THREE-CHANNEL DIGITAL RADIO VECTOR FIELD SENSOR: DESCRIPTION AND DEMONSTRATION

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ABSTRACT

This paper presents a three-channel digital Radio Vector Field Sensor (RVFS), which implements digital quadrature down-conversion. Either the electric vector wave field is measured with three orthogonal dipole antennas or the magnetic vector wave field with three orthogonal loop antennas. Three identical parallel channels with anti-aliasing filters limit the input frequency band to between 0 and 10 MHz and 14 bits Analogue-to-Digital Converters samples the three signals at 25 Msamp/s. By increasing the cut-off frequency of the anti-aliasing filters, the sampling frequency can be increased up to 50 Msamp/s. Digital quadrature mixers reduce the amount of data and output baseband I and Q with 16 bits resolution. The data is streamed up to 10 Mbit/s to the user over a local area network and the user commands the RVFS with a graphical user interface running on a Linux computer connected to the internet.

The RVFS is an implementation of the Information Dense Antenna and since this RVFS measures the full three-dimensional wave field, applications such as polarisation measurements and direction-finding are possible. The RVFS can also function as a radio receiver of long-, medium-, and shortwave radio stations. An important and interesting application is as receiver for LOIS, the LOFAR Outrigger In Scandinavia. Space-borne applications involves electric and magnetic field instruments on board the International Space Station, electric and/or magnetic field instruments on board the Swedish nano satellite Nanospace-1. International projects like the Solar Imaging Radio Array have also shown interest.

1 INTRODUCTION

We present a digital three-channel Radio Vector Field Sensor (RVFS) capable of measuring three components of either the electric or the magnetic field or a combination thereof in a frequency band up to 10 MHz. By measuring the three-dimensional electromagnetic vector wave field, more information can be extracted from the measurements compared to cases when only one or two components are measured. For example, it allows study of physical characteristics such as polarisation and direction of arrival and these characteristics can be calculated [1] from a measurement at only one position. The method, which also is known as the Information Dense Antenna (IDA) technique, have additional applications as described by an accompanying paper [2].

In order to measure the electric vector field, three co-located orthogonal electric dipoles are used. For the magnetic vector field, three co-located orthogonal magnetic dipoles are used instead. A fully digital instrument such as this have many advantages over an instrument with analogue down-conversion. For example, the local oscillator is more stable, higher order mixing products are avoided, and it is easier to synchronize the individual channels. A disadvantage is that the discretisation process creates spurious components.

Currently, three different RVFS are operating continuously streaming data over the internet. One of the instruments is located in Uppsala, 75 km north of Stockholm, and two in Växjö in southern Sweden. The latest version of the RVFS is described in detail in Section 2. The Graphical User Interface (GUI) running on a Linux PC is presented in Section 3. Finally, a short overview of some applications is presented in Section 4.

2 DESCRIPTION OF THE RADIO VECTOR FIELD SENSOR

A block diagram describing the RVFS is shown in Figure 1. In order to give a detailed description, we will follow the signal path from the antennas on the left hand side to the PC on the right hand side and describe each component the signals passes.

- **Antennas**
  The RVFS measures a three-dimensional vector field and therefore, the antennas must span three spatial dimensions. This can, for example, be achieved by using three orthogonal dipoles or three orthogonal loops, as shown in Figure 2. The dipoles are short compared to the wavelength and the loops are small, *i.e.*, their circumference are short compared to the wavelength. In order to compensate for the shortness, the antennas are made active.

- **Pre-amplifiers**
  Active antennas are used. Short dipole antennas are capacitive and must be matched with pre-amplifiers having very high input impedance. As shown in Figure 2, the pre-amplifiers are mounted directly at the base of each antenna element. In order to avoid self oscillations, unity gain has been chosen, while the gain can be set to a higher value for loop antennas.

- **Anti-aliasing filters**
  The sampling speed is 25 Msamp/s, which gives a Nyquist frequency of 12.5 MHz. Anti-aliasing Butterworth lowpass filters of 15^{th} order are implemented, having cut-off frequencies of 10 MHz and an aliasing rejection of 50 dB at 10 MHz. Butterworth filters are chosen as it is maximally flat at DC. If the lowpass filters are replaced by appropriate bandpass filters, higher frequency bands can be measured using undersampling.

- **RF amplifiers**
  The signals are amplified before the digitalisation. In order to achieve the same signal power, electrically short dipole antennas require higher gain than loop antennas. The amplifiers have a total harmonic distorsion of 85 dBc.

- **ADC**
  The 14 bits Analogue-to-Digital Converters (ADC) sample nominally at 25 Msamp/s, but have a maximal sampling rate of 65 Msamp/s. ADC:s capable of sampling up to 125 Msamp/s are also available. The spurious-free dynamic range is larger than 93 dBc at 5 MHz and full bandwidth.

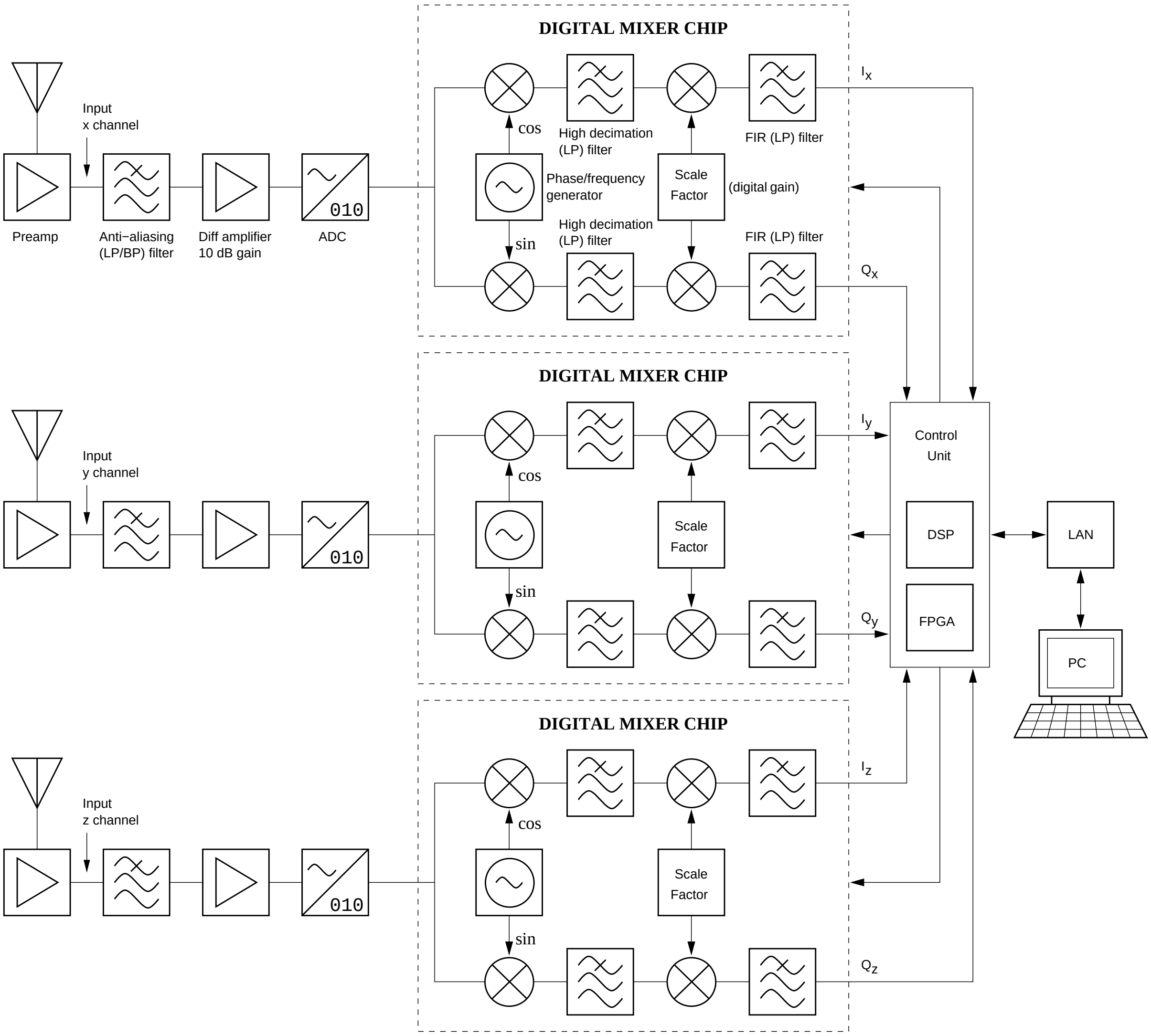

Figure 1: Block diagram showing the electronics of the three-channel digital radio vector field sensor. The three inputs of the instrument are marked with arrows and the antennas are external and can be exchanged.

- **Digital mixers**

  Down-conversion is implemented digitally by using dedicated chips with quadrature mixers. These mixers output complex baseband I and Q and allow output resolutions of 16+16, 24+24, 32+32, and 38+38 bits, but only the 16+16 bits resolution can be used for this instrument. The mixers operate at the same frequency as the ADC:s up to a maximum of 52 MHz and this sets the upper limit for the sampling frequency of the instrument.

  The mixer chips allow a frequency selectivity of less than 0.006 Hz and, for the nominal sampling frequency, a maximum bandwidth of 195 kHz. However, via the GUI the centre frequency can be set from DC up to 12,498.9 kHz in steps of minimum 0.1 kHz, and the bandwidth is limited to between 1.5 kHz and 82.1 kHz. The upper value for the bandwidth is bounded by the maximum speed at which data can be output from the instrument to the network. For the largest bandwidth, the 16+16 bits output resolution gives a data stream for all three channels of 3×82.1 kHz $\times\ 2 \times 16$ bits $= 7.88$ Mbit/s.

  After mixing the lowpass filtering is done in two steps with digital scaling in between. The combination of a high-decimation filter and a finite impulse response (FIR) filter give

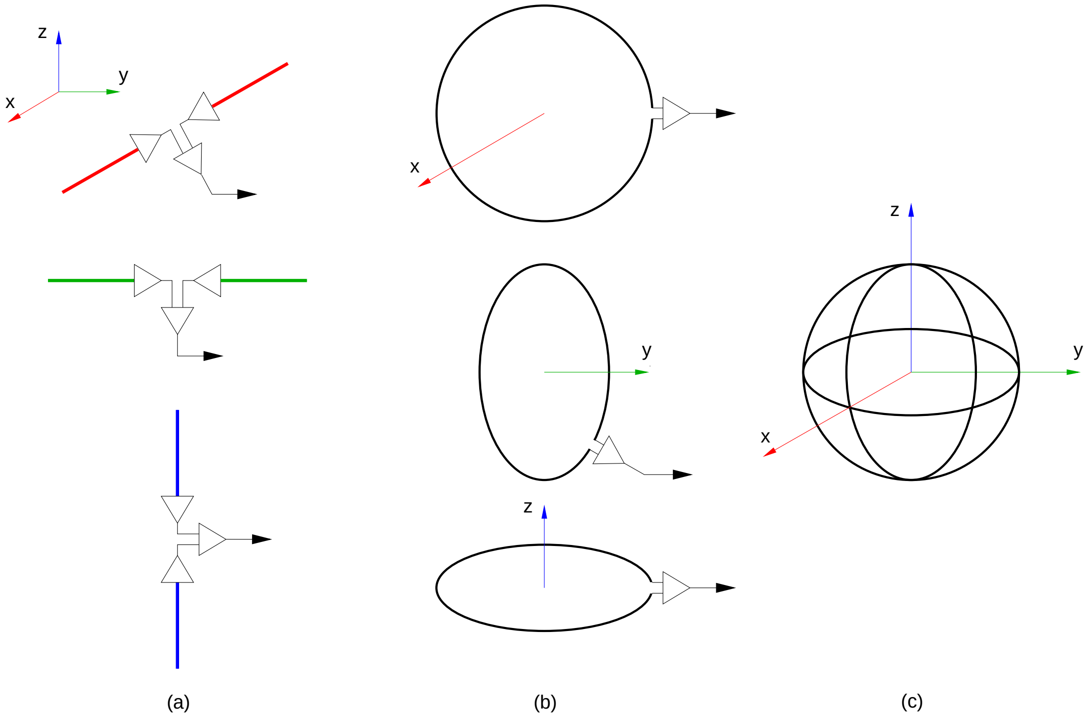

Figure 2: Two sets of orthogonal antennas spanning three spatial dimensions are shown. In (a), electrically short dipole antennas oriented along the x, y, and z axes are displayed. These antennas measure the three components of the electric field. Electrically small loop antennas are shown in (b). These are oriented so that they measure the corresponding components of the magnetic field. In (c), the vector antenna, formed by putting the three orthogonal loops together, is illustrated.

a combined response resulting in a -3 dB to -102 dB filter shape factor of less than 1.5, a passband ripple less than 0.04 dB, and a stopband attenuation larger than 104 dB. The spurious free dynamic range is larger than 102 dB.

- **Control unit**
  A control unit consisting of a Digital Signal Processor (DSP) and a Field Programmable Gate Array (FPGA) controls the operation of the instrument. Both run at 50 MHz.

- **LAN**
  Each RVFS is given an IP-address and streams data to the user over the Local Area Network (LAN) with User Datagram Protocol (UDP) at a speed of 10 Mbit/s. Each data package is given a unique number, which enables the user to sort them in the correct order. Commands to the RVFS are transferred over the network in the opposite direction.

- **PC/User interface**
  In order to control the RVFS a graphical user interface, GUI, has been developed. The GUI can be run on a Linux PC and allows the user to interact with the instrument. The PC calculates the Fast Fourier Transform (FFT) so that the data can be displayed in the frequency domain by the GUI. More details about the GUI are presented in Section 3. The RVFS can also be steered from the command line of the PC and this may be more convenient when large amounts of data will be saved.

Apart from the specific components shown in Figure 1, other general physical data are presented in Table 1

Table 1: Specifications

Size	$150\times100\times40$ mm^3
Weight	300 g
Power	5 W
Max input	-35 dBm
SNR	10 dB at -103 dBm input power for 3.4 kHz bandwidth at 5.0 MHz

3 GRAPHICAL USER INTERFACE

The graphical user interface (GUI), designed for operating the Uppsala RVFS, is available at the web site [3] of the Physics in Space program of the Swedish Institute of Space Physics. This GUI, which is shown in Figure 3, can be run on a Linux PC and when it is known what the different panels represent, it is essentially self-explainatory.

In order to give an illustrative example, we have chosen to set the centre frequency at the carrier of a powerful radio station. We have chosen 6120 kHz, which is Radio Finland transmitting from Pori (61°29'N, 21°46'E) Finland. The bandwidth is set to 17.3 kHz. Both the centre frequency and the bandwidth are displayed at the bottom of the Figure.

The GUI consists of a number of panels. The lower left panel shows the power spectra for the three channels, where the whole bandwidth of 17.3 kHz is displayed on the horizontal frequency axis. In the upper left panel, the passband state of polarisation is shown with the same frequency scale as in the panel below. The lower right panel displays the angles of arrival for all the frequencies in the passband. In the panels marked Phase and Doppler, the phase difference between the channels and the Doppler shift of one of the channels are shown, respectively. The Ellipse panel illustrates the orientation and ellipticity of the polarisation ellipse. Finally, mnemonics of how to operate the GUI are given in the upper central part of the GUI. A more detailed presentation of the panels follows below.

3.1 POWER SPECTRUM

The power spectrum of the three channels are shown in the lower left panel of Figure 3. Different colours are used for the three channels: red for x, green for y, and blue for the z channel. The centre frequency (in this case 6120 kHz) is displayed in the middle showing the carrier of the radio station. With a bandwidth of 17.3 kHz, frequencies 8.65 kHz below and above 6120 kHz are shown to the left and to the right of the carrier, respectively. The effect of the mixer's lowpass filters is seen as the roll-off of the power towards the ends of the spectra and the passband is clearly less than the bandwidth. The power axis is logarithmic displaying 10 dB per division.

3.2 POLARISATION

In the upper panel, the state of polarisation is shown for all frequencies within the bandwidth. Blue colour represents linear and red colour circular polarisation. The same frequency axis as for the spectra is used, but since the calculated polarisation only is reliable for frequencies within the passband, only these frequencies are displayed.

The calculation of the polarisation involves two steps. First, the coordinate system has to be

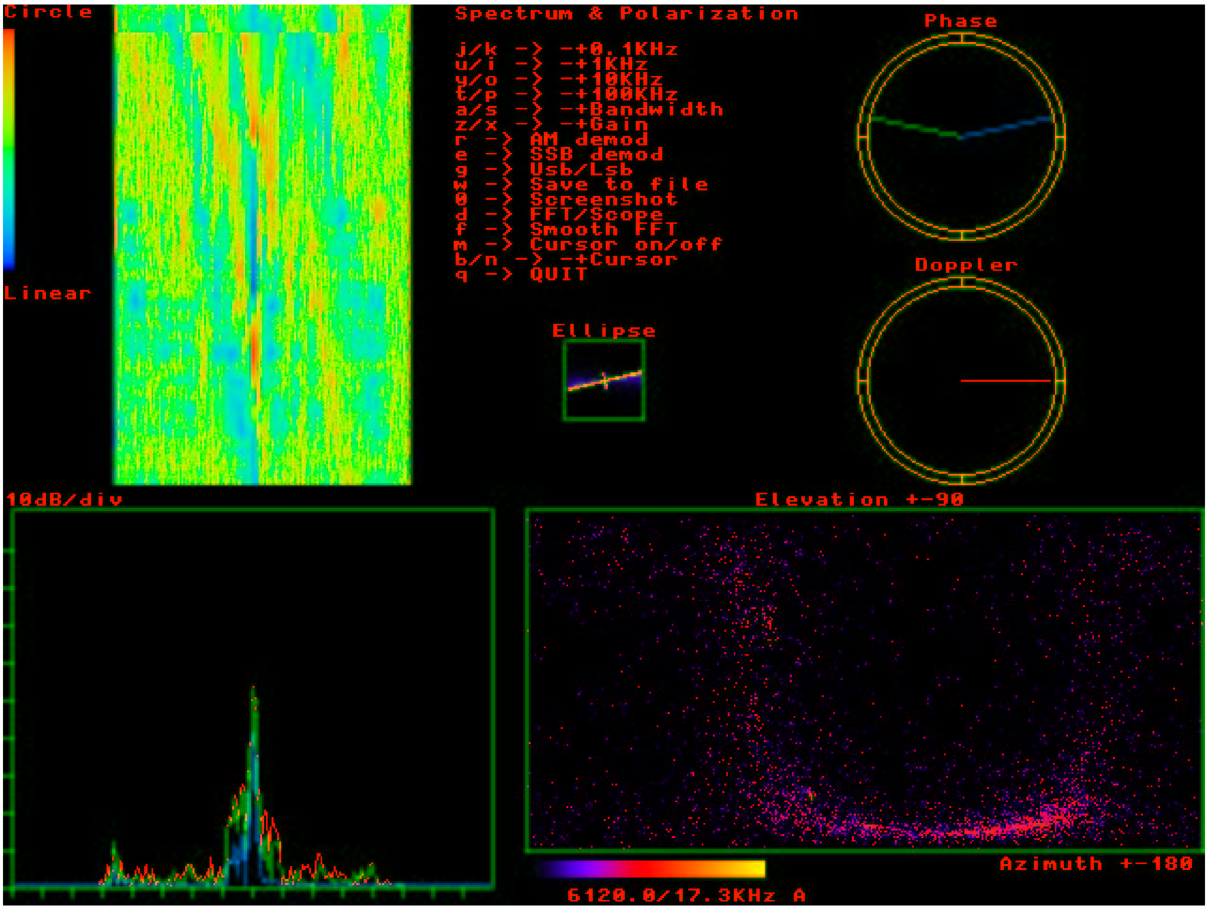

Figure 3: The graphical user interface for Linux. In reality, the Figure is in colour.

rotated so that the direction of arrival is along the new z axis and the transverse components of the wave field lies in the new x-y plane [1]. The polarisation can then be calculated, for example in terms of the Stokes parameters, using standard procedures [4].

3.3 ANGLE OF ARRIVAL

The angle of arrival is determined using transverse plane wave assumption [1]. In the lower right panel, the direction of arrival is shown in terms of the elevation and azimuthal angles for all frequencies in the passband. The elevation angle is measured $\pm 90°$ from the horizon and the azimuthal angle $\pm 180°$ from the x-direction, which deviate eastward from north by $10°$. The azimuthal angle is taken positive towards west. Only right-handed polarised waves are represented correctly in the panel. If an incoming wave is left-hand polarised and incident from, say an elevation angle of $40°$ and an azimuthal angle of $55°$, it would appear like a right-handed wave incident from an elevation angle of $-40°$ and an elevation angle of $55° - 180° = -125°$.

3.4 DOPPLER

The Doppler panel shows the dynamic Doppler shift for the centre frequency. This is equal to the change of the phase with respect to time. For clarity, only the x channel is displayed.

3.5 PHASE

In the Phase panel, the phase differences between the channels are displayed. The x channel has been chosen as reference and the green pointer shows the phase difference between x and y, while the blue pointer shows the phase difference between x and z.

3.6 POLARISATION ELLIPSE

The small Ellipse panel displays, for the centre frequency, the shape and tilt of the polarisation ellipse. This panel is closely related to the upper left polarisation panel, which shows the polarisation for the whole passband. When both axes are equal we have circular polarisation and when one of the axes is zero the polarisation is linear; in between those extremes we have elliptical polarisation.

3.7 AUDIO RENDITION

Something which is not displayed graphically in the GUI is the ability to demodulate the received signal and present audio rendition from the speakers of the PC. This property allows the user to listen to radio stations. Amplitude Modulation (AM) or Single SideBand (SSB) modulation with either the upper or lower sideband can be chosen.

3.8 CONTROL

Mnemonics of how to operate the RVFS is also shown in the GUI. By pressing appropriate keys on the keyboard, the settings of the instrument can be changed. The centre frequency can be adjusted from DC up to the Nyquist frequency in steps of either 0.1, 1, 10, or 100 kHz. The bandwidth can be selected among a number of fixed values, where 1.5 kHz is minimum and 82.1 kHz maximum. As mentioned in Subsection 3.7, the signal can be demodulated and played back as sound. The demodulation can be done for AM and SSB modulated signals. Data can also be saved to a file. The PC can stop calculating FFT:s and present the data in oscilloscope mode. By averaging over several FFT bundles, a smooth FFT can be presented and this setting affects all panels of the GUI. Finally, a cursor can be presented in the spectra and it can be moved up and down in frequency.

4 APPLICATIONS

Applications of the radio vector field sensor involves measurements of vector fields with applications such as polarisation measurements and direction-finding. An important and interesting application is as receiver for LOIS [5], the LOFAR Outrigger In Scandinavia. The purpose of LOIS is to enhance the capabilities of the giant radio telescope LOFAR (Low Frequency Array) [6] by also adding transmitters and network in southern Sweden with Växjö as the base.

Concerning space-borne applications, a number of different satellite projects have shown interest in the technique. In order to monitor the electric and magnetic fields, a RVFS will be installed on board the International Space Station (ISS) [7]. Similar RVFS:s are planned to fly on board Nanospace-1, which is a nano-satellite being built by Ångström Space Technology Centre at the Ångström laboratory in Uppsala. International projects like the Solar Imaging

Radio Array (SIRA) [8] have also shown interest. SIRA aims at studying the sun with radio receives placed on board 16 microsatellites forming a spherical array.

References

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