Postprint: Study on AD Conversion Accuracy Requirements for the Digital Front-End Key Module of Astronomical Fabry-Perot Filter Controllers

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Abstract

Fabry-Perot filters have found increasingly widespread application within China's astronomical community. The Fuxian Lake Solar Observatory of Yunnan Observatories has recently procured two Fabry-Perot filters for deployment in spectroscopic observations with the 1-meter New Vacuum Solar Telescope. Given that domestic research on Fabry-Perot filters remains relatively limited and relevant foreign documentation is not readily accessible, comprehension of their control system is essential not only for independent development but also for routine operational maintenance. Addressing this need, this study introduces the fundamental principles of Fabry-Perot filters, delineates their control system architecture, and specifically examines the analog-to-digital conversion precision requirements for the digital front-end. Through calculation of the F-P parallel plate control precision, an appropriate analog-to-digital converter satisfying the specifications is identified.

Full Text

The Research on Accuracy Requirements of Digital Front-End AD Converter for Key Modules of Astronomical Fabry-Perot Interferometer Controllers

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Abstract

Fabry-Perot Interferometers (FPIs) have become increasingly widely used in China' s astronomical community. The Fuxian Lake Solar Observatory at Yunnan Observatories has recently purchased two FPIs for spectral observations with the 1-meter New Vacuum Solar Telescope. Since domestic research on FPIs remains limited and relevant foreign technical documentation is not readily accessible, understanding their control systems is essential not only for developing indigenous FPI technology but also for daily operational maintenance. This paper introduces the fundamental principles of FPIs, describes their control systems, and investigates the analog-to-digital (AD) conversion accuracy requirements for the digital front-end of these control systems. By calculating the control precision required for F-P parallel plates, we ultimately identify AD converters that meet these stringent requirements.

Keywords: Fabry-Perot Interferometers, Fabry-Perot Controller, Digital Circuits, AD Converter

1 Overview

In its simplest form, a Fabry-Perot cavity consists of two parallel plates with high reflectivity and high transmittance [Figure 1: see original paper]. Such cavities have broad applications across multiple wavelength regimes. Beyond optical instruments, they are extensively employed in microwave systems and gravitational wave detection, where Fabry-Perot resonators can store photons for milliseconds. They also serve as sensors, such as infrared detectors and polarimetric measurement tools.

Fixed-gap Fabry-Perot devices, known as etalons, typically employ precision-machined quartz spacers to support the reflective surfaces and meet optical requirements. While theoretically the gap could be altered through external pressure or temperature changes, such systems are practically limited to single-wavelength applications. These etalons are most commonly used in laser communication systems.

In astronomical spectroscopic observations, Fabry-Perot etalons significantly enhance the resolving power of imaging spectrometers, enabling the resolution of extremely fine spectral line differences. In solar observation instruments, they function as narrowband filters that isolate desired spectral lines for imaging, with the H line and Ca-K line filters being prime examples. Compared to other filter types, FPIs offer substantial advantages in transmittance, and advanced designs can achieve scanning frequencies in the Hz range during spectroscopic observations, providing clear speed advantages.

Proposed by French physicists Charles Fabry and Alfred Perot, the Fabry-Perot Interferometer exploits resonance phenomena to create wavelength-selective transmission. The transmitted wavelength in vacuum satisfies:

$$\lambda = \frac{2d \cdot \cos \alpha}{m}$$

where d is the plate separation, α is the incident angle, m is the interference order, and λ is the transmitted wavelength. This creates a comb-like transmission characteristic [Figure 2: see original paper], which requires cascading or combination with other filtering devices when a single wavelength is needed. The tunable wavelength, minimal optical components, and lack of special crystal materials make FPIs particularly suitable for wavelength scanning applications (such as solar H scanning) where photon flux is low and large apertures are required. Although theoretically scanning could be achieved by changing the refractive index of the medium within the cavity, practical implementation is extremely difficult. Consequently, wavelength scanning is realized by varying the plate separation d.

Astronomical FPIs were first developed by Ring et al. in 1956, with Dobrodski conducting trial observations by 1959. The earliest successful solar observations using FPIs were reported by J.V. Ramsay et al. in 1967, employing an open structure with photographic plates as focal plane detectors. Since then, FPI applications in astronomy have grown increasingly widespread, with performance steadily improving. In recent years, Chinese observatories have begun introducing FPIs for experimental observations. For instance, the Fuxian Lake Solar Observatory has purchased two FPIs for use with the 1-meter solar telescope.

However, current FPI controllers still employ analog circuits, with no digital controllers reported in the literature. Compared to analog circuits, digital circuits offer higher precision, making research into digital FPI controllers both necessary and valuable.

2.1 Control System Overview

Fabry-Perot interferometers demand extremely strict mechanical fabrication and alignment tolerances. Applying automatic control technology can relax these mechanical installation requirements. Furthermore, astronomical observations—particularly solar observations—require scanning across several to dozens of points within the H spectral line width, necessitating adjustable optical gaps for wavelength scanning. The fundamental requirements for the control system thus include maintaining parallelism, gap precision, and scanning capability.

Purely electrical systems employ various electrical micrometry techniques, specifically capacitive, inductive, and piezoelectric methods. While inductive micrometry has successful domestic applications, its use is limited by magnetic permeability variations due to multiple factors. Piezoelectric methods have even more disadvantages and are rarely employed. Capacitive micrometry is universally preferred for FPIs primarily because it can be made compact and offers stable performance.

Unlike optoelectronic systems that directly measure optical path differences, electrical systems use capacitive sensors to measure plate spacing, requiring periodic calibration of the relationship between "electrical" spacing and optical path. Current practice involves recalibration approximately every three days—a labor-intensive process. The recalibration criterion is when the central wavelength at zero position deviates by 15% from the design value.

As shown in Figure 3 [Figure 3: see original paper], two pairs of capacitors are orthogonally arranged at the edges of the FPI plates: CX1 and CX2 in the X-direction, and CY1 and CY2 in the Y-direction. Each capacitor consists of electrode pairs coated on the upper and lower plates. Theoretically, when the plates are perfectly parallel, CX1 = CX2 and CY1 = CY2; any inequality indicates misalignment in the corresponding direction.

With orthogonal capacitor pairs and three piezoelectric ceramic pillars (A, B, C) arranged at 120° intervals [Figure 4: see original paper], the feedback system can correct the plate parallelism by applying output voltages to the piezoelectric actuators. This configuration ensures the rotation center remains at the mirror center during tip-tilt correction, thereby maintaining a constant optical gap.

2.2 Actuators and High-Voltage Drive Circuits

In the optical band, the maximum actuator stroke requirement originates from scanning needs, approximately 2 m, with continuous variability preferred. Piezoelectric ceramics (PZT) are the optimal choice, providing sufficient adjustment margin. Early implementations required stacking multiple PZT layers bonded to glass—a complex fabrication process—and astronomers and engineers had to devote considerable effort to developing high-voltage drive circuits. However, PZT actuators and their drivers have become widely available commercial products with extensive market penetration, enabling selection of suitable off-the-shelf components for astronomical applications.

2.3 Overall Control Circuit

Signals from the sensors are extremely weak and must be amplified and processed to satisfy feedback control requirements. For the CX channel [Figure 5: see original paper], a differential capacitor pair (CX1/CX2) is driven, and the output from their common junction is detected. When the two capacitors are equal and the drive signals VA and VB have equal amplitude but opposite phase, the output is zero; any inequality produces a non-zero output. This signal is amplified, demodulated by a phase-sensitive detector (PSD), processed through an operational amplifier matrix to calculate the required signals for the three PZT channels (A, B, C), and then amplified by high-voltage drivers to complete the closed-loop control. Here, Vcom serves as a reference signal with constant phase difference relative to VA.

However, fabrication tolerances prevent CX1 and CX2 from being perfectly identical, resulting in unequal outputs even when the physical gap is equal.

Moreover, equal physical gaps do not guarantee equal optical gaps, necessitating compensation for CX1 and CX2. The CY1/CY2 pair requires similar compensation, and even after independent X and Y compensation, differences between the X and Y channels must be addressed. Additionally, since wavelength scanning requires adjustable gaps, the system must provide controlled gap adjustment. When CZ equals Cref, the output is zero. CZ does not affect plate parallelism, while Cref provides a gap reference for adjustment and compensates for environmental factors through identical temperature, humidity, and pressure conditions. After considering these factors, three balancing adjustments (X-balance, Y-balance, Z-balance) are implemented, along with three offset adjustments (X-offset, Y-offset, Z-offset) to compensate for circuit biases and other channel differences. A DA converter forcibly applies bias to the Z-axis for gap adjustment and wavelength scanning, typically using 8-bit resolution for 256-step scanning, though in practice only a few to several dozen steps are used. This yields the complete system framework shown in Figure 6 [Figure 6: see original paper].

2.4 Digitalization of Key Control Circuit Modules

The control system depicted in Figure 6 employs analog circuitry—the current standard practice. However, analog circuits suffer from interference and distortion issues. In contrast, digital circuits process analog quantities through programmable algorithms, offering simpler structure and easier debugging while mitigating these problems. To minimize errors, we have undertaken the digitalization of key control system modules.

Focusing on the X-channel, the digital control module for the CX channel is shown in Figure 7 [Figure 7: see original paper]. The feasibility of this digital control system primarily depends on whether the differential analog-to-digital converter can detect the minimum output difference between CX1 and CX2. The following sections therefore examine the differential analog-to-digital conversion circuit.

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3 Differential Analog-to-Digital Conversion Circuit

This section provides further analysis based on the circuit shown in Figure 5.

3.1 Input Stage

Taking Cx as an example, it is a simple parallel-plate capacitor with capacitance:

$$C_X = \varepsilon \cdot \varepsilon_0 \cdot \frac{S}{d}$$

where ε is the relative permittivity of the medium (for nitrogen at standard conditions, $\varepsilon = 1.00058$, approximated as 1 for sufficient precision), ε_0 is the vacuum permittivity (8.86×10^{-12} F/m), S is the plate area (typically tens to hundreds of square millimeters), and d is the plate separation (5-10 m). Consequently, the capacitance is only tens to one hundred microfarads: $C_X =$ 10–100 pF (we currently select $C_X = 10$ pF for our investigation).

Assuming the X-drive bridge is an ideal source, the equivalent output impedance of the capacitive sensor at the operating frequency of 10 kHz is on the order of hundreds of kilohms, representing a high-impedance signal source. Therefore, the first-stage amplifier must provide sufficiently high input impedance to achieve adequate transmission efficiency and detection sensitivity.

3.2 Differential Circuit Control Accuracy Requirements

If the control accuracy must exceed the spectral bandwidth by two orders of magnitude, taking the central wavelength as 656.3 nm yields a spectral bandwidth corresponding to a plate separation of 0.1 nm, with the Fabry-Perot parallel plates operating at a separation of 29533.5 nm. The required control precision is therefore 3.39×10^{-6}. A 32 kHz square wave is converted to a sinusoidal signal, which after passing through a fully differential amplifier produces two signals of equal amplitude and opposite phase. These signals pass through two parallel-plate capacitors of approximately 10 pF each and enter the differential ADC. Figure 8 [Figure 8: see original paper] illustrates the sinusoidal signal path through the parallel-plate capacitors into the differential ADC circuit.

Considering the various effects on plates placed within the FPI cavity, the equivalent circuit is shown in Figure 9 [Figure 9: see original paper]. The two equal-amplitude, opposite-phase signals from the fully differential amplifier pass through parallel-plate capacitors CX1 and CX2 into the differential ADC, where Z1 and Z2 represent impedances accounting for other factors, U is the signal voltage, and Uo is the differential ADC input voltage. When the plate separation of CX1 and CX2 varies, the voltage difference that must be detected by the differential ADC is calculated as follows:

$$U_{01} = \frac{U}{Z_1 + Z_{CX1}}$$

$$U_{02} = \frac{U}{Z_2 + Z_{CX2}}$$

$$U'_{01} = \frac{U}{Z_1 + Z_{CX1}}$$

$$U'_{02} = \frac{U}{Z_2 + Z_{CX2} + \Delta Z_{CX2}}$$

$$\Delta U_{02} = U'_{02} - U_{02}$$

Thus, $\Delta U > 3.39U \times 10^{-6}$. With $U = 5$ V, $\Delta U_o = 3.39 \times 5 \times 10^{-6} = 1.69 \times 10^{-5}$ V. If digital error must not exceed 1%, the input voltage corresponding to 1 LSB is:

$$1\text{LSB} = 1.69 \times 10^{-7} \text{ V}$$

Therefore, only when $1\text{LSB} < 1.69 \times 10^{-7}$ V can the differential ADC detect the voltage difference.

3.3 Selection of Differential Analog-to-Digital Converter

According to the Nyquist sampling theorem, the ADC sampling frequency must exceed twice the analog input signal frequency, requiring a sampling rate greater than 64 kSPS. While the highest-resolution differential ADC currently available is the 32-bit AD7177-2, its maximum channel scan rate is only 10 kSPS—far below the requirement.

The highest-resolution differential ADCs with scan rates exceeding 64 kSPS available on the market are 24-bit devices. Through screening, we analyze the AD7760 as an example to determine whether it meets the experimental accuracy requirements.

The AD7760 is a high-performance, 24-bit sigma-delta ADC that combines wide input bandwidth, high-speed capability, and sigma-delta conversion advantages, achieving 100 dB signal-to-noise ratio at 2.5 MSPS—making it highly suitable for high-speed data acquisition applications.

The analog input range depends on the reference voltage used. With a 4 V reference, the input range is ±3.2 V differential offset based on a 2 V common-mode voltage, which can be implemented using the on-chip differential amplifier to reduce external signal conditioning requirements. At 78 kHz output data rate, the AD7760 achieves 120 dB dynamic range. With reference voltage $U_{REF} = 4.096$ V, common-mode voltage is $U_{REF}/2 = 2.048$ V, and maximum input voltage is $0.8U_{REF} = 3.275$ V.

Applying Thévenin’ s theorem to the differential ADC input impedance for the CX1 channel yields the equivalent circuit shown in Figure 10 [Figure 10: see original paper]. The analog input voltage to the differential ADC is:

$$U_{01} = \frac{Z_{ADC}}{Z_1 + Z_{ADC}} \cdot U_1$$

The CX2 channel circuit is similar, giving:

$$U_{02} = \frac{Z_{ADC}}{Z_2 + Z_{ADC}} \cdot U_2$$

With $U = 5$ V and $U_O = 0.5U = 2.5$ V:

$$1\text{LSB} = \frac{2.5\ \text{V}}{2^{24}} = 1.49 \times 10^{-7}\ \text{V}$$

Since $1\text{LSB} < 1.69 \times 10^{-7}$ V, the voltage difference between CX1 and CX2 exceeds the differential ADC' s LSB. Therefore, the AD7760 converter satisfies the design requirements.

3.4 AD7760 Accuracy Analysis

ADC conversion accuracy is typically expressed through resolution and conversion error. This section analyzes the conversion error. Conversion error represents the difference between actual and ideal digital outputs, usually expressed as a multiple of the least significant bit. Using manufacturer data for the AD7760, we analyze its accuracy errors as shown in Table 1 .

From the dynamic range formula $20 \times \log(2^n/1)$, we obtain $n = 20$ bits. The conversion error is therefore:

$$U_{\text{conversion error}} = \frac{2.5\ \text{V}}{2^{20}} = 2.38 \times 10^{-6}\ \text{V}$$

Since $U_{\text{conversion error}} \ll \Delta U_o = 1.69 \times 10^{-5}$ V and all DC accuracy errors are less than 0.01%, their impact on the input signal is negligible. Thus, AD conversion error has minimal effect on Fabry-Perot plate voltage control, meeting the filter' s requirements.

Table 1. AD7760 Parameters

Parameter	Test Conditions/Comments	Value
SNR	Input amplitude = -0.5 dBFS	100 dB (typical)
SFDR	Non-harmonic, input amplitude = -6 dBFS	dB (typical)
THD	Input amplitude = -0.5 dBFS	dBc (typical)
DNL	Guaranteed 24-bit monotonicity	% (typical)
INL		% (typical)
Zero error drift		% (maximum)
Gain error drift		%FS/°C (typical)

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4 Conclusion and Outlook

Currently, FPI programmability remains low, with development proceeding slowly. Available literature indicates that core control loops are still fully analog, with programmability limited to peripheral functions such as state maintenance, locking procedures, mode switching, and wavelength scanning. Preliminary estimates suggest that AD/DA converters introduce excessive errors under such high-precision control requirements—though the relative maturity and adequate performance of analog approaches may explain their continued use. However, long-term development necessitates digitalization and programmability. In large telescope segmented mirror applications, fully analog core loops are unreliable for long-distance transmission, making digitalization essential—a transition with numerous successful precedents.

Our calculations demonstrate that commercially available differential ADCs can meet the design requirements for digital FPI controllers, establishing the feasibility of control system digitalization. Future work will focus on in-depth research toward implementing a fully digital control system for Fabry-Perot interferometers.

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