UViip Data Collection at DRAO

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1 Experimental Setup

The experimental setup consists of three main components: the transmit station, the receive station, and the small beamformer. Each of these components is described in detail below.

1.1 Transmit Station

A half-wave wire dipole cut for the amateur 80m band was erected at 223 Abbott Street, Penticton, BC[1]. The lot measures 37m in the East-West direction. It was not possible to orient the dipole null in the direction of DRAO due to the geometry of the transmit site. The transmit station is 19.86 km from the receive station at DRAO.

The transmit antenna was connected to an RF power amplifier capable of 100W output. The signal source used was a Tektronix AFG3252 Dual Channel Arbitrary Function Generator. It was used to generate both CW tones and sweeps. The sweep duration was set to 0.4s to match the beamformer integration time. The sweep bandwidth was set to 6 kHz. The signal generator was synchronized to a GPS-based frequency reference.

1.2 Receive Station

Eight active HF antennas[2] were set up at DRAO on tripods in the field adjacent to the HCTF. Five antennas (numbered 1-5) were placed in an East-West line with nominal 15m spacing. The remaining three antennas (numbered 6-8) were aligned North-South with antenna 2 with nominal 20m spacing, resulting in an offset-T configuration. The dipole whips were aligned North-South, with the preamp box facing East. This is an attempt to place the null of the dipole in the direction of the transmitter to reduce the effect of any groundwave propagation. Each antenna was run back to the HCTF funnel via equal-length coaxial cables[3]. Inside the funnel each cable was connected to a power inserter and 80m bandpass filter[4].

Additional gain was required to raise the signal level to be compatible with the beamformer. Eight low-frequency amplifiers[5] were available, but needed to be placed in series to sufficiently raise the signal level[6]. Due to this limitation only four antennas could be operated at a time. A first configuration used antennas 1, 4, 5, and 6. A second configuration used antennas 2, 6, 7, and 8.

[1] 49.500172°N, 119.588228°W (Google Maps).
[2] DX Engineering Active Horizontal Receive Antenna DXE-ARAH3-1P.
[3] RG-6 type 75Ω cable.
[4] Array Solutions AS-80-BPF.
[5] Mini-Circuits ZFL-500LN or similar.
[6] 60-90 MHz investigations done for Rich Bradley's CDT proposal used the same two-amplifier arrangement.

1.3 Small Beamformer

The *small beamformer* is a prototype 16-input "post-correlation" digital beamformer designed for use with NRC's phased array feed (PAF) projects. Narrowband beamforming uses a weight-and-sum approach to produce a beam in a desired direction from an array of antennas. One approach to producing a wider bandwidth beam is to perform this operation over many narrow frequency channels. The advantage of a digital beamformer is that it can typically produce multiple simultaneous beams.

Frequency channel k of beam j is formed from the inner product of a complex weight vector $\mathbf{w}$ and the vector of sampled antenna voltages $\mathbf{x}[n]$:

$$b_{jk}[n] = \mathbf{w}_{jk}^H \mathbf{x}_k[n] \tag{1}$$

In astronomical measurements we are often interested in estimating the power spectral density S for beam j over some averaging period of N samples:

$$\begin{aligned} S_{jk} &= \frac{1}{N}\sum_{n=1}^{N} b_{jk}[n] b_{jk}^*[n] && (2) \\ &= \frac{1}{N}\sum_{n=1}^{N} \mathbf{w}_{jk}^H \mathbf{x}_k[n] \mathbf{x}_k^H[n] \mathbf{w}_{jk}. && (3) \end{aligned}$$

Under the assumption that the weight vector $\mathbf{w}$ is static or does not change faster than the averaging period, this equation can be rearranged as:

$$\begin{aligned} S_{jk} &= \mathbf{w}_{jk}^H \left(\frac{1}{N}\sum_{n=1}^{N} \mathbf{x}_k[n] \mathbf{x}_k^H[n] \right) \mathbf{w}_{jk} && (4) \\ &= \mathbf{w}_{jk}^H \widehat{\mathbf{R}}_k \mathbf{w}_{jk} && (5) \end{aligned}$$

The small beamformer measures $\widehat{\mathbf{R}}_k$. In a "real-time" digital beamformer, the weight vector $\mathbf{w}_{jk}$ must be known *a priori* to produce the time series $b_{jk}[n]$. A post-correlation beamformer cannot produce the time series, only the PSD estimate. However, the beam weights do not need to be known.

For the purpose of the UViip experiment, the ability to estimate the PSD of a beam is not of primary importance. Instead the *cross power* measurements contained in the off-diagonal cells of $\widehat{\mathbf{R}}_k$ are used to estimate the relative phase between all pairs of antennas. The number of cross power measurements is

$$\frac{N_{ant}\left(N_{ant}-1\right)}{2}. \tag{6}$$

The auto power estimates are provided for completeness but do not contain any phase information.

The key parameters when operating the beamformer for PAF experiments and the UViip experiment are summarized in Table 1. The UViip configuration nominally covers the amateur radio 80m band, 3.5–4.0 MHz. For convenience the sample rate is adjusted such that the channel bandwidth is exactly 1 kHz. One should note that the data is collected in an *even* Nyquist zone, which means that the sense of the frequency/channel relationship is reversed: increasing channel is decreasing in frequency.

2 Results

A plot showing a short excerpt of the magnitude and phase of each of the cross power measurements is shown in Figure 1. Although magnitude is not important, it is encouraging that the magnitudes of each measurement correspond well within a roughly 10dB range. We also note that the presence of strong

Parameter	PAF	UViip	Unit
Channels	512	512	N/A
Sample Rate	768	1.024	MSPS
Channel Bandwidth	750	1	kHz
Integration Time	1	0.4	s
Integration Count	750000	400	FFT Frames
Frequency Range	1152–1536	3.584–4.096	MHz
Nyquist Zone	4	8	N/A

Table 1: Comparison of key beamformer parameters for PAF and UViip experiments.

fading indicates that the propagation is most likely by skywave. We also reason that the measured phase differences are not consistent with groundwave propagation. For an 80m groundwave and 20m spacing we would expect 2→6, 6→7, and 7→8 to read 90°. We would also expect 2→7 and 6→8 to read 180°, and 2→8 to read 270°.

The phases in the bottom plot indicate a consistent dataset: the cumulative phase around a set of three or more antennas is close to zero[7]. Spikes in this plot correspond to data loss in the form of packet drops.

A plot showing a short excerpt of the phase waterfall from each of the cross power measurements is shown in Figure 2. It seems that there is a lot of interesting structure here even over 6kHz bandwidth. I am a bit skeptical about whether this is real or an artifact of the instrument.

2.1 Challenges

The CKOR tower[8] transmits with 10 kW at 800 kHz and is located 11 km from the receive station at DRAO. The alias of this signal appears near the center of the band of interest. Without additional amplification, this is the only signal that could be seen. Without filters, the additional amplifiers were driven into non-linear operation by this signal. The 80m bandpass filters help to reduce it to a manageable level.

The additional amplifiers we could find limited operation to four of eight receive antennas. This significantly reduces the number of cross power products in the dataset from 28 to only 6.

Initial difficulties with the GNURadio software and USRP devices led us to use a simple signal generator rather than an SDR approach for the transmitter. Although the SDR issues were resolved, we stuck with the signal generator approach for simplicity given the limited time.

Some of the active receive antennas were possibly damaged by the tripods falling over in the night. They were lowered slightly (from 20 ft. to 16 ft.) after this occurred for better stability.

Finally, the small beamformer does not have all the features you would want in an instrument for this experiment. However, I believe it should give some insight into how one might design and build a more suitable instrument. The integration time was reduced to a practical minimum without design changes. This caused some issues with dropped packets that are apparent in the data. One might identify and cut out these points as a first step in data reduction.

[7] Review the concept of "closure phase" in radio interferometry.

[8] 49.421758°N, 119.606310°W (Google Maps)

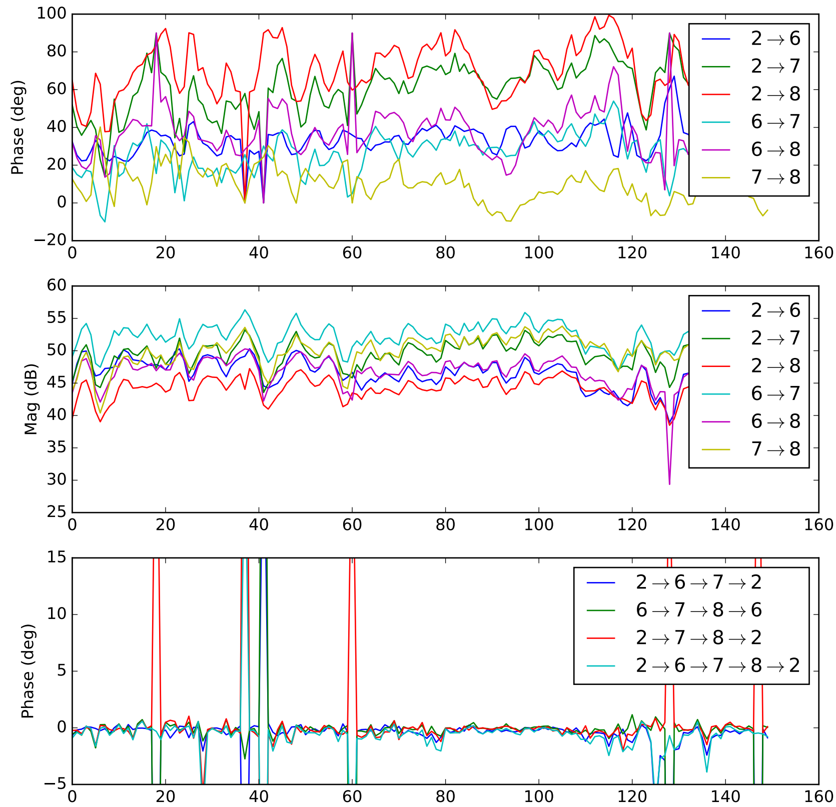

Figure 1: Excerpt of phase and magnitude of CW cross power measurements in configuration 2.

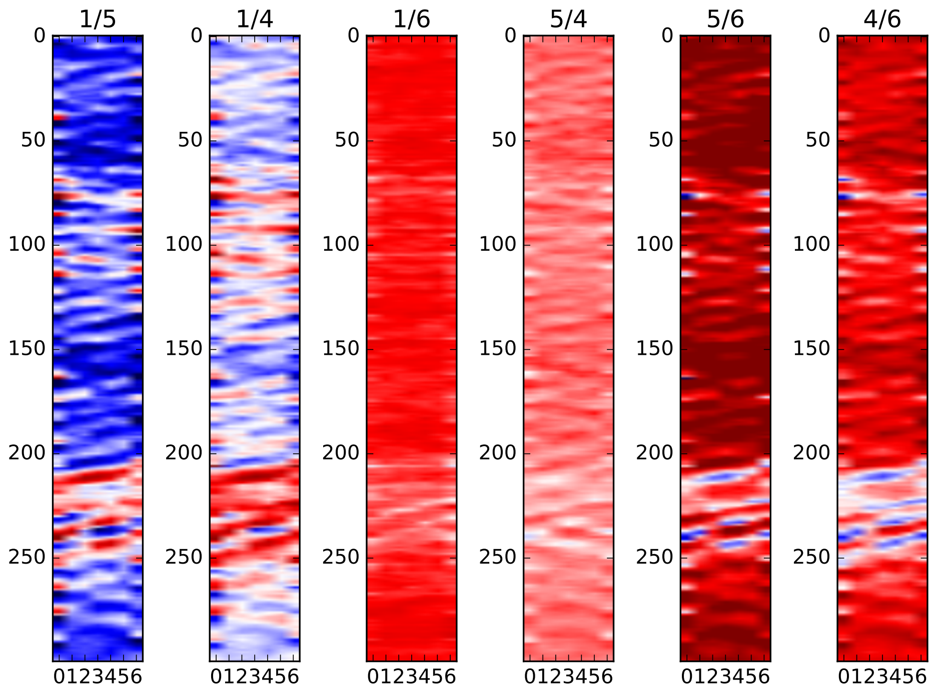

Figure 2: Excerpt of phase waterfalls for a sweep covering seven frequency channels in configuration 1.

2.2 Data Files

Example Python scripts were provided with the data illustrating how to read the files. In general each record is 8229 bytes long. The final 8192 bytes of each record are 512 complex values in binary format. The first 37 bytes of each record are a text string containing the row, column, and UTC timestamp.

File Name	Config	Description
`3700KHZ_CW.dat`	1	CW at 3700 kHz.
`3700KHZ_CW_2.dat`	1	CW at 3700 kHz, second attempt.
`3800KHZ_CW.dat`	1	CW at 3800 kHz.
`3700_3706_Sweep2.dat`	1	400ms sweep from 3700–3706 kHz, 30 minutes.
`3700_CW_Config2.dat`	2	CW at 3700 kHz, 30 minutes.
`3800_Config2.dat`	2	CW at 3800 kHz, 10 minutes.
`3720_3726_Sweep_Config2.dat`	2	400ms sweep from 3720–3726 kHz, 30 minutes.

3 Conclusions and Recommendations

The results seem reasonable based on cursory inspection of the data. As a first step I suggest producing a second set of files in your preferred working format where missing values have been either cut out or interpolated over[9]. The missing data seems to be an unfortunate side effect of decreasing the integration time.

It may be possible to take an iterative approach to determining the virtual height, starting from a plane wave assumption to get the initial estimate, then applying a spherical wavefront model to the phase

[9]Missing values are indicated by $0 + j0$. It is possible to use `np.where()` to get a list of array indices where this occurs.

difference to produce a refined height estimate. It may be worth noting in the data reduction that there is an elevation difference between Penticton and DRAO, I believe it to be about 400m.

I recommend researching possible implementations for a more suitable instrument. One of the most important aspects will be multichannel direct RF sampling that is sample-aligned *without* training. This implies distributing a sample clock and time signal directly to each ADC through a proper phasing network, rather than distributing a reference clock to each device which then generates its own version of the sample clock for the ADC. This eliminates the need for an external calibration source just to "phase up" the array.

As the required bandwidths are very small, the data can continue to be processed in software. However, I recommend moving away from GNURadio as it is constantly in flux and performance is somewhat limited. The astronomical community is increasingly adopting tools for fast packet processing[10], pipeline-oriented computing[11], and GPUs for building high-performance instruments using commodity hardware.

[10] i.e. DPDK (`http://dpdk.org/`)
[11] i.e. HASHPIPE (`https://github.com/david-macmahon/hashpipe`)