# A Comparative Study of Coherent and Incoherent Dedispersion for Pulsar Signals: Postprint

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## Abstract

During propagation through interstellar space, pulsar signals undergo dispersion due to the presence of the interstellar medium; consequently, dedispersion of the received signals is required to recover the original pulsar signals. Currently, dedispersion methods are primarily categorized into two approaches: coherent dedispersion and incoherent dedispersion. Relatively speaking, coherent dedispersion offers complete dedispersion, employs a relatively simple algorithm, and preserves the temporal resolution of the original data; however, it entails a high computational cost, though rapidly advancing computer technology has now effectively addressed this issue. To precisely characterize the differences between these two dedispersion methods, we quantitatively compared their performance using correlation coefficient analysis: below a certain frequency threshold, the former yields superior dedispersion results compared to the latter. Additionally, we determined the observation frequency at which both dedispersion methods produce equivalent results.

## Full Text

## Comparative Study of Coherent and Incoherent Dedispersion of Pulsar Signals

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### Abstract

During propagation through interstellar space, pulsar signals become dispersed due to the presence of interstellar medium, necessitating de-dispersion of the received signals to recover the original pulsar signals. Current de-dispersion methods are primarily divided into two categories: coherent de-dispersion and incoherent de-dispersion. Relatively speaking, coherent de-dispersion offers complete dispersion removal, employs a simpler algorithm, and preserves the time resolution of the original data, though it requires greater computational resources—a limitation that has been largely overcome by rapid advances in computer technology. To accurately understand the differences between these two methods, this study employs correlation coefficient analysis to quantitatively compare their effectiveness: below a certain frequency threshold, coherent de-dispersion yields superior results to incoherent de-dispersion. Additionally, we determine the observational frequency at which both methods produce equivalent results.

**Keywords:** pulsar; coherent de-dispersion; incoherent de-dispersion

Pulsars are celestial objects with extreme physical conditions including ultra-high temperature, pressure, density, magnetic field, electric field, and gravitational field. They are generally considered products of supernova explosions, with typical radii of approximately 10 km yet masses comparable to the Sun, and core densities reaching $10^1$ g • cm $^3$ [1]. The prevailing view holds that pulsars are rapidly rotating magnetized neutron stars whose rotation axes are inclined relative to their magnetic axes, with radiation beams emanating from both magnetic poles. Pulsar radiation spans nearly the entire electromagnetic spectrum, encompassing radio, infrared, optical, ultraviolet, X-ray, and gamma-ray frequencies. This radiation exhibits high periodicity consistent with the star' s rotation period, with minimal period derivatives.

These extreme physical characteristics and high periodicity of pulsar radiation hold significant research value and application prospects [2]. Scientifically, pulsars can be used to verify and develop physics and astronomy theories under extreme conditions; studies of millisecond pulsar binaries have already tested general relativity and gravitational wave radiation [3,4]. For engineering applications, millisecond pulsars can serve as precise clocks and for interstellar navigation [1,5]. Since millisecond pulsars exhibit period derivatives smaller than $10^{1}$ s • s $^1$, minimal period noise, and relatively high period stability that continues to improve over time—surpassing even hydrogen masers—timing observations of multiple millisecond pulsars in different sky regions can be combined to create an averaged pulsar clock for correcting the long-term stability of existing atomic clocks.

To conduct such research, precise pulsar pulse arrival times must be obtained [1] (Time of Arrival, TOA). However, due to the interstellar medium, received pulsar signals experience dispersion. For theoretical simplicity, the interstellar medium is treated as a cold, low-density plasma with refractive index for electromagnetic waves of frequency f:

$$= \sqrt{1} - ($$

where is the plasma frequency, $= \sqrt{}$ ~8.5kHz ( cm $^3$) ~1.5kHz, and is taken as 0.03 cm ³ [1].

For radio observations, the received pulse signal is a one-dimensional temporal pulse profile, where dispersion delay occurs between pulses at different frequencies. The delay time of the spectral starting frequency signal relative to the cutoff frequency signal [1] is:

= × × ( 1

where DM (Dispersion Measure) represents the dispersion quantity of interstellar medium along the propagation path, = , with units of cm ³ · pc; is the average electron density along the propagation path; D is the dispersion constant of interstellar medium, = 2 4148.808MHz²pc ¹cm³s; and and are the starting and cutoff frequencies of the receiving band in MHz.

Equation (2) shows that dispersion delay across a certain bandwidth causes phase shifts, amplitude reduction, and pulse profile broadening in the time domain, limiting arrival time resolution. Therefore, de-dispersion of received pulsar signals is necessary to obtain precise arrival times, and fitting these arrival times yields relevant physical parameters for studying the pulsar' s radiation mechanism and other characteristics.

[Figure 1: see original paper] Flow chart of de-dispersion algorithms; the upper half shows the coherent de-dispersion flow chart, the lower half shows the incoherent de-dispersion flow chart.

The objective of de-dispersion is to eliminate dispersion effects within the signal band, currently achieved primarily through incoherent and coherent de-dispersion [1]. Incoherent de-dispersion operates on time series by dividing the signal into channels using a filter bank, then shifting each channel' s signal by an appropriate delay relative to a reference channel to align pulses, as shown in Figure 1. Coherent de-dispersion performs continuous de-dispersion across the passband in the frequency domain using the transfer function of interstellar medium (chirp function), also shown in Figure 1.

[Figure 2: see original paper] Pulse profile of PSR J2322+2057. Solid line: profile after coherent de-dispersion. Dashed line: profile after incoherent de-dispersion [6].

Previous studies have compared these two methods. Reference [6] observed PSR J2322+2057 at 430 MHz, obtained average pulse profiles after both coherent and incoherent de-dispersion, and calculated pulse arrival time precision, finding the RMS error ratio of the latter to the former to be 0.3, as shown in Figure 2. Reference [7] used DSP algorithms at 327 MHz to compare integrated profiles from both methods, finding that coherent de-dispersion yielded 10–15 times greater pulse amplitude and time resolution than incoherent de-dispersion [7]. Domestically, the pulsar observation team at Xinjiang Astronomical Observatory of Chinese Academy of Sciences established a coherent de-dispersion system with 64 MHz bandwidth using a MK5A-based VLBI recording system, comparing results with those from a previously used 2×128×2.5 MHz multi-channel incoherent de-dispersion system [8], concluding that coherent de-dispersion is superior, though without systematic quantitative analysis. This paper aims to quantitatively analyze the differences between the two methods using correlation coefficient analysis.

## 1 Principles of De-dispersion

The two de-dispersion methods are based on different principles. Incoherent de-dispersion performs discontinuous de-dispersion through phase shifting of signals in each frequency band in the time domain, while coherent de-dispersion performs continuous de-dispersion based on frequency-domain multiplication, as described below.

### 1.1 Incoherent De-dispersion

The incoherent de-dispersion process first divides the time-domain signal with observation bandwidth BW into numerous narrow channels using a filter bank, then shifts each channel' s signal by an appropriate delay in the time domain, and finally accumulates the amplitudes of all aligned channels to obtain the de-dispersed time-domain signal sequence, as shown in Figure 3 [Figure 3: see original paper]. The advantages of incoherent de-dispersion are small data volume and low computational cost. Its disadvantages are: (1) dispersion effects within individual channels are not eliminated—increasing the number of channels can reduce residual dispersion, but the uncertainty principle res 1/(2 × ) shows that more channels increase the time resolution of individual channel signals, requiring appropriate channel number adjustment based on requirements; (2) since incoherent de-dispersion involves shifting single-channel time series, it loses signal phase information.

[Figure 3: see original paper] Schematic diagram of de-dispersion principles [9]. The upper part shows the principle of incoherent de-dispersion, the lower part shows the principle of coherent de-dispersion.

### 1.2 Coherent De-dispersion

The dispersion effect of interstellar medium is equivalent to a phase shifter, so the received pulsar signal is equivalent to the original signal passed through this phase shifter, which can be characterized by the transfer function ( ) [1]:

( 1 + ) = 2 D DM 1 ( 1+ )

where is the local oscillator frequency and 1 is the intermediate frequency. From the transfer function ( ), the original signal can be completely de-dispersed by multiplying it with its complex conjugate (− ), eliminating dispersion across the entire observation bandwidth, as shown in Figure 3. The maximum time resolution is 1/(2 · ). This method can be used for high-precision millisecond pulsar timing and studies of pulsar radio emission processes.

Theoretically, differences between the two de-dispersion results are primarily caused by the cumulative effect of residual dispersion in each channel, so analyzing their effectiveness can be achieved by analyzing this residual dispersion.

For incoherent de-dispersion of upper sideband signals, Equation (2) shows that the maximum delay across bandwidth BW is:

= D DM (2 + ) 2( + )²

The delay for a single channel is:

= D DM {[ + ]³ 2⁄ − 4 √ +

where is the bandwidth of a single channel, = _ ; _ is the number of filter bank channels; and n ranges from [1, _ /2]. For :

D DM [ + ]³

## 2 Pulsar Signal Simulation, De-dispersion Algorithms, and Comparison Method Implementation

This study uses MATLAB to simulate pulsar signals as received by radio telescopes, implementing both de-dispersion processes and quantitative comparison of their effectiveness, as detailed below.

### 2.1 Original Signal Simulation

Pulsar radiation signals are extremely weak, requiring long integration times to improve signal-to-noise ratio. To simplify calculations, we simulate one period of baseband signal. To facilitate comparison of de-dispersion effectiveness, we adopt a short period of 0.00390625 seconds, and for computational efficiency, we select sampling rate (2 Gbps), sampling duration, and signal bandwidth BW as powers of two. The baseband signals before and after adding dispersion are shown in Figure 4 [Figure 4: see original paper].

[Figure 4: see original paper] (a) Baseband analog signal before adding dispersion; (b) Baseband signal after adding dispersion. Signal spectral bandwidth BW: 1 GHz, starting frequency fo: 1 GHz, dispersion measure DM: 40 cm $^{3}$ • pc. Figure 5 uses the same values.

The simulation process involves: (1) generating baseband signals with bandwidth BW, starting frequency fo, and spectral index -2.0 [1]; (2) transforming the frequency-domain baseband signal to time domain via inverse Fourier transform for Gaussian pulse modulation; (3) transforming the modulated signal back to frequency domain, multiplying by transfer function H(f) to add dispersion; and (4) transforming the dispersed frequency-domain signal back to time domain and adding Gaussian white noise to create the simulated pulsar time-domain signal.

### 2.2 De-dispersion Algorithm Implementation

Based on simulated pulsar signal data of length _ , MATLAB programs implement the de-dispersion process and correlation between the two de-dispersed sequences and the pre-dispersion sequence.

#### 2.2.1 Incoherent De-dispersion Steps

(1) Data binning: Divide the simulated baseband data into equal sequential bins. (2) Polyphase filtering [10,11]: Apply polyphase filtering to data in each bin, reducing sequence length; this mitigates spectral leakage from Fourier transforms. The process involves multiplying each bin' s data by sinc function sequences of equal length, dividing the resulting sequences into four segments, and sequentially adding corresponding points to obtain data of the original bin length. (3) Fourier transform: Perform Fourier transform on data in each bin. (4) Channel separation and shifting: Using the cutoff frequency as reference, shift each channel according to its delay. From Equation (2), the relative delay is _ = × × (1/ ). (5) Inverse Fourier transform and summation: Apply inverse Fourier transform to data in each bin, then sum within bins to obtain the binned data sequence. The incoherent de-dispersion result is shown in Figure 5.

[Figure 5: see original paper] (a) Two-dimensional spectrum after incoherent de-dispersion; (b) Two-dimensional spectrum after coherent de-dispersion.

**2.2.2 Coherent De-dispersion Steps** Since the baseband signal contains only one period, we simplify computation by setting the processing length to one period. The steps are: (1) Direct Fourier transform: Transform the simulated baseband data to frequency domain. (2) Frequency-domain de-dispersion: Multiply frequency-domain data by the de-dispersion function (− ). (3) Inverse Fourier transform: Transform the de-dispersed frequency-domain data back to time domain, obtaining de-dispersed time-domain data of original sequence length. (4) Binning: Fold the de-dispersed data into bins matching the length of incoherent de-dispersion results, then accumulate data within each bin. The coherent de-dispersion result is shown in Figure 5.

### 2.3 Quantitative Comparison of De-dispersion Effects

To quantitatively analyze both methods, we cross-correlate their results with the pre-dispersion data to obtain correlation coefficients:

_ = )

where belongs to sequence X of length N and yi belongs to sequence Y of length N. It is generally accepted that absolute correlation values below 0.3 indicate no linear correlation, above 0.3 indicate linear correlation, 0.3-0.5 indicate low correlation, 0.5-0.8 indicate significant (moderate) correlation, and above 0.8 indicate high correlation; only an absolute value of 1 represents perfect linear correlation, indicating identical signals with the same pulse width and signal-to-noise ratio. The procedure involves: (1) folding the pre-dispersion simulated data to match the length of incoherent de-dispersion results, and (2) cross-correlating both de-dispersion results with this binned data to obtain correlation coefficients.

## 3 Quantitative Comparison of Two De-dispersion Methods

We first present the computational complexity of both methods based on Fourier transform theory and record their processing times. Second, we quantitatively compare their effectiveness. Finally, we estimate the starting frequency of the signal spectrum when both methods produce equivalent results.

During signal simulation and de-dispersion, dispersion measure DM ranges from 1-40 cm $^3$ · pc in steps of 1 cm $^3$ · pc. Signal spectral bandwidth BW takes values of 32 MHz, 64 MHz, 128 MHz, 256 MHz, 512 MHz, and 1 GHz, with single-channel bandwidth of 1 MHz. Signal spectral starting frequency fo ranges from 256 MHz to 8 GHz, with 64 MHz steps for computational time and effectiveness comparisons, and 16 MHz steps for determining the starting frequency where effects are equivalent.

### 3.1 Comparison of Correlation Coefficients from Both Methods

Correlation coefficients between each method' s results and pre-dispersion data are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper]. We first analyze how these coefficients vary with different parameters.

[Figure 6: see original paper] Correlation coefficient between coherent de-dispersion results and pre-dispersion data; for display convenience, coefficients are multiplied by 1000.

Figure 6 shows that coherent de-dispersion yields correlation coefficients approaching 1, indicating that—neglecting errors from discretization—it can perfectly recover the original pre-dispersion signal. Comparing both figures reveals that smaller BW values increase coefficient fluctuations, related to Equation (9). Additionally, spectral leakage occurs during data processing due to truncation frequencies from periodic binning and finite-length discrete Fourier transforms, with these effects increasing as BW decreases.

Figure 7 shows the difference in correlation coefficients between both methods. For a given DM, the coefficient difference decreases exponentially with fo within a certain range, but approaches 1 with diminishing fluctuations beyond a threshold value f1. This indicates that incoherent de-dispersion performs worse than coherent de-dispersion when fo is below f1, with the performance gap narrowing as fo increases; above f1, both methods produce equivalent results. The figures also show that for fixed fo, coefficient variation curves with DM exhibit greater fluctuations at smaller BW due to spectral leakage errors. For fixed fo and DM, the coefficient difference decreases with increasing BW, while f1 increases as

BW decreases. From Equation (6) and Figure 7, we conclude that—within a certain observational frequency range—coherent de-dispersion outperforms incoherent de-dispersion, with the performance gap decreasing exponentially with observation bandwidth and frequency, while increasing with dispersion measure following a power-law relationship. We can also identify the observational starting frequency where both methods yield equivalent results.

[Figure 7: see original paper] Difference in correlation coefficients between the two de-dispersion methods.

### 3.2 Starting Frequency for Equivalent De-dispersion Effects

When both methods produce equivalent results, the single-channel delay in incoherent de-dispersion approaches a near-zero constant. For incoherent de-dispersion with constant channel bandwidth , Equation (6) yields:

$[\ +\ ]^3$

For constant , we derive:

$+\ \sqrt{\ }^{3}$

Using MATLAB, we implemented quantitative comparison of both methods and determined the spectral starting frequency where effects are equivalent. In our implementation, DM ranged 1–40 cm $^{3}$ · pc in 1 cm $^{3}$ · pc steps; BW took values of 32 MHz, 64 MHz, 128 MHz, 256 MHz, 512 MHz, and 1 GHz with 1 MHz channel bandwidth; fo ranged 256 MHz–8 GHz with 64 MHz steps for timing/effectiveness comparisons and 16 MHz steps for determining equivalent-effect frequencies. Quantitative results demonstrate that coherent de-dispersion outperforms incoherent de-dispersion within certain observational frequency ranges, providing guidance for method selection based on observational requirements. Finally, we investigated the starting frequencies yielding equivalent effects under different dispersion measures and bandwidths, offering reference values for specifying observation bands in incoherent de-dispersion pulsar systems. While polyphase filters were employed to mitigate spectral leakage, the issue persists, particularly at low and high frequencies. Future work will expand the range of dispersion measures and single-channel bandwidths while further improving spectral leakage mitigation.

Starting frequency fo (in MHz) for equivalent de-dispersion effects under different BW and DM values; partial data shown.

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*Note: Figure translations are in progress. See original paper for figures.*