Application of Ratio Correction Method in Radio Spectrum: Postprint

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Abstract

Molecular spectral lines can manifest in radio frequency spectra; however, the employment of discrete digital power spectrum analysis algorithms introduces discretization errors, rendering it difficult to obtain accurate spectral information of molecular lines. This study investigates and addresses the frequency offset issue inherent in discrete digital power spectrum analysis of radio frequency spectra through the ratio correction method. As a type of spectral correction approach, this method is distinguished by its simplicity, convenience, and computational efficiency. The correction effectiveness of this method is determined by analyzing variations in normalized frequency offset under conditions of identical RF signals with different resolutions, as well as different RF signals with different resolutions. Spectral correction was ultimately achieved for radio frequencies of 80.0 MHz, 141.8 MHz, and 270.8 MHz, with the corresponding spectral resolution improved to 7.5 Hz/channel. Through comparative analysis of experimental results, the optimal frequency resolution of the test system was established as 50 Hz/Channel or 200 Hz/channel.

Full Text

Application of Ratio Correction Method in Radio Spectroscopy

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Abstract

Molecular spectral lines can be observed in radio spectra, but discrete digital power spectrum analysis algorithms introduce discretization errors that make it difficult to obtain accurate spectral information for these lines. This study investigates and applies the ratio correction method to address frequency offset issues arising from discrete digital power spectrum analysis in radio astronomy. As a spectral correction technique, this method is characterized by its simple, convenient, and computationally efficient algorithm. The correction effectiveness is evaluated by examining variations in normalized frequency offset under conditions of identical RF signals with different resolutions, and different RF signals with different resolutions. We successfully performed spectral correction at radio frequencies of 80.0 MHz, 141.8 MHz, and 270.8 MHz, achieving an improved spectral resolution of up to 7.5 Hz/channel. Comparative analysis of experimental results determined that the optimal frequency resolution for the test system is 50 Hz/channel or 200 Hz/channel.

Keywords: Discrete spectrum analysis; Ratio correction method; Spectral lines; Spectral resolution

Spectral lines serve as powerful tools in astrophysical research, enabling investigations of the physical and chemical environments, evolutionary histories, and classification of celestial objects. Similar to power spectra predicted by various radiation mechanisms, spectral line studies involve single-frequency, multi-frequency, or continuous spectra, manifesting as either absorption or emission lines. These lines originate from hierarchical astronomical structures ranging from stars and nebulae to galaxies, the Local Group, and the entire universe. Multi-wavelength observations enable systematic understanding of these objects. Among numerous spectral lines, the HI 21-cm line serves as a crucial probe for verifying Big Bang theory and revealing the early reionization epoch of the universe [1]. Various line series and recombination lines in spectroscopy facilitate studies of physical parameters such as temperature and velocity of celestial objects, while dust radiation and molecular spectral lines provide essential tools for investigating star formation and interstellar medium.

Different spectral lines have distinct wavelengths, many of which fall within the radio band (0.3 mm–20 m) and can be detected using radio telescopes or antenna arrays. To maximize spectral line detection, besides requiring excellent radio astronomical observing environments, telescopes must possess sufficient sensitivity and resolution. Consequently, the development of key equipment such as low-noise amplifiers, broadband receivers, large-aperture antennas, and multi-beam or focal plane arrays (wide field of view) has become a major research focus internationally and domestically. Equally important are the development of multi-channel digital backends, high-speed data processing and storage systems, and observational techniques or strategies.

In addition to spatial and temporal resolution requirements, molecular astrophysics and spectral line observations impose stringent demands on the frequency resolution of backend systems [2]. In studies of interstellar medium and star formation, the velocity or velocity gradient fields of celestial objects represent important physical quantities. These manifest as redshift or blueshift—Doppler motion—relative to the local standard of rest defined in astrometry and galactic dynamics. Such velocities cause detected spectral line frequencies to drift relative to laboratory-measured frequencies, and higher frequency resolution enables precise measurement of this drift, thereby improving the reliability of velocity measurements. Additionally, line broadening can be more accurately determined. As shown in [Figure 1: see original paper], physical information such as velocity and temperature of celestial objects can be obtained from the discrete spectral profile of H(96) , demonstrating that higher spectral resolution yields more accurate astrophysical information.

In practice, observing equipment and methodologies introduce certain frequency drifts and velocity broadenings into spectra, creating systematic errors that necessitate spectral correction. Although widely applied in engineering fields, spectral correction remains underutilized in astronomy. During spectral analysis, fitting methods are typically employed to test channel stability and channel spacing consistency, with spectral correction methods rarely used and offset corrections seldom applied. This approach suffices for spectral line observations with modest frequency resolution requirements (10^1-10^2 Hz). However, as astronomical observation demands increase and receiver/backend precision and stability improve accordingly, simple fitting becomes inadequate, making spectral correction particularly crucial.

Spectral correction represents an important research topic in signal processing. Since computers can only process finite samples and sampling points, time-domain signals must be truncated and digitally discretized, inevitably causing energy leakage and fence effects that produce significant errors in amplitude, phase, and frequency of discrete spectra [3-4]. For single-frequency harmonic signals after windowing, amplitude errors can reach up to 36.4%, phase errors up to 90°, and frequency errors up to 0.5 frequency resolution bins [5].

Numerous discrete spectrum correction methods exist domestically and internationally, among which the ratio correction method is commonly used. Based on the composition structure of the original time-domain signal, these methods 主要分为两类：一类主要针对单频信号，另一类针对密集频谱. Since radio astronomical spectral line signals are primarily single-frequency signals—even those caused by energy level splitting have large spacing between frequency components—this paper focuses exclusively on single-frequency signal spectral correction. For single-frequency signals, five power spectrum correction methods exist: ratio correction method, energy centroid method, FFT+FT continuous refinement method, phase difference method, and phase difference plus single-point FT method [6]. This study simulates radio astronomical observation hardware and software systems and employs the ratio correction method, which offers algorithmic simplicity, fast computation, and high precision [7], to perform frequency calibration on noise source signals processed through LabView programs and agile transceivers.

1 Ratio Correction Method

In spectral line research, frequency, flux, and polarization constitute important observables. Since frequency stability and measurement bias indirectly affect flux and polarization measurements and calibration during integrated observations, this section focuses exclusively on frequency calibration applications of the ratio correction method.

The ratio correction method establishes an equation with normalized correction frequency as the variable by utilizing the ratio of window spectrum functions for two spectral lines near the main lobe peak with a normalized frequency difference of 1, then solves for the normalized correction frequency to perform frequency, amplitude, and phase corrections [8]. Multiple approaches exist for solving the normalized correction frequency: direct formula derivation (ratio formula method), iterative solution (ratio iteration method), and search-based solution (ratio peak search method).

Assuming the normalized window function' s spectral magnitude expression is W (f), and since the magnitude is positive within the main lobe, the spectral magnitude function equals the normalized window spectrum function completely. W (f) is symmetric about the y-axis, meaning the main lobe center is at the coordinate origin.

If a periodic signal' s frequency exactly aligns with an emission (absorption) spectral line frequency, the calculated frequency, amplitude, and phase are all accurate. More commonly, the signal frequency does not fall precisely at a channel center, causing the peak spectrum to reflect inaccurate frequency and amplitude values with large phase errors. The main lobe center is not at the coordinate origin but has a certain offset f (-0.5 f 0.5).

In high-precision radio astronomical measurements, accurate spectral line information must be precisely measured, so spectral offset should be minimized as much as possible. Let f__y denote the spectral line emission frequency and f__r denote the spectrometer reception frequency. Under ideal equipment conditions, ground test experiments should yield f__y = f__r. However, with analog-to-digital conversion technology development and discrete digital signal application, continuous spectra become discretized. Since the spectral line emission frequency f__y lies within a specific channel K (amplitude spectrum line number) but not necessarily at the channel center position f , combined with time-domain signal truncation effects, the deviation between f__y and f can be significant. Through spectral correction, high precision (Hz-level) can be achieved such that f _c = f__y = f__r.

In actual spectra, assuming the number of sampling points is 2N and the sampling frequency is 2f_s, then the number of channels is N, the sampling bandwidth is f_s, and K [1, N/2-1] [9]. If channel K has amplitude Y_k, and its adjacent channels K-1 and K+1 have amplitudes Y_{k-1} and Y_{k+1} respectively, then the frequency corresponding to channel K is:

When Y_{k-1} > Y_{k+1}, as shown in [Figure 2: see original paper]:

$$\frac{Y_{k-1}}{Y_k} = \frac{W(f_1 + 1)}{W(f_1)}$$

When Y_{k-1} < Y_{k+1}, as shown in [Figure 3: see original paper]:

$$\frac{Y_{k+1}}{Y_k} = \frac{W(f_1 - 1)}{W(f_1)}$$

For a rectangular window, the frequency correction amount is:

$$\Delta f = \frac{Y_{k-1} - Y_{k+1}}{Y_{k-1} + Y_k + Y_{k+1}}$$

The corrected frequency [10] is:

$$f_{0_c} = (K + \Delta f) \cdot \frac{f_s}{N}$$

As shown in [Figure 4: see original paper], the above correction algorithm applies to discrete spectra with a starting frequency of 0 Hz. However, in practical applications, this starting frequency is generally not 0 Hz, requiring further calculation for specific fields. In radio spectra, the true frequency is:

$$f_r = f_{LO} + f_{0_c}$$

where f_{LO} represents the local oscillator frequency. For multiple local oscillator stages, the frequencies of all stages must be summed to obtain f_{LO}.

2 Experimental Setup

In radio astronomical observations, astrophysical spectral line signals are at L-band and higher frequencies (>1 GHz), requiring down-conversion to reduce pressure on digital backend sampling. Signals from the observed source, after passing through the antenna and receiver, are modulated to tens or thousands of megahertz, and such intermediate frequency signals are then sent to the backend for sampling and calibration.

To simulate such an intermediate frequency signal, a standard signal source was used with output frequency set to 141,800,000.00 Hz. Meanwhile, the NI2901 agile transceiver served as the analog-to-digital conversion and data sampling device, with a LabView program developed to set backend parameters and control the operation process. Additionally, through power spectrum calculations within the program, the input bandwidth was divided into N digital channels to refine the signal bandwidth, thereby improving frequency resolution to meet various astronomical requirements.

The experiment configured different frequency resolutions to observe the performance of the ratio correction method under different astronomical requirements. Although higher resolution benefits astronomical observations, it must align with current technological development levels, necessitating reasonable parameter configuration. Details are provided in . The carrier input and actual carrier sections of reveal certain deviations between set parameters and equipment responses, which introduces inconvenience for data analysis. To ensure statistical significance, each configuration was tested five times.

For specific observing bands, intermediate frequency signals differ due to variations in observed sources and detected molecules. Considering that the 40-meter radio telescope' s molecular line backend has an intermediate frequency input bandwidth of 1 GHz (2 GHz after upgrade), spectral line signals may appear at tens or hundreds of MHz positions within the passband. Therefore, experimental groups at 80.0 MHz and 270.8 MHz were also established to study the ratio correction method' s performance with different output signals and frequency resolutions. Differing from parameters, when the RF signal was 80 MHz, the carrier input was 79.9795 MHz and actual carrier was 79.9795 MHz; when the RF signal was 270.8 MHz, the carrier input was 270.7695 MHz and actual carrier was 270.77 MHz.

3 Results Analysis

Through multiple tests and data analysis, theoretical and technical defects were identified and resolved, yielding several results. Careful analysis of these results facilitates further research into spectral correction theory and application of relevant methods to actual observations. This paper established different experimental groups for different purposes, described separately below.

First, the normalized frequency offset f exhibits certain patterns when the RF signal is identical but frequency resolution differs. In and [Figure 5: see original paper], 0–4 represent the indices of five tests. The figures show that when frequency resolution is too high, values vary across tests, whereas at lower frequency resolution, test results show better consistency, indicating system instability under high spectral resolution requirements. Moreover, more scatter points have f > 0, meaning Y_{k-1} < Y_{k+1} in most cases, which matches and [Figure 6: see original paper]. Additionally, [Figure 5: see original paper] and [Figure 6: see original paper] demonstrate that regardless of resolution level, normalized frequency offset always falls within [-0.5, 0.5]. Therefore, the ratio correction method achieves better correction results at higher frequency resolution. For the equipment used in this experiment, practical observing frequency resolution can be selected among 50 Hz/channel, 100 Hz/channel, or 200 Hz/channel.

Second, with identical frequency resolution but different RF signals, the normalized frequency offset f also differs. and [Figure 7: see original paper] show that when RF signals are 80 MHz, 141.8 MHz, and 270 MHz respectively, normalized frequency offsets differ significantly, with substantial variations between high and low frequency resolution cases. The figures reveal that when frequency resolution is 50 Hz/channel or 200 Hz/channel, the system is most stable for normalized frequency offsets f of all three signals, with values within [-0.2, 0.2]. Combined with [Figure 5: see original paper] and [Figure 6: see original paper], this indicates the ratio correction method is best and fastest when observing at high frequency resolution and analyzing normalized frequency offset.

These results are understandable: since the ratio correction method uses only three adjacent points, it shows high dependence on frequency resolution. If observations are conducted at high frequency resolution followed by normalized frequency offset analysis, the ratio correction method becomes the optimal and most efficient correction approach.

4 Summary and Outlook

The ratio correction method is simple and practical, providing great convenience for radio astronomical spectral analysis. Based on known test frequencies, this work, though differing from actual observations, represents pioneering work for improving future observational data quality. Only when systematic errors and external interference are well avoided can studies of celestial dynamics, kinematics, temperature, and density be credible. The specific significance includes three aspects: (1) testing frequency stability of signal sources or local oscillators, with long-term monitoring revealing variation patterns; (2) in frequency-switching observations requiring continuous local oscillator frequency changes, monitoring local oscillator frequency stability and accuracy is necessary; (3) although regular frequency stability testing is generally not required in actual astronomical observations, this work provides valuable reference for determining instrument errors, testing instrument performance, and enabling more in-depth frequency calibration and monitoring.

In the future, before antenna observation of spectral line signals, this paper resolves the spectral correction problem and also specifies recommended resolution settings (50 Hz/channel or 200 Hz/channel) for dynamic spectral correction work. Additionally, Doppler effects from celestial objects also cause frequency drift in spectra, which will be the focus of next-step research and can be conducted alongside source and spectral line selection.

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References

[1] ROHLFS K, WILSON T L. Tools of Radio Astronomy[M]. JIANG Biwei, trans. Beijing: Beijing Normal University Press, 2008: 11.

[2] ZENG Qin, MAO Ruiqing, PEI Chunchuan. Microwave Spectral Line Diagnostics in Astrophysics[M]. Beijing: Science and Technology of China Press, 2006: 12.

[3] DUAN Huming, QIN Shuren, LI Ning. Review of Correction Methods for Discrete Spectrum[J]. Journal of Vibration and Shock, 2007, 26(11): 138-145, 189.

[4] DING Kang, ZHU Xiaoyong. Research and Development of Spectrum Correction Theory[C]//Proceedings of 1999 Chinese Conference on Neural Networks and Signal Processing. 1999: 528-532.

[5] ZHU Xiaoyong, DING Kang. Comprehensive Comparison of Discrete Spectrum Correction Methods[J]. Signal Processing, 2001, 17(1): 91-97.

[6] DING Kang, XIE Ming, YANG Zhijian. Theory and Technology of Discrete Spectrum Analysis Correction[M]. Beijing: Science Press, 2008.

[7] SONG Lianjun. Research on Dense Spectrum Correction Methods for Radio Astronomical Signals[D]. Kunming: Yunnan University, 2017.

[8] DING Kang, XIE Ming, WANG Zhijie. Correction Methods and Error Analysis for Amplitude, Phase and Frequency of Discrete Spectrum[J]. Dynamic Analysis and Testing Technology, 1996, 14(1): 10-29.

[9] XIE Ming, DING Kang. Correction Method for Spectrum Analysis[J]. Journal of Vibration Engineering, 1994, 7(2): 172-179.

[10] XIE Ming, DING Kang. A New Correction Method for Discrete Spectrum Analysis[J]. Journal of Chongqing University (Natural Science Edition), 1995, 18(2).

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