, FPGA programming and embedded systems should be able to produce a new generation of sampler modules in about three years. This would be a continuing effort with each generation doubling the bandwidth and capability. The **equipment and materials cost is expected to be $200-400k per year**. The total cost over ten years is **~$9M**.

After a decade of effort the team should have three new generations of samplers and have prototype **8-bit samplers with 20 GHz bandwidth and 40 Giga-samples per second that could enable a variety of important astronomical discoveries**.

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