A new general purpose high performance HF Radar

(Adapted from the 2008 URSI General Assembly Commission G Submission and Presentation)

Richard. N. Grubb[1], Robert Livingston[2], Terence W. Bullett[3]

[1]Consultant, 7762 Brockway Drive, Boulder CO 80303, rgrubb@computer.org

[2]Scion Associates, 439 Fillmore Street, Port Townsend WA 98368, livingston@scion-associates.com

[3]CIRES/NGDC, 325 Broadway, Boulder CO 80305, Terry.Bullett@noaa.gov

Abstract

A new HF radar/ionosonde system using digital RF technology is described that matches or exceeds the performance of the late 1970's NOAA/SEC HF Radar/Dynasonde. A new active antenna preamplifier and front end analog design achieves excellent linearity and low frequency performance from electrically short receiving dipoles. The multi channel receiver uses direct digital RF sampling and down-conversion, providing a wide dynamic range and stable phase matching between channels. The exciter uses flexible digital up-conversion. The radar provides experimenters with direct network access to raw data for their own processing as well as secure remote control.

1. Background

The original NOAA HF Radar (or Ionospheric Sounder) system, now alternately known as the Dynasonde or Advanced Ionospheric Sounder, was designed and built by NOAA/SEC in the late 1970's with support from the National Science Foundation. It was designed to be a flexible general purpose tool for making research measurements of the ionosphere [1]. The system was an evolution from previous pulse based ionosondes. In particular it embodied the capabilities of the Dynasonde and Kinesonde phase coherent systems [2] that had been developed earlier in the Boulder Laboratories. However, by employing later analog and digital technology, in particular by digitizing the whole complex echo signal return, and using multiple parallel receiver channels for simultaneous measurements of signals from an array of spaced receiving antennas, it opened up new possibilities for the measurement technique at the time. It also set a new standard for improved electromagnetic compatibility with other services in the HF and MF spectrum by employing matched transmitter and receiver pulse shaping and a linear transmitter.

Several of the original systems are still in use for ionospheric monitoring and research in different parts of the world. However these are aging, even though the original 1970's computers and digital hardware have been replaced by one or two new generations of technology. This has prompted the development[4] of the new system, described in this paper, which has been designed to meet the same conceptual requirements. Unlike the earlier system, where a special preprocessor was needed to select echoes for subsequent recording and bring the data rate down to be compatible with the minicomputer technology of the time, the new system is designed to record all the raw data and provide maximum flexibility to the experimenter for developing their own analysis software. Twelve of these new systems are currently being constructed. The first of these are now installed at the NASA Wallops Island Flight Facility, NOAA at Boulder Colorado and the Jicamarca Radio Observatory in Peru.

2. Overall Description

Recent digital technology has made it possible to implement a coherent pulse transmitter and receiver system using digital signal processing [3]. The basic arrangement of the RF section is shown schematically in Figure 1 and is simply a digital implementation of the well known analog direct conversion architecture. The entire received signal spectrum, from 0.1 to 25 MHz, is low-pass filtered to reject aliasing and digitized to 14 bits at an 80 MHz sample rate. Recent high speed ADC's are able to make this conversion with harmonic and spurious components at < -90 dB with respect to full scale. The data stream from the ADC is then multiplied by numerically generated sinusoidal quadrature components at the desired receive frequency, and the resulting baseband components are decimated and low pass FIR filtered. This provides the desired receiver quadrature component output at a suitably reduced sampling rate. For typical bandwidths, with adequate dither, the processing gain inherent in decimation and filtering gives a dynamic range of greater than 100 dB. For the transmitted pulse, an accurately timed quadrature component baseband serial data stream is generated and clocked into the digital up-converter. This is then shaped by appropriate FIR low pass filters to a suitable bandwidth limited form to match the receiver filters. The filtered stream is then interpolated to the 80 MHz clock frequency and up converted to the required frequency by multiplying with numerically generated quadrature components identical to those used in the receiver. These components are then summed and input to a high speed DAC to provide the low level analog RF output. Coherence between transmitter and receiver is ensured by phase synchronization of the two numerical oscillators from a GPS clock.

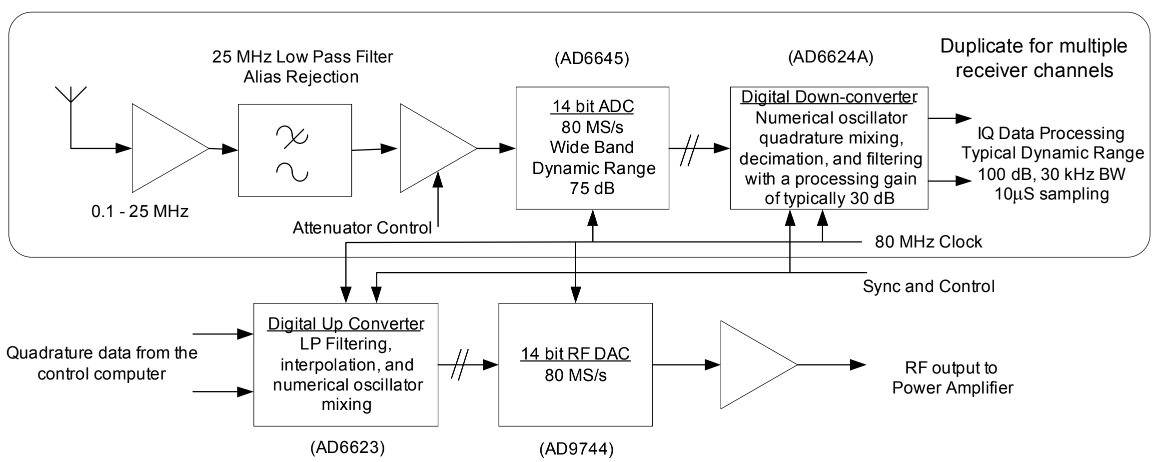

Figure 1. Digital HF Radar RF Section, Simplified Block Diagram

The process of digital down conversion and up conversion (DDC, DUC) is provided by a pair of commercially available single chip subsystems resulting in an extremely low component count implementation. This system can match or exceed the performance of a wide band analog frequency agile receiver. Furthermore the digital approach provides the important advantages of (1) exact phase and amplitude matching of the digital sections of multiple parallel receiver channels, and (2) the provision of a uniform group delay in the pass band through FIR filtering to assure a stable phase measurement throughout the received pulse. Figure 2 shows the dynamic range and threshold sensitivity of the prototype receiver using the FIR filter described below. The I and Q outputs from the DDC are only 16 bits wide, but these can be internally gain controlled or switched into a quasi floating point mode. The dynamic range can be further extended for larger signals when required by the use of a software controlled 32 dB variable attenuator prior to the ADC driver. Figure 3 shows the clean spectral response of the receiver when fed with a near full scale unmodulated carrier signal offset 1 kHz from the tuned frequency.

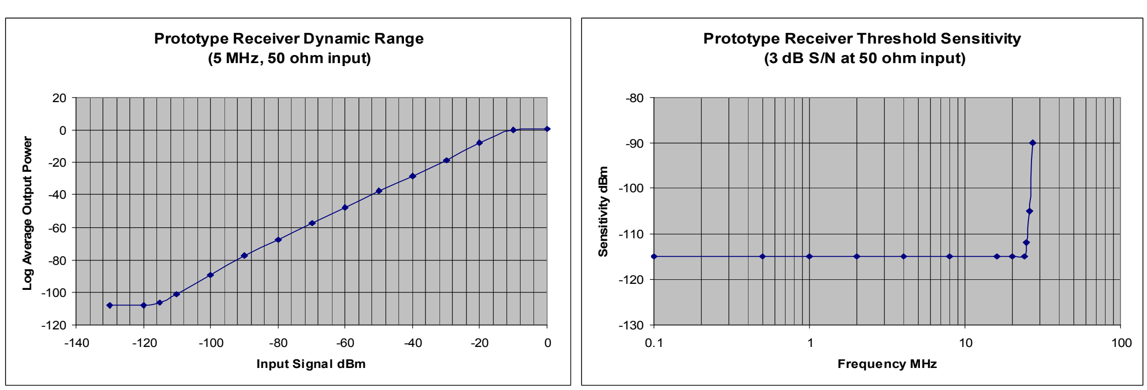

Figure 2. The measured dynamic range and threshold sensitivity of the prototype receiver including the ADC driver amplifier are shown above.

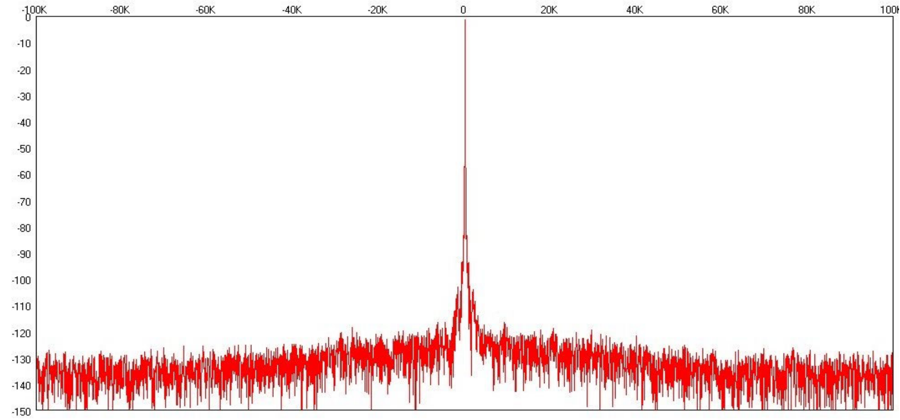

Figure 3. FFT of the receiver IQ output when fed with an unmodulated carrier signal at 1 kHz offset from the tuned frequency.

The FIR filtering that sets the receiver bandwidth is extremely flexible and can be chosen to meet the needs of the experimenter. The impulse response of the 160 tap filter chosen for initial use is a raised cosine to the fourth power. This closely approximates the frequency response of the pair of maximally flat time delay 4 pole crystal filters used in the original HF Radar. The decimation is chosen to provide a 100 kHz sampling rate at the output of the receiver, again duplicating the earlier system. Figure 4 shows the impulse and frequency response of this filter.

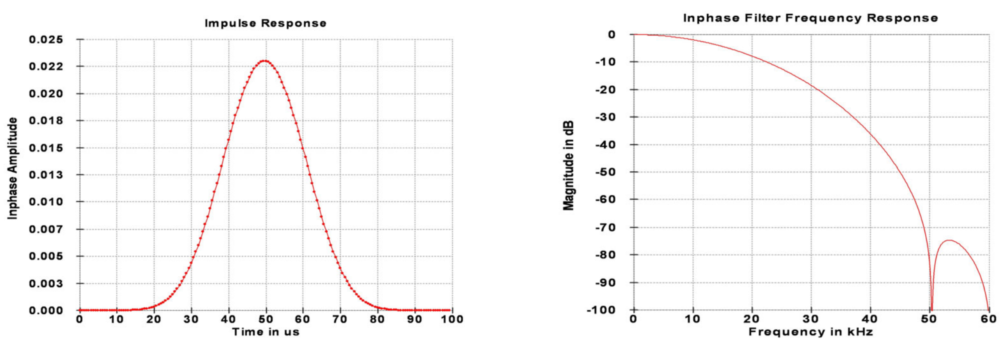

Figure 4. Impulse and Frequency response for the 160 tap raised cosine to the fourth power filter.

The analog portions of the system must be carefully designed so that they do not degrade the digital system performance. In particular, the amplification of the wide band signals from the receiving antennas before digital conversion must be linear enough to minimize spurious signal generation from the crowded LF - HF spectrum. The Dynasonde type of application has traditionally used wide band dipole receiving antennas that work well in practice when spaced up to one quarter wave above the ground at the highest frequency of operation. Relative to loop type antennas the dipole has the advantage of being less sensitive to local vertically polarized signals from AM broadcast transmitters. However, the dipole sensitivity to down coming signals necessarily falls with frequency due to its decreasing electrical height above ground.

A new very linear wide band dipole preamplifier has been developed for this system. For true wide band operation the dipole must be electrically short in length. Numerical analysis of a dipole of overall length 4m shows it to have a nearly uniform source impedance of just 20 pF from each element up to 10 MHz, with the resistive term only becoming significant above 15 MHz. To provide a uniform coupling of the voltages induced across the dipole with frequency, the preamplifier must either present a very high impedance to preserve the response at low frequencies, or be in a charge sensitive configuration with capacitive feedback to the dipole terminals. The latter approach was selected because it has better noise performance and linearity. The basic arrangement and appearance of the preamplifier and a typical installation at Jicamarca is shown in Figure 5. Calibration is conveniently coupled into the summing junctions with 1pF capacitors making it straightforward to relate the calibration to received signal strength, given that the dipole length and source capacitance are known.

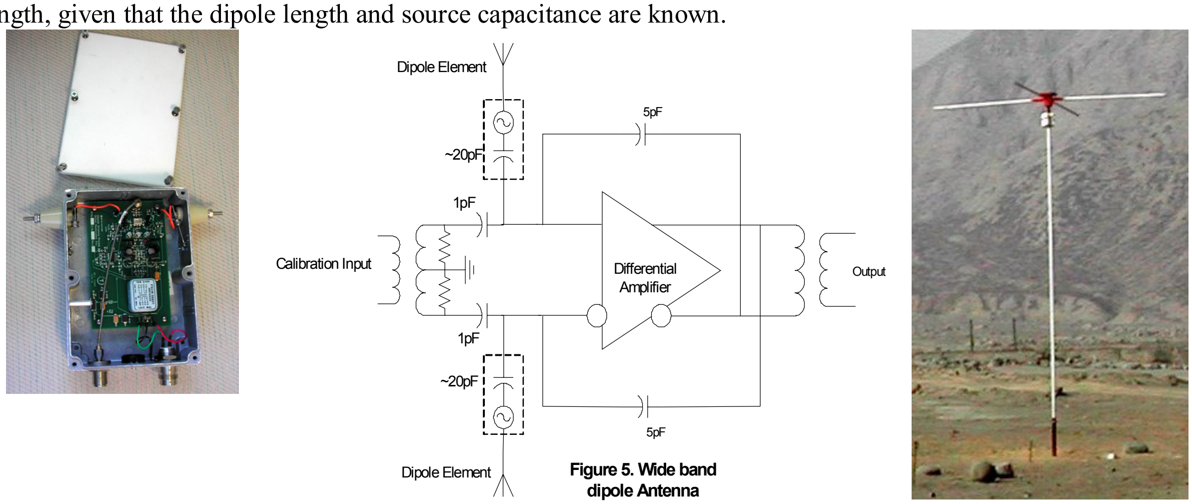

Figure 5. Wide band dipole Antenna Preamplifier

The preamplifier is realized with discrete semiconductors. A balanced JFET input stage is followed by a balanced cascode bipolar transistor output stage that is transformer coupled to the 100 Ω balanced output. Tests with the 4m dipole show the overall performance to be atmospheric noise limited over the whole frequency band at mid latitudes. The frequency response is from 50 kHz to 28 MHz at -3 dB. Intercept points at 1 MHz. are; Third Order > +40 dBm, Second Order > +60 dBm and at 10 MHz; Third Order > +30 dBm, Second Order > +55 dBm. The common mode rejection at 1 MHz and at 10 MHz is > 50 dB.

A critical test of the whole receiver chain is its ability to successfully measure a small threshold signal at its wide band front end when presented with the whole spectrum of signals in the LF, MF and HF bands. The results of one test are shown below in Figure 6. A 4m dipole and preamplifier were set up in the Boulder Colorado area feeding the prototype receiver. The ensemble of signals, including primarily the AM broadcast band, measured approximately 0.5 V pk-pk at the ADC input. A small unmodulated carrier signal offset a small amount from the tuned frequency was applied via the preamplifier calibration input at a selected clear frequency near 5 MHz. The display is a plot of successive I and Q values from the receiver at 10 µS intervals. The three plots show successively the background noise, the noise plus a threshold signal adjusted to equal the noise, and the noise plus a larger signal. When adjusted for the calibration circuit loss and the calibration coupling, the threshold signal is equal to just over 1 µV/m at the dipole.

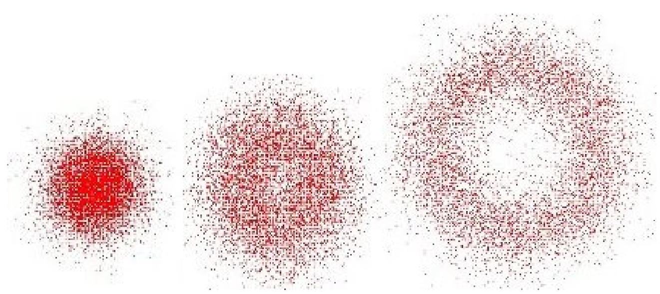

Figure 6. Overall receiver performance at 5.4 MHz when exposed to the full radio spectrum.

In a parallel development, a numerical modeling program has been undertaken to optimize the design of a vertex down log periodic transmitting antenna for use with the radar. The antenna uses two planes that are built with zigzag dipole outlines supported by rope catenaries from 4 towers. Compared with other antennas that have been commonly used for vertical ionospheric sounding, for example the delta and vertical rhombic configurations, this antenna has a much more uniform impedance and notably more uniform overhead illumination of the sky. Antennas of this type are now installed at Wallops Island and Jicamarca Radio Observatory. The appearance of this antenna in a computer simulation is shown in Figure 7 below.

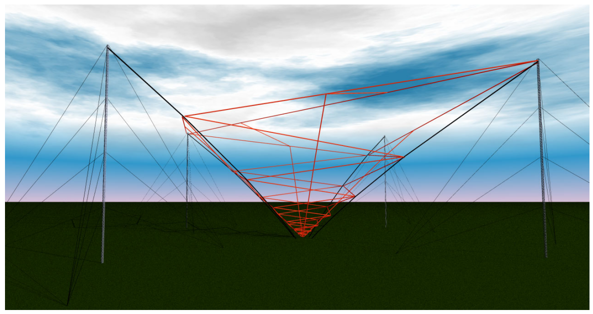

Figure 7. Computer model of the Vertex Down LPA Transmitting Antenna.

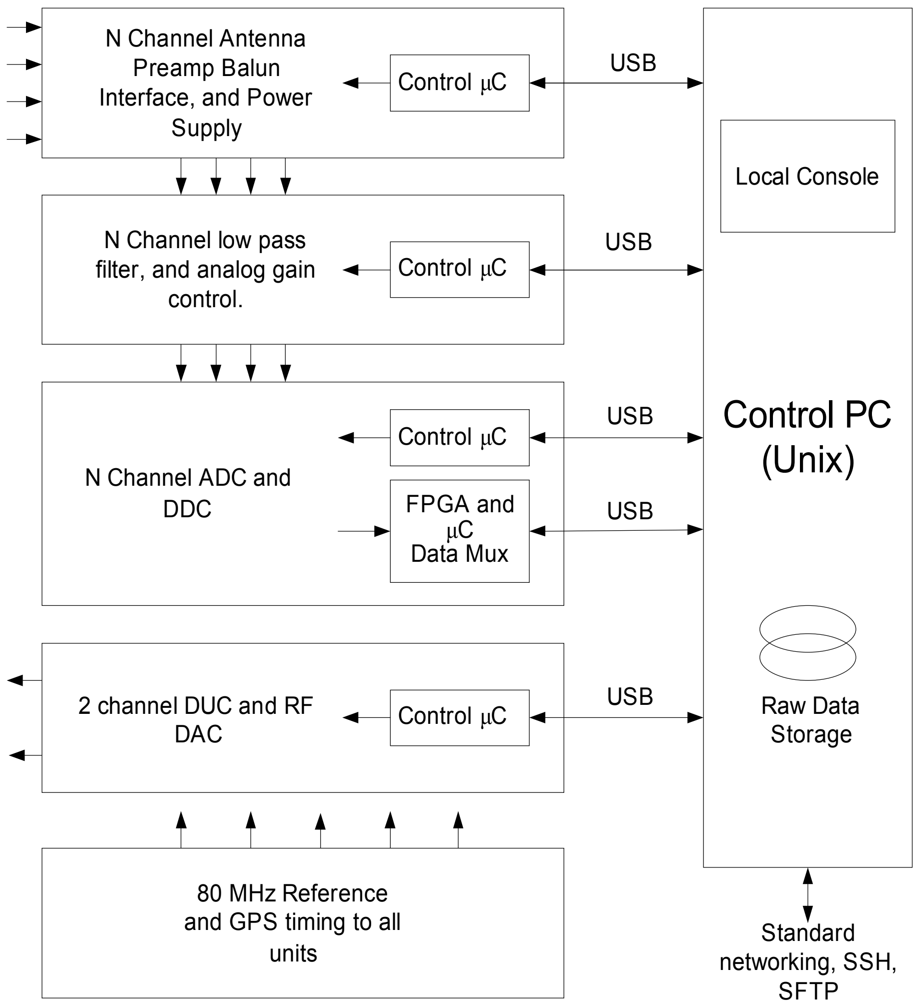

Figure 8. Overall System Block Diagram. Each block is contained in a 1U rack enclosure with self contained power supplies.

The current radar system configuration, shown in Figure 8, allows for up to eight receiver channels in pairs. An alternate 50 ohm unbalanced input can be selected at the low pass filter chassis for other types of receiving antenna systems or direct calibration loop back. The blanking and gain control for each of the channels is provided by a digitally controlled CMOS attenuator and switches that exhibit a third order intercept of > +50 dBm. The low pass filters that reject signals above the Nyquist folding frequency are accurately group delay matched and have an attenuation of >100 dB for frequencies above 30 MHz. A low noise balanced amplifier buffers the input to the ADC preceding the down conversion.

Physically, the analog portion of the system consists of two 1U rack enclosures, the preamplifier balun interface and power supplies, and the low pass filtering and analog attenuators and gain stages. The digital portions of the radar consist of four 1U enclosures, a very low jitter 80 MHz reference and GPS clock, an eight-channel receiver, a two-channel exciter and the control computer. All the reference signals are distributed to the receiver and exciter using fixed length 50 Ω coaxial cables to assure phase coherence throughout the system. The receiver and exciter enclosures are autonomous, that is they have their own timing state machines and tuning memories that are loaded prior to data collection. Exact synchronization of the two timing state machines is assured by distribution of a single universal time synchronized pulse from the GPS clock that is selected by the operator as the start time of a data collection.

The receiver ADC input has a potential bandwidth of 200 MHz. This would make it possible to adapt the system from the ADC onward as a VHF Radar by utilizing the upper Nyquist sub bands with alternative input filtering and an up conversion following the exciter.

USB based microcontrollers are used throughout the system for communication with the control computer. Prior to data collection, multiple microcontrollers program the receiver and exciter microport control registers, store tuning words in memory, and program the state machine FPGA. Thus, all system control functions are pre-programmed prior to a sequence of data collection, and only need to be activated by the start pulse from the GPS clock. The system data multiplexer also uses a USB-core microcontroller and FPGA combination to multiplex and buffer up to 8 channels of data from the receiver chips, and to place those data in the USB endpoint buffer FIFO for transmission to the control computer. Cumulative rates exceeding 1.2 M 16-bit complex samples per second are achievable with the multiplexer. Once the timing state machines have started a data collection, the only active USB traffic is the digital data traffic from the multiplexer endpoint FIFO to the control computer.

The timing controller in the exciter enclosure is also the source of the IQ serial sequence that forms the transmit pulse. Two deep memories for transmit and calibration waveforms are pre-programmed, and clocked out at particular times within the pulse repetition interval. Phase coded pulses can be generated if required. The calibration pulse is generated within the sequence, usually at the start of the range gate, and fed to the preamplifiers in the field through phase matched cabling, but can also be switched into the analog input for tight loop calibration purposes.

The autonomy of the receiver and exciter also make it suited for bistatic operation. Two reference enclosures are required in that case. The internal GPS clock already assures exact (15 ns) timing synchronization of waveform and data collection. The only hardware change that would be necessary is to substitute a disciplined rubidium oscillator in place of the standard low noise 80 MHz OCXO.

The moderately high performance x86 control computer that is provided with the system uses Debian Linux as an operating system. All of the software for that CPU, and also for the various microcontrollers, is written in high-level C under Open Source licensing. The program directory hierarchy follows standard UNIX traditions, and is ordered per system function so that a user can better understand how the system operates. The system can be fully remote controlled through a secure network interface.

Received raw IQ data files are available to the user through the network connection with the control computer at the sampling rate (nominally 100 kHz) consistent with the usual system operational bandwidth. All the subsystem control parameters are recorded as metadata along with the data in the files to reduce any data interpretation ambiguities. A typical frequency and range sweep can produce up to a gigabyte of raw data. Unless very fast wide area network connections are available it is desirable to have a local analysis computer that can reduce the volume of data for either local storage or remote transmission. Open source data analysis software based on the earlier HF Radar software is being developed by a number of groups. Proprietary Dynasonde application software is also available.

Figure 9.

Figure 9 shows a system with 8 receive channels housed in a 40 inch rack cabinet. This also contains the 4 kW (optionally 2 or 1 kW) solid state class AB linear power amplifier. The standard amplifier operates in the frequency range from 0.5 – 30 MHz.

3. Results

Figure 10 shows a raw power ionogram plotting Signal to Noise Ratio made with the HF radar at Wallops Island, VA, on 05 Nov 07 at 15:18UT (10:18LT). This is a classic, quiet mid-latitude daytime ionogram, with E, F1 and F2 traces of both ordinary and extraordinary polarizations. The E region trace is slightly range spread. The bright yellow line at the bottom of the image is the field calibration pulse. This ionogram was taken in a Dynasonde B-mode of operation, with 8 antennas, an 8 pulse set and 4 repeats of 4 nominal frequency ramps. Nominal frequencies start at 1 MHz and increase logarithmically with a 0.5% increment. For this display, the receiver output power is incoherently averaged for all 10 μS samples at each nominal frequency, a SNR is computed at each frequency, and the data are plotted on a linearly scaled frequency axis. The signal to noise ratio values approach 50 dB.

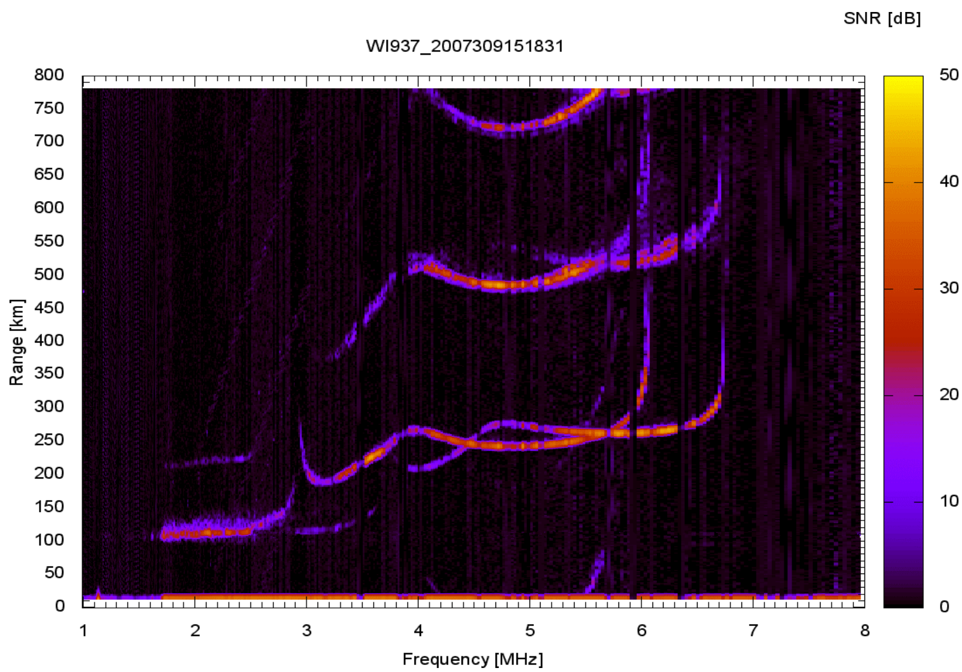

Figure 10.

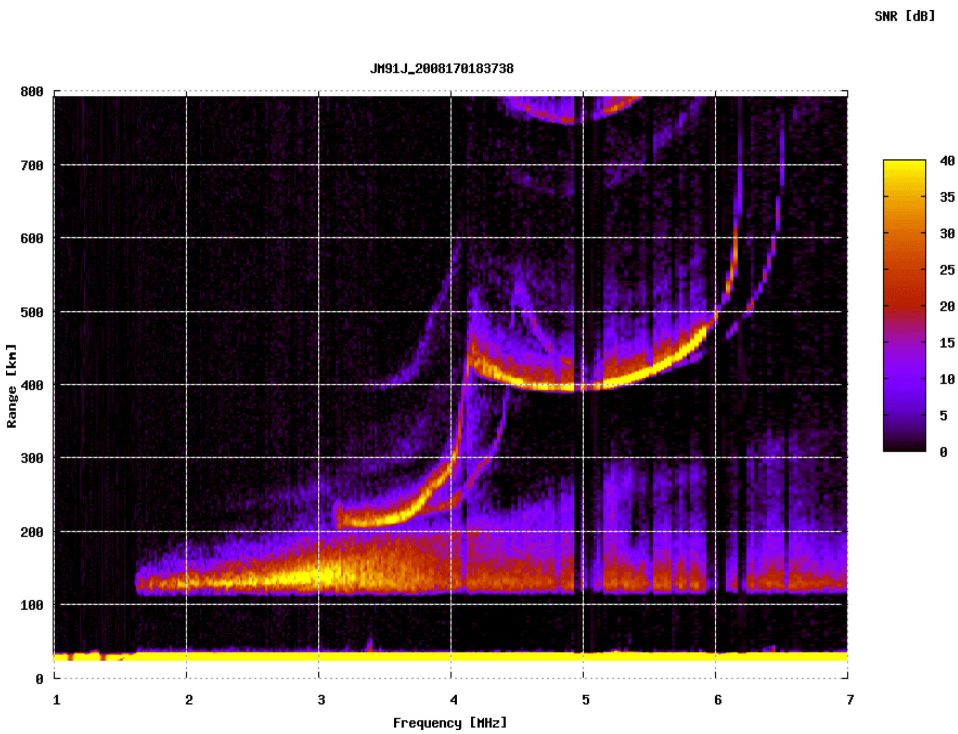

Figure 11

A second similarly plotted, but more complex example from Jicamarca in daytime is shown in Figure 11. A single dipole used for reception favored the O trace. Note the clearly displayed F1 layer dynamics and the slant E electrojet.

[4] The new HF Radar development was supported by the US Air Force SBIR Phase II Contract F19628-03-C-0019 and NASA Grant NNG04WF11I

4. References

1. Grubb, R.N. ‘The NOAA SEL HF Radar System (Ionospheric Sounder)’ *NOAA Technical Memorandum ERL SEL-55*. October 1979.

2. Wright J.W. and M.L.V. Pitteway, "Real-time acquisition and interpretation capabilities of the Dynasonde", *Rad. Sci*., 14, 815-835, 1979.

3. Davies, N. C. ‘A High Performance HF Software Radio.’ *Proc 8th Int. Conf. On HF Systems and Techniques*, IEE Conf. Publ. 474 (IEE 2000), pp249-256.

R. N. Grubb Issue 3. 9/22/08