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Fast implementation of coherent dispersion compensation

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Abstract. The interstellar medium consists of gas and dust components, almost all of which are completely transparent at centimeter wavelengths. The main cause of radio wave scattering in the interstellar medium is ionized gas—plasma. The behavior of radio waves propagating through such a medium is described by the dispersion equation in a rarefied plasma. The plasma frequency is generally a function of position and time, because it depends on the electron density along the line of sight. The dispersion measure physically represents a column of free electrons between a pulsar and the Earth. Thus, the dispersion measure is a value that determines the delay of radiation pulses of cosmic objects. The delay of radio emission is due to the fact that the refractive index of the plasma depends on the wavelength. Long waves propagate more slowly than short ones, so a signal emitted simultaneously at different frequencies arrives to the observer at long waves later than at short ones. One type of astrophysical objects for which the pulse delay can be measured are pulsars. Since observations are always carried out in a certain wavelength band, the presence of a delay interferes with the study of the fine time structure of pulsar pulses. Without dispersion correction, pulsar observations in a wide frequency band become impossible. The presented work considers the implementation of the coherent dispersion compensation method on a heterogeneous computing structure. Processing in the spectral domain allows the simultaneous search for fast radio bursts (giant pulses), radio pulsars, and refinement of the dispersion measure of the found pulses. It is shown that the proposed implementation on modern computing accelerators allows real-time processing in a wide frequency band that meets modern requirements.

Keywords: pulsars: general; instrumentation: interferometers; methods: numerical

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1 Introduction

The interstellar medium consists of gas and dust components, almost all of which are completely transparent at centimeter waves (Lorimer & Cramer 2005). The main cause of the scattering of radio waves in the interstellar medium is ionized gas, i.e., plasma.

The behavior of radio waves propagating through such a medium is described by the dispersion equation in a rarefied (collisionless) plasma:

$$w^2 = c^2k^2 + w_{\mathrm{p}}^2, \tag{1}$$

where k is the wave number and w_{p} is the plasma frequency.

The plasma frequency w_{p} is generally a function of position and time, because it depends on the electron density in the line of sight $n_{\mathrm{e}}(x,t)$ and is defined as

$$w_{\mathrm{p}} = \sqrt{\frac{4\pi e^2 n_{\mathrm{e}}}{m_{\mathrm{e}}}}, \tag{2}$$

where e and m_{e} are the electron charge and mass, respectively.

Typical values for the electron density n_{e} for our Galaxy are in the range of 0.01 to 1 cm^{-3}, resulting in a plasma frequency w_{p} from 5 to 50 kHz. This is significantly lower than pulsar observing frequencies, which are typically from 100 MHz to 10 GHz, so the approximation $w \gg w_{\mathrm{p}}$ is acceptable. As follows from Eq. (1), the group velocity of radio waves passing through the interstellar medium is determined as

$$v_{\mathrm{g}} = \frac{\partial w}{\partial k} = c\left(1 - \frac{w_{\mathrm{p}}^2}{w^2}\right)^{1/2} \cong c\left(1 - \frac{w_{\mathrm{p}}^2}{2w^2}\right), \tag{3}$$

provided that the final approximation is $w \gg w_{\mathrm{p}}$. The pulse signal of a pulsar (wave packet) passes at a distance d through the medium in a time T defined as

$$\begin{aligned} T &= \int_0^d \frac{1}{v_{\mathrm{g}}} dx \cong \frac{d}{c} + \frac{1}{2w^2c}\int_0^d w_{\mathrm{p}}^2(x)\,dx \\ &= \frac{d}{c} + \frac{1}{w^2}\frac{4\pi e^2}{2cm_{\mathrm{e}}}\int_0^d n_{\mathrm{e}}(x)\,dx = \frac{d}{c} + \frac{1}{w^2}\frac{2we^2}{cm_{\mathrm{e}}}\mathrm{DM}. \end{aligned} \tag{4}$$

This expression is valid as long as the change in the electron density concentration n_{e} at a fixed wavelength can be neglected.

The dispersion measure is defined

$$\mathrm{DM} = \int n_{\mathrm{e}}(x)\,dx. \tag{5}$$

This parameter physically represents a column of free electrons between a pulsar and Earth. Thus, the dispersion measure is a value that determines the delay of radiation pulses of cosmic objects (Eatough et al. 2009).

The wave packet is subject to dispersion or delay in time δT:

$$\delta T = \left|\frac{\partial T}{\partial w}\right| \varDelta w \cong \frac{\varDelta w}{w^3}\frac{w\pi e^2}{cm_{\mathrm{e}}}\mathrm{DM} \cong 8.3\ \mathrm{\mu s}\ \frac{\varDelta w(\mathrm{MHz})}{w^3(\mathrm{GHz})}\mathrm{DM}(\mathrm{pc\,cm^{-3}}). \tag{6}$$

Without dispersion correction, observing pulsars in a wide frequency band becomes impossible. If the delay value δT becomes comparable to the pulsar period, the pulse energy will be “smeared” over the entire period.

The best, most accurate, method is coherent dispersion correction based on the fact that dispersion is a coherent effect. This means that the phase of radio waves varies with frequency according to the dispersion measure DM. This process can be described in the frequency domain by a simple transfer function $H(w) = e^{i\,\phi(w)}$. By applying the inverse filter it is possible to completely eliminate the dispersion effect. The phase in this case is determined as

$$\phi(w; w_0) = \frac{2\pi D w^2}{w_0^2(w_0 + w)}. \tag{7}$$

Such a filter can be applied to a signal with a bandwidth $\varDelta w$ and a central frequency w_0. In this case, w is a frequency band offset so that $|w| < \varDelta w/2 \ll w_0$. The coefficient D is related to the more commonly used dispersion measure DM as $\mathrm{DM} = 2.41 \times 10^{-4}\, D(\mathrm{s\,MHz^2})$.

The Fourier transform of $H(w)$ gives the impulse response $h(t)$ of such a dispersion compensation filter. For the filter defined by Eq. (7), this will be a chirp pulse with a width δT, centered at $t = 0$. The signal dispersion process can be represented as a convolution of the original signal with $h(t)$.

2 Realization

The fast dispersion compensation is implemented on a software correlator with a heterogeneous computing structure. Graphics processing units (GPU) or Alveo V80 can be used as computation accelerators. The software correlator can work both in FX and XF mode depending on the problem being solved. It performs the following main processing steps: bit repacking, fringe rotation and delay tracking, fractional delay correction, spectrum multiplication and integration, Van Vleck quantization correction. Additionally, the correlator can perform phase calibration signal extraction and pulsar gating and binning. For spacecraft navigation, additional tools are used, such as detection and estimation of the Doppler shift and its variation with time and also the Kalman filter for precise frequency detection in a narrow band, which compensates for residual phase rotation. Weighted window functions are used to minimize spectral leakage. The stages of dispersion compensation are described in more detail in (Girin et al. 2023).

The fast implementation is achieved by additional manual code optimization for the low-level Parallel Thread Execution instruction set, which allows increasing the performance up to three times compared to the CUDA library. When performing a discrete Fourier transform (DFT), the data is divided into segments corresponding to the DFT length. Performing a convolution operation corresponds to a cyclic shift in the time domain, and the first n points corresponding to this time shift will be erroneously multiplied by the data at the end of the segment. To avoid such distortion, it is necessary to discard the data which leads to the loss of a signal whose duration corresponds to the time shift. As a result, it is necessary to increase the segment sizes and discard the distorted ones, which leads to an increase in the volume of the processed data. With a short DFT size, the ratio of useless and useful data may be too large. Therefore, the DFT size should be as large as possible. The high bandwidth memory of computing accelerators can be combined into a single virtual space, which allows increasing the duration of one segment to several minutes.

3 Summary

The implemented approach for dispersion compensation using a heterogeneous computing structure allows continuous processing, minimizing the introduced errors inherent to segmented processing. The implemented approach minimizes distortions and improves the quality of coherent dispersion compensation.

References

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