Applications of Chirp Signals in Astronomical Observations (Postprint)

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Abstract

A Chirp signal is a signal whose frequency varies continuously and regularly with time. Due to its excellent autocorrelation properties, it has important applications in real-time broadband high-precision spectral measurements. Through the analysis of Chirp signals, this paper introduces the pulse compression technique based on linear Chirp signals and the principle of Chirp transform spectrometers, reviews the applications and development history of Chirp transform spectrometers in infrared spectral measurements of planetary and cometary atmospheres over the past 30 years, and proposes research directions for improving the performance of Chirp transform spectrometers in conjunction with current developments in electronic technology.

Full Text

Abstract

Chirp signal is a signal whose frequency changes continuously with time according to a certain rule. Due to its excellent autocorrelation characteristics, Chirp signal has important application in real-time high-precision spectrum measurement. This paper introduces the characteristics of the Chirp signal and the principle of spectrum measurement based on the pulse compression. It reviews the development of Chirp Transform Spectrometer (CTS) and its application in measurement of infrared spectrum of planetary atmosphere and comets for the last 30 years. Considering the latest electronic technologies, the development trend of CTS is pointed out.

Keywords

Chirp signal; Pulse compression; Chirp transform spectrometer; Spectral analysis of planetary atmosphere; Surface acoustic wave

Introduction

Chirp signals are characterized by their frequency varying continuously with time according to a specific law. Compared to single-frequency signals, they exhibit superior autocorrelation properties. Bell Laboratories leveraged these characteristics to implement pulse compression technology in radar systems, which improved ranging accuracy, increased the signal-to-noise ratio of received signals, and enhanced radar resolution and sensitivity while reducing transmit power [1-3]. In radio applications, Chirp signals have become a key technology for improving measurement precision and SNR, finding widespread use in radar, spectrum measurement, and spread-spectrum communications [4].

In astronomical research, spectral measurement of molecular and ionic radiation and absorption lines provides information about material composition and environmental conditions. Planetary atmospheric radiation and absorption spectra lie in the infrared band—higher than the microwave RF band of conventional electronic equipment but lower than the visible band of optical devices. Due to component performance limitations, IR spectral measurement equipment for planetary atmospheres has difficulty simultaneously meeting the requirements for broadband and high-precision real-time spectral measurement, constraining IR spectroscopic studies of planetary atmospheres [5-7].

According to the principles of spectral morphology and atmospheric models, precise measurement of the shape of radiation or absorption spectral lines from planetary atmospheres can yield information about atmospheric composition, temperature, and pressure. For IR spectral line observations, the IR band spectral signal is typically down-converted via IR front-end equipment to an intermediate frequency (IF) band that meets bandwidth requirements, and back-end processing equipment is used to obtain broadband, high-precision spectral shapes. To meet these measurement requirements, several IR back-end spectrometers have been developed, including autocorrelation spectrometers, acousto-optical spectrometers, and filter bank spectrometers. However, these devices cannot simultaneously satisfy the demands for high precision and broadband real-time measurement, and suffer from instability and calibration difficulties [5].

Theoretically, pulse compression based on Chirp signals can be used to implement the mathematical operations of Fourier transform, converting spectral measurement into multiplication and convolution operations between the signal and Chirp signals [3,5]. The Chirp Transform Spectrometer (CTS) implements this principle using electronic devices, particularly surface acoustic wave (SAW) filters, to generate and convolve Chirp signals, solving the problem that traditional atmospheric IR spectral observation equipment could not simultaneously meet bandwidth and spectral precision requirements.

The Max Planck Institute for Radio Astronomy successfully developed CTS for Earth atmosphere, planetary atmosphere, and comet atmosphere measurements using SAW filter devices and Chirp signals. These spectrometers employ a superheterodyne reception scheme, are particularly suitable for installation on spacecraft, and exhibit excellent parameters in terms of power consumption and stability. The performance of CTS has continuously improved and has been successfully applied to millimeter-wave atmospheric sounding, the Rosetta comet detector's microwave remote sensing equipment (MIRO), and the German Receiver for Astronomy at Terahertz frequencies (GREAT) on SOFIA [5-9].

CTS using SAW filters for broadband IR back-end spectral measurement offers advantages of simple structure, wide measurement bandwidth, high precision, low power consumption, and high reliability [5,10]. However, issues with SAW filter devices regarding insertion loss, bandwidth, and frequency flexibility limit further performance improvements of SAW-based CTS [5]. With the development of digital electronics, the Max Planck Institute utilized Direct Digital Synthesis (DDS) chips to generate linear Chirp signals. DDS chips can generate pre-distorted broadband linear Chirp signals that match device distortions to correct dispersion in analog circuits, and can flexibly change the bandwidth and frequency points of Chirp signals. Researchers have used vector signal generators to produce 1 GHz bandwidth linear Chirp signals for high-precision molecular spectroscopy measurements [6,9,11]. The application of DDS has further improved CTS performance.

1. Chirp Signals and Pulse Compression

1.1 Characteristics of Chirp Signals

The defining characteristic of Chirp signals is that their frequency changes continuously with time. Signals with frequency varying linearly with time are called linear Chirp signals, while those with frequency varying exponentially are called exponential Chirp signals. Chirp signals are ubiquitous in nature, appearing in phenomena such as the Doppler effect, gravitational waves, and bird chirps (the original English meaning). Linear Chirp signals are commonly used in electronic equipment for astronomical observations.

For a linear Chirp signal, the frequency varies linearly with time. The frequency expression is:

$$f(t) = f_0 + \frac{(f_1 - f_0)t}{T}$$

where f_0 is the initial frequency, f_1 is the final frequency, and T is the frequency sweep period. The phase $\phi(t)$ is a quadratic function of time t:

$$\phi(t) = \phi_0 + 2\pi \left(f_0 t + \frac{(f_1 - f_0)t^2}{2T} \right)$$

Within one frequency sweep period, the time-domain expression of the Chirp signal is:

$$s(t) = A\cos[\phi(t)]$$

Linear Chirp signals are also called quadratic phase signals. The time-domain waveform and frequency-time relationship of a linear Chirp signal are shown in [Figure 1: see original paper]. The waveform shows progressively denser oscillations over time, with frequency increasing linearly from low to high. Chirp signals are also commonly used as sweep-frequency signals in electronic equipment.

[Figure 1: see original paper] A linear Chirp signal and its spectrogram

The frequency-time relationship for a Chirp signal can be expressed as:

$$f(t) = f_0 \times k^{t/T}$$

where k is the base determining the exponential rate of frequency change. The phase of the Chirp signal is:

$$\phi(t) = \phi_0 + 2\pi f_0 \int k^{t/T} dt$$

Within one frequency sweep period, the time-domain expression is:

$$s(t) = A\cos[\phi(t)]$$

[Figure 2: see original paper] shows the time-domain waveform and frequency-time curve of an exponential Chirp signal. The frequency increases exponentially from low to high with periodic repetition, and the rate of frequency change is faster than that of linear Chirp signals.

[Figure 2: see original paper] An exponential Chirp signal and its spectrogram

1.2 Pulse Compression

The principle of pulse compression is to modulate a characteristic signal onto the transmitted signal in signal processing, and then use the same characteristic signal for correlation at the receiver to detect the transmitted signal. Modulating with a characteristic signal increases the signal' s autocorrelation, making it easier to detect and measure. Pulse compression is commonly applied in radar, sonar, and echo detection to increase ranging precision and improve detection SNR [4].

For example, in radar echo detection using rectangular pulse signals, if the pulse width is T, the correlation function is a triangular function of width $2T$. If two echoes are separated by less than T, their correlation functions will overlap and become indistinguishable. Using pulse compression technology, a linear Chirp signal with bandwidth Δf is modulated onto the transmitted signal, and the same Chirp signal is used for detection at the receiver. The autocorrelation function of the Chirp signal can be expressed as:

$$R(\tau) = \mathrm{sinc}(\pi \Delta f \tau) e^{j2\pi f_0 \tau}$$

The main lobe width is $1/\Delta f$. The detection results are shown in [Figure 3: see original paper] and [Figure 4: see original paper].

[Figure 3: see original paper] Echo detection using rectangular pulse signal [Figure 4: see original paper] Echo detection by pulse compression using Chirp signal

Compared with rectangular pulse echo detection, Chirp signal pulse compression technology provides higher SNR and resolution in autocorrelation detection. The width of the compressed pulse is inversely proportional to the frequency range of the Chirp signal—the wider the Chirp signal’ s frequency range per unit time, the sharper the correlation peak and the higher the measurement precision.

2. Chirp Transform Spectrometer

2.1 Principle of Spectrum Measurement Using Chirp Signals

The principle of spectrum measurement using Chirp signals can be derived from the Fourier transform. The Fourier transform can be expressed as:

$$S(f) = \int_{-\infty}^{\infty} s(t) e^{-j2\pi f t} dt$$

where $s(t)$ is the time-domain signal and f is the signal frequency. Let τ be the frequency sweep time and μ be the rate of frequency change with time. The term $2ft$ can be decomposed as:

$$2ft = t^2 + \tau^2 - (t-\tau)^2$$

The Fourier transform can then be expressed as:

$$S(f) = e^{-j\pi\mu\tau^2} \int_{-\infty}^{\infty} \left[s(t) e^{-j\pi\mu t^2} \right] e^{j\pi\mu(t-\tau)^2} dt$$

This shows that the Fourier transform can be represented as the signal $s(t)$ multiplied by a linear Chirp signal $e^{-j\pi\mu t^2}$, then convolved with a linear Chirp signal $e^{j\pi\mu t^2}$ having the opposite frequency sweep rate, and finally multiplied by the phase factor $e^{-j\pi\mu\tau^2}$. Using this principle, the multiplication and convolution operations with Chirp signals can implement Fourier transform to calculate the signal spectrum.

2.2 Implementation Principle of Chirp Transform Spectrometer

The principle of the spectrum measurement device implementing Chirp signal pulse compression is shown in [Figure 5: see original paper] [5-7].

[Figure 5: see original paper] The principle of CTS

The input signal is the IF signal after down-conversion of the IR spectral signal, with bandwidth f_{IF}. The generated linear Chirp signal is modulated onto this IF signal. The modulated signal is then convolved with a Chirp signal having the opposite frequency sweep rate to achieve pulse compression detection based on the Chirp signal. In this process, the time delay of the corresponding correlation peak corresponds to the frequency of the measured IF signal. By measuring the time delay signal shape, the IR spectral shape can be obtained in real time. The Chirp Transform Spectrometer converts frequency measurement into time delay measurement.

Since a Chirp signal can be decomposed into a linear superposition of frequency components, measuring the time delay signal shape allows real-time measurement of the spectrum. The implementation block diagram is shown in [Figure 6: see original paper].

[Figure 6: see original paper] A block diagram of CTS

The Chirp signal generator produces a linear Chirp signal, which passes through a mixer to modulate the measured IF signal. After filtering and amplification, the signal is input to a SAW filter to implement convolution with the Chirp signal. The output is a linear Chirp signal with time delay. Through data acquisition, storage, and signal processing, the correlation peak signal of the Chirp signal is obtained. By measuring the time delay of the correlation peak signal, the spectrum of the measured signal can be calculated.

2.3 Applications of Chirp Transform Spectrometer

Chirp Transform Spectrometers have been deployed in ground-based, airborne, and space-based observations since their first development and application in the 1980s. They have conducted IR spectral line measurements of Earth atmosphere, comets, and interstellar medium molecules.

CTS was first applied to ground-based atmospheric detection, measuring ozone, water vapor, and carbon dioxide molecules in Earth' s mesosphere to obtain atmospheric profiles of molecular density and study their motion and transport in the atmosphere. The Chirp Transform Spectrometer at ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research) has conducted routine observations of water vapor molecular spectra in Earth' s middle atmosphere for one solar cycle (1996-2006), accumulating data for improving Earth atmospheric models and atmospheric radiation spectral shape theory [23-24].

The Stratospheric Observatory for Infrared Astronomy (SOFIA) uses a 2.5m infrared reflecting telescope on a Boeing 747SP aircraft flying at altitudes above 15 km to avoid atmospheric water vapor absorption of IR spectra, enabling continuous observations with higher sensitivity. The German REceiver for Astronomy at Terahertz frequencies (GREAT) on SOFIA uses a Chirp Transform Spectrometer to observe spectral lines of carbon ions, molecules, and oxygen atoms in three bands (1.6-1.9 THz, 2.6 THz, and 4.7 THz) [8-9].

ESA's Rosetta comet detector, the first to successfully orbit and land on a comet, carried multiple-band IR observation equipment to study planetary surface and atmospheric composition, evolution, and structure, as well as interstellar material characteristics. The Microwave Instrument for Rosetta Orbiter (MIRO) uses a Chirp Transform Spectrometer to measure IR spectral line shapes of water, ammonia, and carbon dioxide in the comet tail and evaporating gases of comet 67P/Churyumov-Gerasimenko, obtaining composition and pressure information [25].

In China, CTS has been applied to radio astronomical observations of interstellar molecular spectral lines. The Urumqi radio telescope' s molecular line observation system based on CTS has discovered more than a dozen possible water maser sources [21-22]. CTS has also been applied at the Purple Mountain Observatory' s Qinghai station for 22 GHz water maser observations, with a center frequency of 529 MHz and real-time bandwidth of 39.9 MHz.

2.4 Development Trends of Chirp Transform Spectrometer

Chirp Transform Spectrometers were developed starting in the early 1980s and practically applied in the mid-1980s. shows the typical specifications of CTS for different project applications from 1983-2004 [5-7].

Specification of CTS

Parameter	1983	1996	2004
IF Frequency (MHz)	70	1400	2150
Bandwidth (MHz)	40	400	215
Spectral Resolution (kHz)	40	40	41.7
Mass (kg)	23	2.3	2.3
Power (W)	140	14	14

The data show that over time, the IF frequency, measurement bandwidth, and dynamic range of Chirp signal measurements have all improved, while power consumption and mass have significantly decreased. These improvements benefit from advances in SAW filter devices and digital processing components. The increase in IF frequency and measurement bandwidth also owes to higher signal sampling rates and data processing speeds. After 1996, newly developed CTS achieved more than 1-2 times improvement in measurement bandwidth, with power consumption and mass decreasing by an order of magnitude.

Deep space exploration imposes stricter requirements on spectrometer power consumption and mass. The GREAT-CTS deployed on SOFIA in 2004 achieved a spectral measurement bandwidth of 215 MHz with maximum measurement frequency of 4.7 THz, mass of 2.3 kg, and power consumption of 14 W. The application of direct frequency synthesis has significantly improved the efficiency and precision of IR spectral line shape measurements for planetary and cometary atmospheres, providing rich and accurate data for atmospheric models.

The wave of informatization has promoted the widespread application of electronic technology, especially digital processing technologies that are evolving rapidly. CTS first adopted direct digital synthesis to generate broadband Chirp signals in 2004. Over the past decade, introducing higher-performance SAW filter devices and other novel digital processing technologies into CTS will certainly further improve its performance to meet the needs of real-time observations with wider bandwidth and higher precision, providing better observation means for planetary atmosphere and interstellar medium research in China while achieving low power consumption and high stability.

Technologies such as Field Programmable Gate Array (FPGA) implementation of Fast Fourier Transform combined with CTS measurement, digital RF signal acquisition and playback, software-defined radio [26-28], and magnetostatic surface wave filter technology [29] can all be applied to CTS. In particular, with advances in microelectronics, digital devices offer better flexibility and performance than analog devices like SAW filters. IR back-end measurement equipment implemented with digital autocorrelators may gradually replace SAW-based CTS. However, it should be noted that for airborne and space applications with strict stability and power requirements, CTS implemented with SAW filters remains an effective measurement approach.

Conclusion

Chirp signals exhibit excellent autocorrelation properties. The Chirp Transform Spectrometer, implemented based on Chirp signals and pulse compression principles for measuring IR band molecular spectral line shapes, provides a means to obtain planetary and cometary atmospheric composition, temperature, and pressure parameters. CTS uses SAW filter devices to implement Chirp signal generation and convolution operations. Benefiting from the excellent performance of SAW filters, CTS offers advantages of small size, low power consumption, and high reliability compared to autocorrelation spectrometers, acousto-optical spectrometers, and FFT spectrometers. CTS has been deployed in ground-based, airborne, and space-based detection equipment for measuring spectral line shapes of Earth atmosphere, comets, and interstellar medium molecules.

With the development of electronic technology, the application of direct digital synthesis devices has further improved CTS performance. Technologies such as digital acquisition and playback, software-defined radio, and magnetostatic surface wave filters can be applied to CTS to enhance measurement performance. High-performance digital devices like FPGAs can be introduced into CTS and combined with FFT spectrometers. Based on the latest digital and SAW filter devices, China can develop new CTS with wider frequency bands and higher precision for IR line measurements, providing better observation means for Earth atmosphere, comet, and interstellar medium research, as well as technical reserves for future deep space exploration and airborne IR astronomical observation projects.

References

[References section preserved exactly as in the original text]

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

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