RASDR 2062: 200 Years of Receiver Evolution[1]

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ABSTRACT

Decades of experimental studies led physicist James Clerk Maxwell to formulate the theoretical foundations of electromagnetic energy in 1862. Thirty years later, another physicist, Henrich Hertz, demonstrated radio transmission and reception and initiated an era of Hardware-Defined Receivers (HDR). Receivers in the span of 150 years evolved from having a design focus in hardware, to a design focus in software, as Software Defined Receivers (SDR) began a 20-y rise to dominance. The SARA development of an SDR that is optimized for Radio Astronomy, RASDR, consists of a minimalist front end and a software-driven user-defined desktop computer back end. This software-rich back end performs the signal processing required to cope with different types of modulation and to resolve/present low S/N data. RASDR is functioning in benchtop mode with multi-modulation detection capability from 0.0001 to 3.84 GHz. Current RASDR software, RASDRWin, performs some basic parameter optimizations, but the SDR software is basically static within an observing session. Current RASDR hardware consists of a benchtop developmental device (RASDR 0) and (with collaboration from the RASDR team) two versions of software-compatible commercially-produced versions, (RASDR 2). A developmental board of the Nuand bladeRF has been received, while commercial versions of bladeRF and the Myriad DigiRed hardware are expected to be received by the RASDR team in late June, so they will be available for inspection and a possible demo.

Beyond the SDR design focus lies the Algorithm Defined Receiver (ADR) in which software will evolve based on signals detected and project goals. Project goals will eventually relate to radio astronomy research. Currently they are not now driven by scientific considerations but by military and commercial interests. Recent DARPA design challenges, cryptoanalysis applications, and multi-million dollar prizes offered by commercial interests and claimed by dedicated software groups now dominate algorithm development.

RASDR 2062 will be an ADR that copes with changing signal structures, interference from natural and other sources, and the probable detection of new forms of signal modulation that arise frequently in

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basic research and that may be found in SETI (Search for Extraterrestrial Intelligence). Such applications require an ADR defined by evolving software having a flexible, purpose-driven algorithm structure.

Introduction

Radio communication is the transfer of information between complimentary instruments (transmitter and receiver). The design of these instruments has been an engineering process that balances required information decoding and transfer rate vs. system complexity and cost. The transmitter must provide sufficient power while its antenna provides sufficient directionality and gain. The receiver antenna must be engineered with similar considerations (excepting power-handling capability) to that of the transmitter antenna. Furthermore, the receiver must provide sufficient sensitivity, selectivity, and noise rejection. The receiver, from the information-handling perspective, has more often been the more complex instrument. It must detect and demodulate the signal, reject interference, and convert the signal to data.

The span between the nineteenth to late twentieth century saw the evolution of HDR (Hardware Defined Receivers), both in component capability and in signal complexity. The end of the twentieth century saw a major shift in engineered design from HDR to SDR (Software-Defined Receivers). Even though the SDR uses massive backend hardware (a computer), the computer is more often regarded as a generic tool where the unique program is executed.

This paper will discuss and give examples of this change from HDR to SDR, exemplify development of a low-budget SDR (e.g., RASDR), and chart the beginnings of the algorithm defined receiver (ADR). This development is already underway in well-funded military and economic circles.

This discussion is part of our RASDR research effort. The Radio Astronomy Software Defined Receiver (D. Fields, SARA Board Supports RASDR Project 2011) (RASDR) is a project by SARA members to develop a very low cost high performance software defined receiver for use by SARA members and others. A minimal amount of SARA funding was provided by the SARA board to allow the creation of a breadboard model using an evaluation board from Lime Microsystems for the RF and Analog to Digital Conversion (ADC) sections. The breadboard RASDR 0 operates between 100 KHz to nearly 4 GHz. The project has been reported on in previous Journal Articles (Oxley, et al. 2013) and previous SARA proceedings (B. Vacaliuc, et al. 2012). At the time of preparing this paper, we hope to offer two presentations and a poster at the 2013 meeting. These presentations are the following:

- **RASDR 2062: 200 Years of Receiver Evolution**
- **RASDRWin Software Update: Operation Under Windows Control**
- **A Tale of Two Receivers: BladeRF and DigiRed are high-performance RASDR 2 receivers for radio astronomy use**

The thesis of this paper is that the successor to SDR will be the Algorithm Defined Receiver (ADR), in which the receiver evolves its own software for signal detection, demodulation, and information extraction. SARA projects using RASDR are one step along this developmental path.

The advent of Hardware Defined Receivers (HDR)

The twentieth century was the era of hardware-defined communications. As shown in Fig. 1, the progression from receivers consisting of simple loops to those with functionality defined by hundreds or thousands of components is a series of milestones associated with the work of major physicists and engineers. These milestones consisted of hardware -- components and systems of components that provided analog functionality. Among this hardware were oscillators, detectors, modulators, amplifiers and mixers.

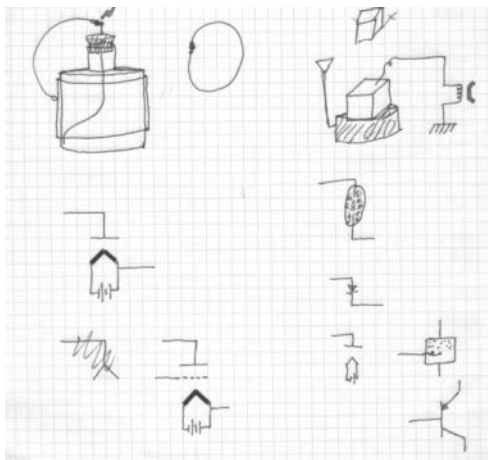

Figure 1. Some significant hardware innovations of the late 19th and early 20th century included spark transmitters and receivers, coherers, and a variety of vacuum and semiconductor devices.

The earliest manmade radio transmitters were Hertzian loops and spark gaps (Hertz 1893). A significant increase in receiver sensitivity resulted in the addition of antennas and the invention of the coherer detector by Branly (E. Branly, Variations of Conductivity under Electrical Influences. Minutes of proceedings of the Institution of Civil Engineers, 103(481) 1890) (E. Branly, On the Changes in Resistance of Bodies under Different Electrical Conditions 1891) (E. Branly 1892). In the hands of careful physicists such as Tesla who employed tuned receivers, large antennas, and biased coherers, these devices could be made to amplify and detect very weak signals (Fields and N.Tesla 2011) (Fields, Kennedy and Roy, Interplanetary Radio Transmission through Serial Ionospheric and Material Barriers 2011).

The use of long wire antennas and higher power spark generators by Marconi and others demonstrated practicality of long range transmissions (The Clifden Station of the Marconi Wireless Telegraph System 1907) (Guglielmo Marconi 2012) (Nobelprize.org. Guglielmo Marconi. The Nobel Prize in Physics 1909 2013). Coherer detectors were laid aside as the ability of tube and crystal detectors to detect complex modulation became appreciated. The importance of Fessenden's benchmark work with mechanically-generated (analogue) signal transmission was described by White (White 1996).

Amplifying hardware other than a few designs based on coherers and magnetic systems, sensitive detectors, and oscillators those extending to higher frequencies, were based on tube and transistor hardware, designs of which were widely applied throughout the twentieth century. The first tube designs were credited to Flemming (Fleming Valve 2013) and DeForest (DeForest 1906) while transistor designs stemmed from the early field-effect devices pioneered by Lilenfeld (Lilenfeld 1930) in 1925 and developed in point-contact configuration in 1947 by William Bradford Shockley, John Bardeen and Walter Houser Brattain (Shockley, Bardeen and Brattain 1956)

Throughout this seminal period, there were advances both in hardware and in information processing techniques, but in all cases, hardware (components) were used to demodulate and process the signals. Until the last quarter of the twentieth century, hardware was 'everything'.

In Hardware Defined Receivers, the hardware (except for some early experiments)was understood to apply to analog signal processing. Digital processing entered receiver design in the last quarter of the century in the form of special-purpose chips. But by the last decade of the century, increasing logic gate density (growing exponentially in accord with 'Moore's law', shown in Fig. 2) made possible the rapid execution of complex software, and the radio frequency hardware ceased to be the primary focus of receiver design.

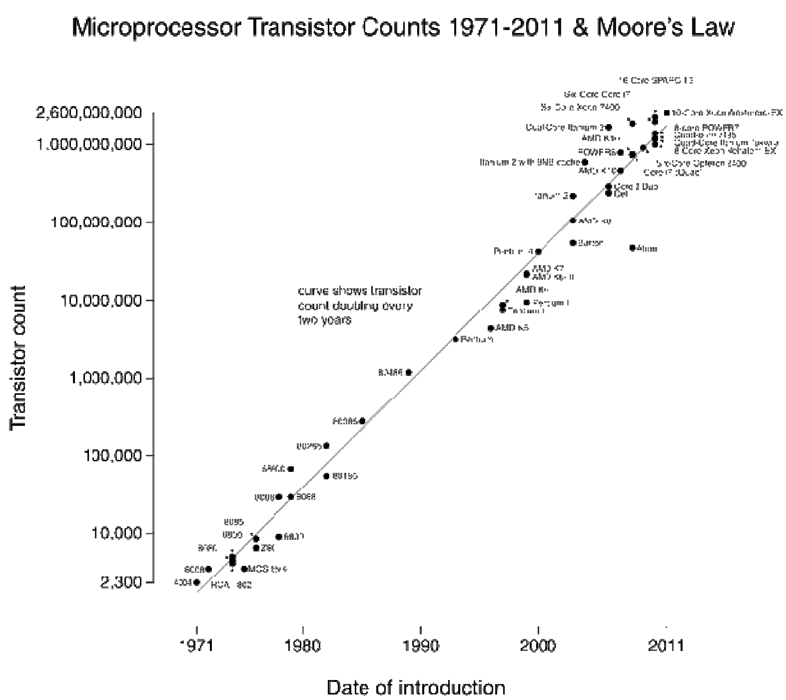

Figure 2. Logic gate density has doubled each 20 years, shifting the focus in receiver design from front-end hardware to back-end software (Wikipedia n.d.).

Hardware Defined Receivers were dominant throughout most of the twentieth century. The last decade of the twentieth century saw the advent of software defined receivers. Evolving complex software provided capabilities of flexibility, compactness, and reduced cost that shifted the focused to the processing "back end" of the receiver. In HDR, the hardware was the focus. In the new receivers, called Software Defined Receivers (SDR), the software structured the digital information flow.

Advent of digital processing

Signal processing in the analog domain (circuit) uses function defined by hardware. The hardware implements analog approximations of precise mathematical functions. If this processing is done in the digital domain (software), then mathematical accuracy is more exact. Processing concepts, both simple and complex, that have a valid theoretical foundation, can be coded in software and applied in a more robust fashion.

In the last two decades of the twentieth century, demodulation and limited processing functions moved into the digital domain, as microprocessors were used to process the signals. Digital Signal Processing (DSP) was the first mathematical manipulation of signals to modify or improve the received data. Digital filtering involved linear transformations of the signal, while Fourier transforms permitted transformation of received signal from the time-domain (a series of analogue values or pulses) to the digital-domain (a plot of signal power vs. frequency). The components that may be simulated in SDR software includes detectors, mixers, filters, amplifiers, and demodulators.

Ascendency of software-defined receivers (SDR) over HDR

The situation a the end of the twentieth century was that hardware devices were being produced with the momentum of assured performance and a robust manufacturing industry – but that the flexibility that would be accrued by a software defined receiver (in which functions were defined by digital algorithms) was obvious. The cost curve was to the benefit of Software Defined Receivers (SDR). Of course, even in the SDR, the 'front end' amplifiers, filters, and digitizer circuits, were still hardware-based.

The earlier in the signal stream that the analog to digital conversion occurs, the earlier can be applied the flexibility and precision offered by digital processing.

Digital procession had the firm foundations of Information Theory giants such as Nyquist, Shannon, Whittaker. Digital processing of a frequency F was only possible with sampling at a frequency 2F or higher (the Nyquist criterion). Thus SDR was also driven by the availability of high-speed sampling hardware and high-speed processing. SDR was only possible with the advent of fast computers, and SDR availability and applications have closely tracked the development of high-speed back-end processors.

As stated earlier, SDR is based on hardware, but it is defined by the software. SDRs use an analog front end, a digital interface and a back-end computer that can be functionally reprogrammed for a variety of projects. Figure 3 shows one variation of a SDR.

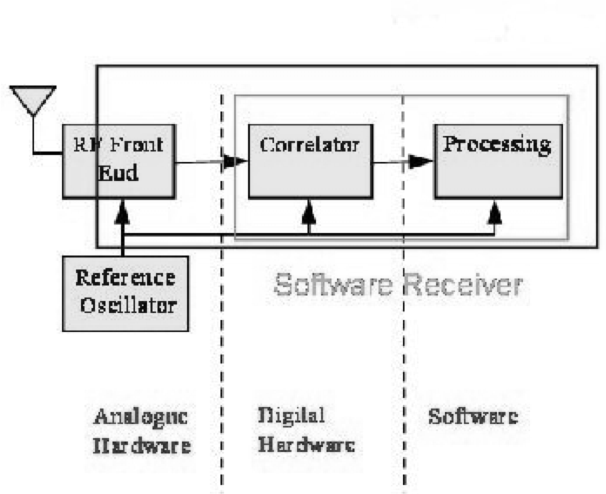

Figure 3. Block diagram of a simple software-defined receiver. The processing shown accepts records that are time-synced to the local oscillator, and subsequent processing, analysis and presentation may be performed by a desktop or work station.

Operational wide-bandwidth SDR designs may be significantly more complex, as shown in this functional diagram for RASDR:

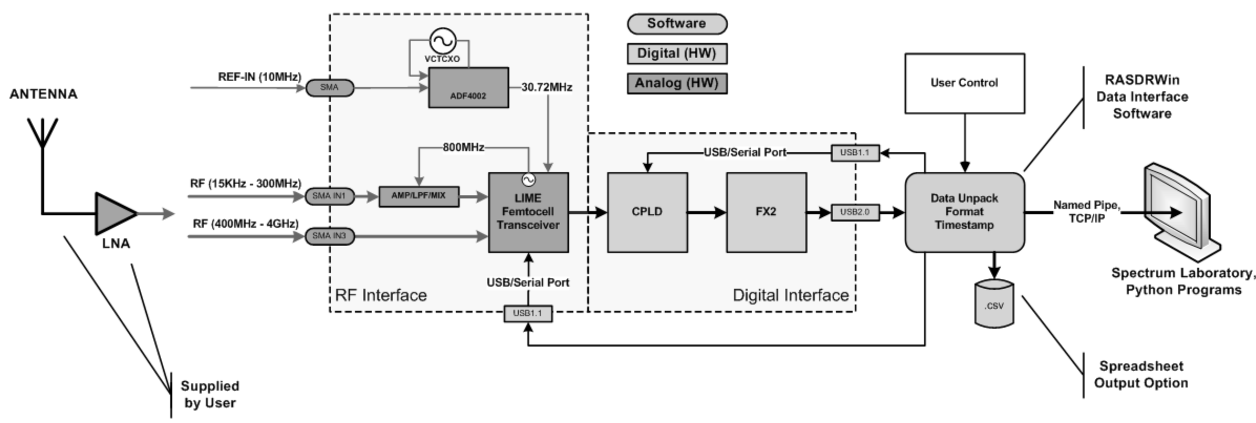

Figure 4. Functional diagram of the RASDR SDR.

Goal-driven software – The Algorithmic Approach

Goal-driven software approaches are making the first inroads in business and military arenas. Driving the competition for successful algorithms are financial success, military conquest, and lucrative prizes. These approaches are extensions of optimization programs that determine operating functions of complex systems (Fields and Watson, OPTRM -- A Hydrologic Transport Model with Parameter Optimization ORNL/NSF/EATC-14 (1975)).

Key financial algorithms predict commercial success, or stay microseconds ahead of the Wall Street competition. For example, Epagogix is a UK-based company founded in 2003 that uses neural networks and analytical software to predict which screenplays or movies will provide a good possibility of return on investments. (Wailgum 2009). Algo-Trading is rampart, with over 80% of market trade entries based on computer-generated trades, but these are not, except for the trading practices designated ‘high frequency trading’ using evolving algorithms of the sort considered in this article.

As to military interest, one of several approaches to algorithmic approaches already being used in receiver design is "AMR" Automatic Modulation Recognition (AMR), which has received strong military support. (Wei and Wakin 2012).

Prize-driven algorithm developments come from various sources. For example, on September 21, 2009, BellKor's Pragmatic Chaos algorithm was announced as the winner of the $1M Netflix Prize at a ceremony in New York City. The evolving Pragmatic Chaos algorithms provided more than a sustainable 10% improvement over previous strategies. The celebration of this award is noted in Fig. 5.

Figure 5 Celebration of the $1,000,000 Netflix award to Pragmatic Chaos (Bellkor's Pragmatic Chaos 2009).

The 2012 Nobel prize in Economics was awarded for development of algorithms *"for the theory of stable allocations and the practice of market design"* (Roth and Shapley 2013). Algorithms in the health field are exemplified by the Heritage $3M Health Prize for algorithms to identify future hospital admissions based on patient history. (Network 2013).

Finally, a prize-driven algorithm development prize with direct relevance to ADR is the currently-offered DARPA Spectrum Prize (DARPA.mil 2013) (DARPA 2013) in which the challenges are as follows:

- Can you and your team program a radio to dominate the spectrum?
- Can you engineer software-based radios that transmit data faster than a competitor using identical hardware?

These questions are followed by an invitation: “ Entries for this prize must be submitted before January 31, 2013.”

Even in the realm of law enforcement, algorithmic approaches are being developed at Stanford and other institutions (Shay 2013) and discussed at the Stanford “We, Robot” conference (Stanford 2013). Thus it may be anticipated that algorithmic concepts will be applied in Software Defined Receivers.

Importance of an Algorithm Defined Receiver

The incorporation of algorithms with active decision-making in military, industrial, and radio-astronomy receivers will provide several options, including the following:

Automatic software optimization of operating parameters (stage bandwidth, gain, etc.)

Receiver Identification of new and novel data

Selection/Evolution of receiving algorithm (modulation and decoding)

Optimization of demodulation/decoding algorithms

Extraction and use of information contained in received data stream

Interpretation of path information and optimization of operating regime

Identification of critical actionable items (Alerts, IFF, signal loss, alternative path selection)

Inversion of ADR parameters and other information for transmitter control (antenna, power, modulation, cloaking)

Tactical mission and research goal modification

These demands mitigate an evolving algorithmic approach to receiver design that is totally beyond the capability of static hardware designs. But the roots of the approach are beginning to be seen in RASDRWin and other SDR software.

It is instructive to examine the RASDR design process and how this project is progressing to see the level that industry is embracing SDR and ADR design concepts.

Genesis of the Algorithmic Approach in SDR receivers other than RASDR

Software that optimizes I/Q balance has been implemented in current SDRs for pre-operation optimization of control parameters (Touil and Forte 2012). These algorithms converge to values for optimal parameters (for dc offset values and good image rejection), and can be validated by observing the I/Q phase relationships in the data stream (Foster 2012). The software coding is not modified, but parameter values are optimized, thus improving the receiver operation under computer control.

Algorithmic design concepts for large information processing tasks (not yet applied to ADR) are implicit in recent DARPA initiatives, including Stanford-research based Ayasdi. Ayasdi's Topological Data Analysis approach (Carlsson 2009) was considered one of the top 10 innovations developed at *DARPA* in the last decade. Additional support is being received from the FDA, USDA, and Merck. Topographic Data Analysis is purely algorithm based, and for large data bases is judged far faster than existing approaches using business or mathematics software.

In addition, DARPA is stimulated receiver design by offering radio data encoding/extraction prizes, as indicated above (DARPA.mil 2013).

Thus early Algorithm Defined Receivers are already in production.

Current and developing SDR and ADR Designs: RASDR

Software Designed Receivers are an important part of radio astronomy research, and are implemented and applied at most radio astronomy research sites. SDR is also applied at smaller sites by individuals interested in developing and applying new techniques. One early application (Leach, Trondsan and Matthews 2011) that was presented to SARA by Marcus Leach, used modified, public-domain software.

RASDR 0 hardware development is complete as a breadboard device, and the operating parameter software that runs in RASDRWin is the beginning of an algorithm approach. This part of the software normally runs just before data collection is started (to optimize data collection parameters for the Lime femtocell chip), but it could be triggered by events (high noise levels) or after an elapsed time.

The goal of the RASDR design team has been to provide a high-capability, low cost tool for radio astronomy research to the SARA membership. Initial applications have been primarily under the Windows OS using RASDRWin, but it has also been applied under the Linux OS. RASDR is nominally an SDR receiver, but some ADR functionality may be implemented soon. It is up to SARA members to apply and evolve RASDR, and to document and share their results.

Specific RASDR Benchmarks and Availability

The SARA RASDR team has worked toward several hardware implementations that would differ in cost and capability. RASDR design benchmarks are shown in Table 1

RASDR Hardware designation	Interface	Tuning Range	Bandwidth	Comments
RASDR 0, Benchtop	USB 2.0	100KHz-3.8GHz	7MHz	Completed
RASDR 1	USB 2.0	15KHz-3.8GHz	10MHz	Production in 2013 (on hold)
RASDR 1.5	1 GigE	15KHz-3.8GHz	14MHz	Upgrade to GigE (on hold)
RASDR 2	USB 3.0	15KHz-3.8GHz or 400MHz-3.8GHz	20MHz or 28 MHz	Former 2014 Target. Now available (2013) with Nuand bladeRF (Nuand 2013) or Myriad DigiRed (Myriad March-June, 2013) (see text)
RASDR 2	USB 3.0	As above, but with GPS time stamp and different clocking scheme	28 MHz	Anticipated performance with DigiRed (Myriadrf n.d.) (Myriad March-June, 2013) engineering design (see text)

Table 1. RASDR versions, basic specifications and performance targets.

This table is based on the need to have widest possible data pipeline speed for radio astronomy applications. But wide bandwidth is costly, so it was envisioned to proceed in stages, with RASDR 0, then RASDR 1 (production USB 2.0 version), RASDR 1.5 (production GigE version) and RASDR2.0, (production USB 3.0 version). Our development schedule has been modified due to the availability of the equivalent of RASDR 2 boards that are based on the same hardware we chose for RASDR 0.

Hardware availability moved ahead significantly by availability of the USB3 high speed interface production version of RASDR 2, which has came on the market as a Kickstarter project by Nuand development under the designation bladeRF (Nuand 2013). The bladeRF does not perform below 400 MHz, since it does not incorporate the up conversion circuit of RASDR 0. Thus Table 1 shows 2 versions of RASDR 2, with different low-end specifications. It should not be difficult to add a low-frequency up converter to the bladeRF board, but this would be at an additional cost.

The RASDR team has just taken delivery of a development version of the bladeRF board, which has the Lime chip, an Altera FPGA and a Cypress FX3 (USB3) chip. This board, as received by the development team on April 10, is shown in Fig. 6.

Figure 6. bladeRF board (RASDR 2.0 - see text) as received from Nuand in April, 2013.

Like RASDR, the bladeRF is open source development and we are now collaborating with Nuand. We expect to receive two additional versions of the bladeRF. If the bladeRf performs as expected, it should fit the needs of SARA.

We will compare of the RASDR 0.0 benchtop receiver and the RASDR 2.0 bladeRF receiver and report the results to SARA. It is likely that the initial comparison will be made using Linux software, rather than wait for RASDR software to be modified to be compatible with RASDR 2.0.

Implementation of RASDR 2 with advanced time stamping

The RASDR development team has also been contacted by Myriad, Inc. (Myriadrf n.d.) and design capabilities were discussed for the new DigiRed package that will be compatible with RASDRWin. The Both Nuand and Myriad are open source designs, and they are based on the same Lime 6002 chip that is central to RASDR design. The Myriad design may be priced lower than the Nuand design, has the important USB 3.0 connectivity (two lines), will probably also accept GPS time stamping, and will have different clocking.

The Myriad design was first released in early 2013 as a component of a development kit, as shown in Fig. 7.

Figure 7 Myriad design kit. The RF section of the kit, somewhat similar in layout to the RASDR 2 design that we expect to be released soon, is shown on the lower right, and is labeled the Myriad-RF board. RASDR 2.5 will not use the DEO components shown here, although we anticipate that an up convertor board will be added.

Delivery of DigiRed Myriad rf boards to the RASDR design team is expected in June or July, 2013

It is anticipated that RASDRWin will control all aforementioned version of RASDR hardware.

Conclusion and Synthesis

Challenges to future communications, control, and research operations will far exceed current SDR capabilities (Filelds, et al. 2013). Just as Hardware Defined Receivers are being replaced by SDR for most applications, the advantages of algorithmic software are becoming apparent.

As the RASDR team has developed hardware and software packages that provide advanced receiver capabilities for radio astronomy and educational activities, it has become clear that there exist capabilities that exceed those normally attributed to Software Defined Receivers. It will be interesting to observe development of these capabilities.

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