Arecibo Upgrade Notes

A DFT FILTER BANK BASED ON THE AUSTEK CHIP: I. BASIC CONSIDERATIONS

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SUMMARY

A DFT filter bank bank is described that is based on the 256-point, 2.5 MHz A41102 Austek Chip. The goal is to analyze a full 10 MHz bandwidth in two polarization channels, yielding time series of power spectra with a minimum amount of aliasing. The design aims to allow use of programmable features of the chip, including (1) the ability to apply multiplicative, downloadable windows to either the time domain or the output transform; (2) to vary the length of the DFT to any value between 2 and 256; and (3) to use the filter bank in real time or offline. Options for recording full-rate data are discussed. For pulsar searching, the detected signals from two polarization channels may be summed before recording to tape. Timing and polarization work requires that the complex DFT outputs be used to form one or four Stokes parameters, respectively, that are synchronously averaged according to the pulsar period. For polarization studies, one must be able to remove Faraday rotation across the analyzed bandwidth. This requires either (1) real time derotation of the Q,U Stokes parameters prior to or along with removing dispersion delays and summing over frequency or (2) recording to disk or tape the averaged Stokes-parameter pulse profiles for each frequency channel.

STRUCTURE OF A PIPELINED DFT FILTER BANK

The primary aim is to provide the detected signal (the intensity) as a function of frequency and time. A single chip can provide 256-point transforms every 102.4 μs. However, the time series of squared magnitudes for each frequency channel is severely undersampled, resulting in signal-to-noise ratios that are nearly a factor of two smaller than for unaliased sampling. The cure is to overlap by 50% and apply a window function to the data blocks. This requires two chips to be working in parallel, each calculating DFT's of 256 valid data points. Other solutions might consist of calculating 256-point transforms of half data and half zeroes with subsequent reconstruction; or polyphase methods might be used. In terms of post-chip processing, however, the simplest approach is the overlap, full data structure.

A configuration to analyze 10 MHz in two polarization channels therefore requires 16 Austek chips, followed by circuitry that takes squared magnitudes and can sum the polarizations. The chips are controllable from an external bus to vary the length of the DFT, download window functions, etc. With sufficient programmability of a post-DFT ALU and multiplier-accumulator, the device can handle computation of squared magnitudes, polarization summing, re-quantizing, and packing prior to writing to disk or magnetic tape as well as handling applications that may require access to the phase information (Stokes parameter computation, Faraday derotation, etc.)

ACHIEVABLE TIME RESOLUTION FOR PULSAR OBSERVATIONS

While each FFT chip provides unity time-bandwidth product and, hence, any time resolution in powers of two of the input sample interval of $0.4\mu s$, dispersion in the interstellar medium (ISM) limits achievable resolutions. As is well known and is shown in 'Time Resolution and Channel

Requirements of Post-detection Pulsar Machines' (NAIC Upgrade Memo XXX), the best achievable time resolution is obtained when the dispersion smearing equals the FFT block time; even then, the time resolution may be limited by scattering in the ISM rather than by dispersion. Figure 1 shows the *best* time resolution that may be obtained (taking dispersion and scattering into account) as a function of frequency and pulsar dispersion measure. The solid lines indicate where the time resolution is limited by dispersion, while dashed lines indicate scattering-limited resolution.

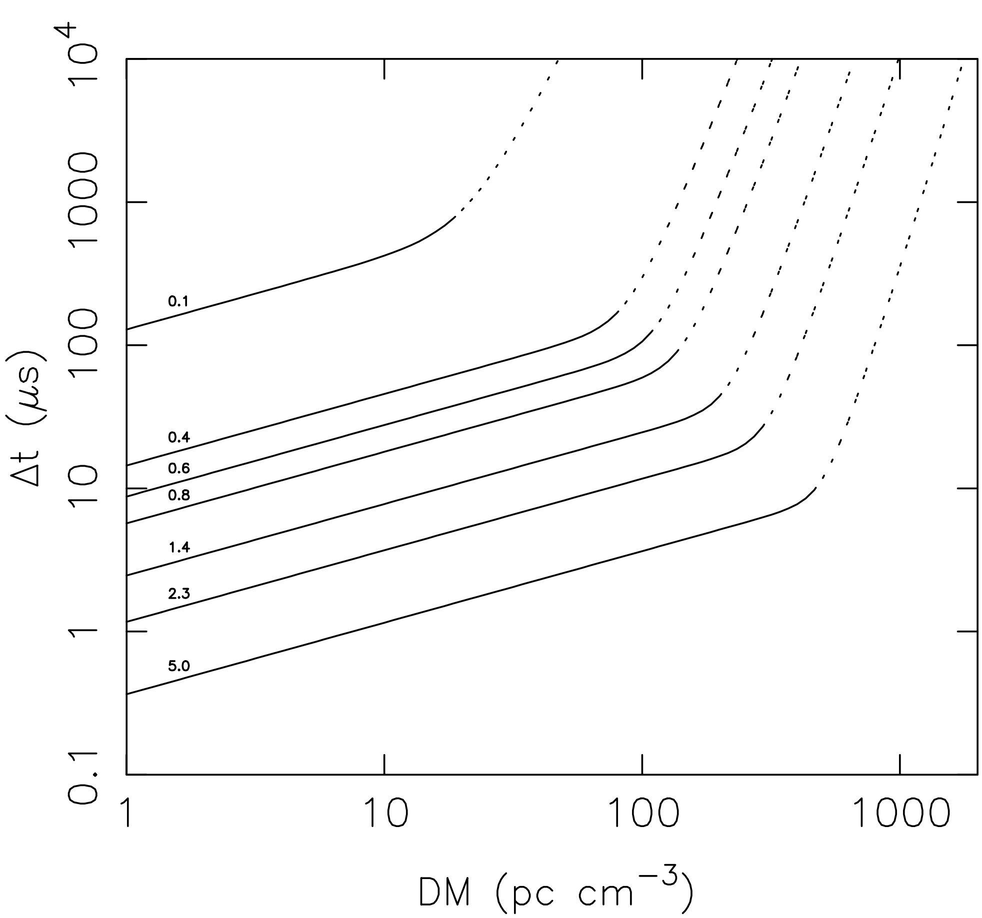

Figure 1: Time resolution of post-detection systems plotted against pulsar dispersion measure. The curves are labeled with radio frequency ranging from 0.1 to 5 GHz. (*Solid lines:*) Time resolution is limited by dispersion; (*Dashed lines:*) Time resolution limited by interstellar scattering.

For a system using the Austek chip in particular, the range of application is shown in Figure 2. Resolutions of 100 μs, or less, are achievable toward the right-hand side of the diagram, labeled 'AUSTEK.' To the left, resolution is limited by dispersion or scattering times greater than the best resolution from the chip. In these cases, the chip output may as well be degraded before recording to disk or tape. These considerations are now looked at in some detail.

Achieving a resolution $\Delta t_{FFT} = N_{FFT}/2B_{chip}$ requires that dispersion smearing be less than

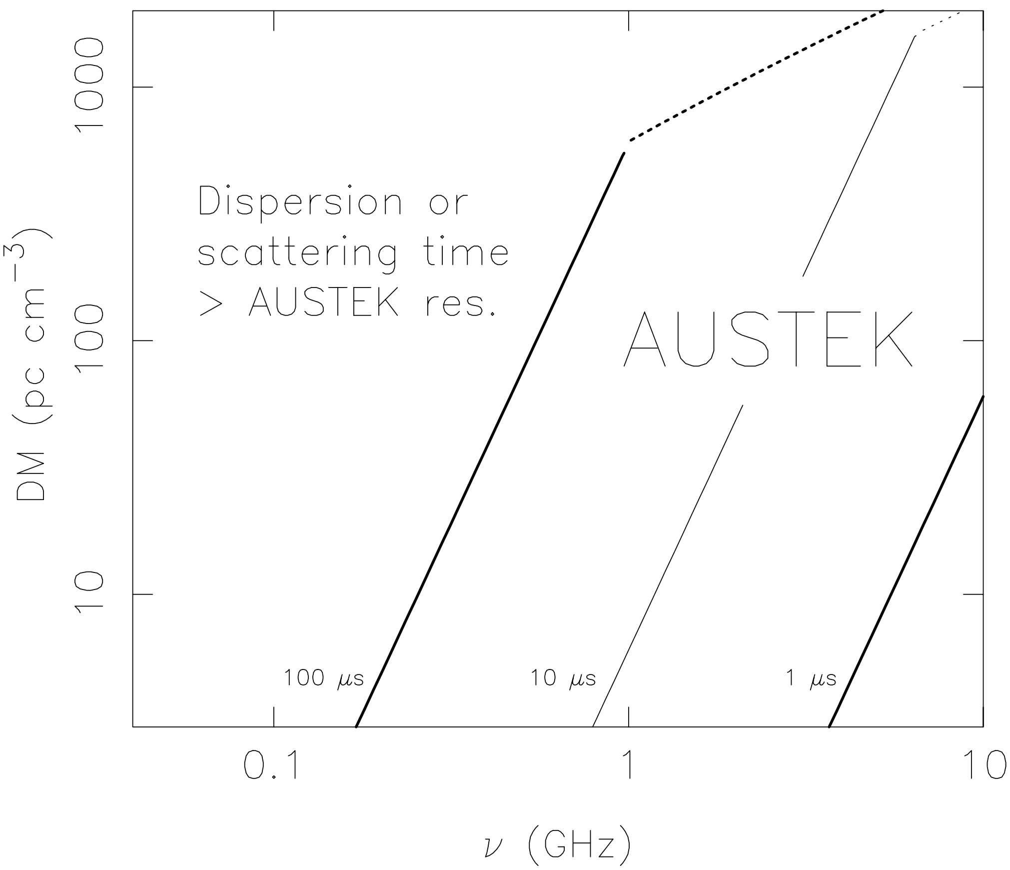

Figure 2: The region in DM-ν space accessible to the Austek chip is between the lines labeled 1 μs and 100 μs. To the left of the line labeled 100 μs, either the dispersion smearing across an individual channel or the pulse-broadening time due to scattering exceeds the sample time per DFT channel at the output of a pair of chips. These curves hold for the case where the chip operates at its largest bandwidth (2.5 MHz) and where the number of output channels is limited to 256. (*Solid lines:*) Achievable resolution is determined by dispersion. (*Dashed lines:*) Resolution is limited by scattering.

Δt_{FFT}, or that the number of channels satisfy

$$N_{FFT} \geq 4.1\, B_{chip,MHz} \left(\frac{DM}{\nu_{GHz}^3} \right)^{1/2} = 10.2 \left(\frac{DM}{\nu_{GHz}^3} \right)^{1/2}, \tag{1}$$

where the second equality holds for $B_{chip} = 2.5$ MHz. Alternatively, for given N_{FFT}, the dispersion measure is limited by

$$DM \leq \frac{N_{FFT}^2 \nu_{GHz}^3}{16.6 B_{chip,MHz}^2} \approx 632\,\mathrm{pc\ cm}^{-3}\, \nu_{GHz}^3, \tag{2}$$

where the approximate equality holds for the largest point transform (256) and the largest bandwidth (2.5 MHz). At 430 MHz, for example, this condition can be satisfied by the 256-point chip running with $B_{chip} = 2.5$ MHz for $DM \leq 50$ pc cm^{-3}. At 1.4 GHz, dispersion measures up to 1730 pc cm^{-3} may be analyzed. The range of dispersion measures that can be tackled decreases rapidly in going to lower frequency. At 300 MHz, $DM \leq 17$ pc cm^{-3}. The consequences of this are that, at low frequencies and high DM, the dispersion smearing time becomes larger than the time interval over which DFT's are output; in other words, for such frequencies and DM's the chip output is *oversampled*. In these cases, the post-chip processor may as well degrade the resolution before recording the data (if, for example, an object with known DM is being observed). Note, also, the cases where the net time resolution is dispersion limited are exactly those for which predetection methods are advantageous.

When dispersion smearing is matched to the chip output sample rate, the time resolution is

$$\Delta t_{FFT} = 2.04\,\mu s \left(\frac{DM}{\nu_{GHz}^3}\right)^{1/2} \leq 51.2\,\mu s. \tag{3}$$

Note that we have built into this calculation the 50% overlap of DFT computations, obtained by using a pair of chips in parallel. †

DATA RATES

For a total bandwidth $B = 10$ MHz, $N_{pol} = 2$ polarization channels analyzed, $N_\Sigma = 2$ polarization channels summed prior to recording, and with m bits per sample, the data rate that must be recorded is

$$R = \frac{2mN_{pol}B}{(\tau/\Delta t_{FFT})N_\Sigma} = \frac{20m \text{ Mbits s}^{-1}}{(\tau/\Delta t_{FFT})}, \tag{4}$$

where $\tau/\Delta t_{FFT}$ is the number of detected samples that are summed, if any. Here $\Delta t_{FFT} = 51.2\,\mu s$ is the time interval between output DFT's (overlapped by 50%). Recording complex data, necessarily without polarization summing, increases the data rate by a factor of four.

RECORDING OPTIONS

The alternatives for handling data rates of $20m$ Mbits s^{-1} or more (eg. ~ 5 Mbytes s^{-1} for $m = 2$) include the following:

(1) An array of 8mm drives with data striping. Phil Perrilat's development system can, in principle, handle 2.5 Mbytes s^{-1} per single board computer (sbc) writing to 5 tapes.

(2) An array of sbc's each writing to a large disk and then to one or more 8mm drives. With a 5 Gbyte disk, 1000 seconds of data could be acquired, then data acquisition could continue on a parallel system while writing from disk to tape. The advantage over (1) is that data striping is unnecessary. However, if the array of sbc's, disks and tape drives cannot keep up with real time, the system will necessarily be a 'burst' sampling one.

(3) VLBA or 19mm drives: can handle > 100 Mbits s^{-1}, so data rates from the Austek system are accomodated. However, similar drives are needed at one or more playback sites, at >$100k each.

(4) Until drive speeds increase for affordable drives and media, an option would be to throttle-down the data rate of the acquisition system to be recordable with, say, option (2).

† The expressions for the required number of channels and the maximum DM in equations (1),(2) are conservative and are based on limiting the dispersion smearing to less than the overlapped sample interval (eg. 50 μs for 256-pt transforms). Searching, in practice, is likely to require resolutions of $\geq 100\mu s$, thus decreasing the coefficient in eqn (1) by a factor of $2^{-1/2}$ and increasing the factor in eqn (2) by 2 for 100 μs. According to how many samples are summed to degrade the time resolution, the data rate in eqn (4) is also reduced accordingly.