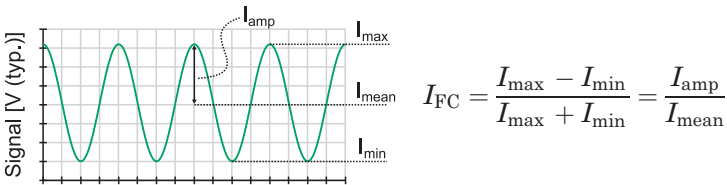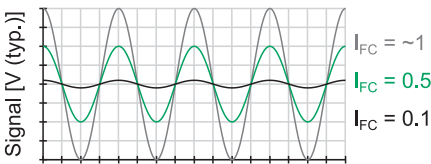## Fringe Contrast

**Fringe contrast** is a measure of the interference quality. Good fringe contrast is needed to accurately measure interference signals. When the contrast is too low, the signal-to-noise ratio decreases. Fringe contrast is scaled 0 to 1, where 0 is no fringe contrast, and 1 is perfect fringe contrast.

$$I_{FC} = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{I_{amp}}{I_{mean}}$$

Be sure to use a DC-coupled detector when measuring fringe contrast. Adjust the interferometer alignment to maximize the fringe contrast in the optical signal. Then, use electronic filtering and amplification to maximize the signal for analog-to-digital conversion.

$I_{FC} = \sim1$
$I_{FC} = 0.5$
$I_{FC} = 0.1$

High DC offset leads to varying fringe contrast for different signal amplitudes.

$I_{FC} = \sim1$
$I_{FC} = \sim1$
$I_{FC} = \sim1$
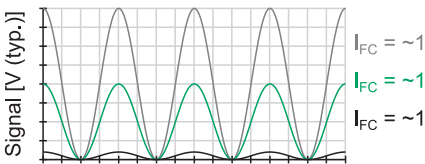
If the signal mean is half of the amplitude, then the maximum fringe contrast is observed.

$ADC_{max}$
$ADC_{min}$
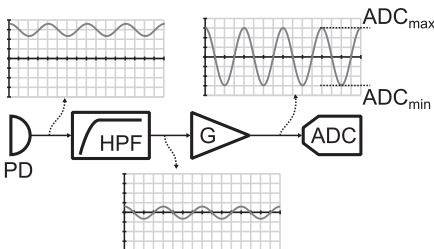
Use a high-pass filter (HPF) and an amplifier (G) to maximize the signal amplitude for analog-to-digital conversion (ADC).

## Displacement from Phase Change

In DMI, narrow-linewidth sources are used, ensuring that interference occurs even when there are long **optical path differences** (OPDs) between the **measurement arm** and **reference arm**. The reference arm of the interferometer is the optical path that the light takes after the main splitting surface until it interferes with the light from the measurement arm. Similarly, the measurement arm is the optical path of the light after the main splitting surface that travels to and from the measurement target before interfering with the light from the reference arm.
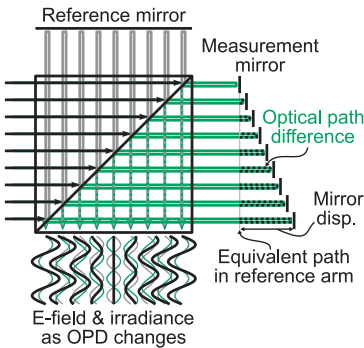
When light reflects $N$ times from a moving target, the optical path is twice the physical displacement, scaled by the refractive index. Thus, $N$ is twice the number of passes:

$$z_o = nNz_p$$

$$\theta = \frac{2\pi z_o}{\lambda} = \frac{2\pi nNz_p}{\lambda} = \frac{2\pi nNz_p f}{c}$$

When the OPD is $m\lambda$ (for $m = 0, 1, 2,...$), the arms constructively interfere because both optical beams are in phase. As the OPD changes to fractions of wavelengths, the corresponding interference phase changes proportionally. These **phase changes** are directly proportional to the change in OPD.

Since the measured phase is a modulo-$2\pi$ signal, the absolute phase is unknown, and only phase changes can be measured.
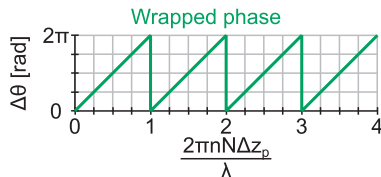
$$\Delta\theta = \frac{2\pi nN\Delta z_p}{\lambda} \rightarrow \Delta z_p = \frac{\lambda\Delta\theta}{2\pi nN}$$

Displacements larger than $\lambda/nN$ result in a wrapped measurement phase signal.
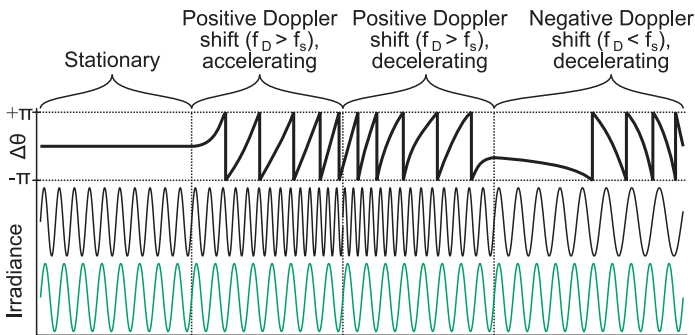
## Heterodyne Directional Sensitivity

**Directional sensitivity** in heterodyne interferometry is obtained based on the frequency difference between the reference interference signal and the measurement interference signal. The reference interference signal (or **optical reference**) is typically constant at a known frequency $f_s$ based on the heterodyne laser source. When the measurement target is stationary, the measurement interference signal is constant and equal to the optical reference. When the measurement target moves, a Doppler shift occurs in the measurement interference signal, causing the frequency to increase or decrease.
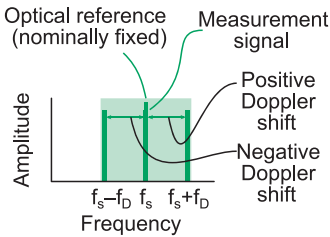


In the **Fourier spectrum**, the optical reference is fixed. When the measurement signal has a frequency lower than the optical reference, the target is moving away from the interferometer because the signal is undergoing a negative Doppler shift. Similarly, measurement signals with a higher frequency than the optical reference undergo a positive Doppler shift.



Because the phase change is measured relative to a signal with a defined frequency, there is no directional ambiguity. As long as the phase is correctly unwrapped or fringes are counted, heterodyne interferometers are inherently sensitive to direction.
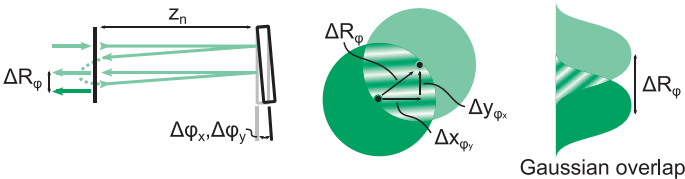
## Beam Walkoff

PMIs are largely insensitive to small target mirror tip-and-tilt motion due to the retroreflector in the interferometer. Small mirror tip-and-tilt motions do lead to lateral displacements between measurement and reference arms in PMIs. This lateral displacement, or **beam walkoff**, reduces the achievable fringe contrast because a smaller overlapping zone is created that generates the interference signal.
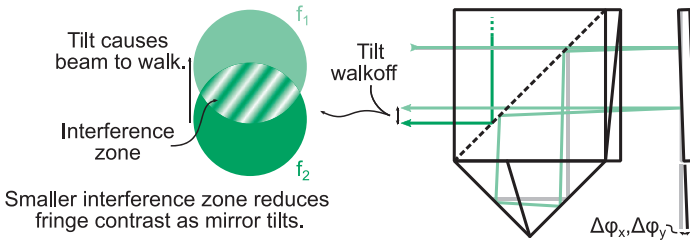


The amount of walkoff scales based on the distance $z_n$ between the interferometer and the target. Even for small rotations, the walkoff can be significant if the distance to the target is large. For small angles, the walkoff is $\sim 2\Delta\varphi/z_n$, which discounts the additional walkoff that will occur in the beamsplitter and retroreflector. Both tip and tilt will generate walkoff, so the total beam overlap shifts by $\Delta R_\varphi$.

$$\Delta R_\varphi = \sqrt{\Delta x_{\varphi_y}^2 + \Delta y_{\varphi_x}^2}$$



In many cases, the interfering beams have a Gaussian profile. Small walkoff changes cause the overlapping area, and thus the fringe contrast, to significantly decrease.

## Time Interval Analysis

**Time interval analysis** is a relatively simple method to measure the phase in heterodyne interferometry. Its origins stem from when microprocessor options for fixed- or floating-point calculations were limited. Both interference signals are detected, converted to a voltage using a transimpedance amplifier, and then converted to a square wave using a **zero-crossing detector** (ZCD). The two square waves then behave as digital 1-bit signals that can be compared to a fast clock (CLK).
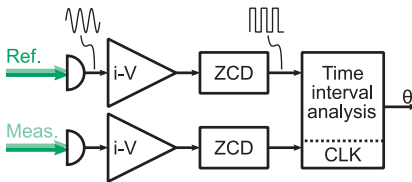


The timestamp triggered by zero crossing is then recorded using two counters, one for the reference and one for the measurement. During a specific measurement interval, the numbers of zero crossings and timestamps are recorded. The number of displaced fringes is determined by the difference in zero crossings between the measurement and reference signals. Fractions of a fringe can be interpolated by analyzing the timing of the last two measurement crossings and the last reference crossing.



$$\frac{\theta}{2\pi} = R - M + \left( \frac{T_{m,i} - T_r}{T_{m,i} - T_{m,(i-1)}} \right)$$
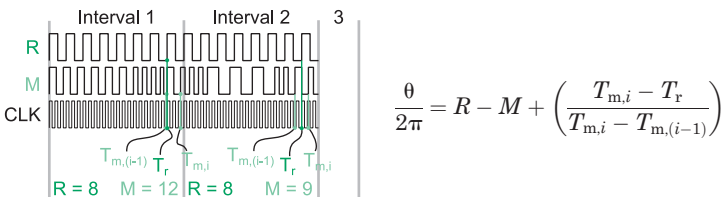
**Time interval analysis advantages:**
- Relatively simple electronics processing.
- No unwrapping algorithm needed.

**Time interval analysis disadvantages:**
- Jitter in signals can cause false zero crossings.
- Signals are essentially averaged over an interval.

## Straightness Interferometer

The displacement interferometer can be reconfigured as a **straightness interferometer** to measure straightness errors. Straightness errors are lateral changes in the position of a target in the directions mutually orthogonal to the translation direction.

The typical straightness interferometer uses a **Wollaston prism** and **straightness optics** at the interferometer and target. The Wollaston prism splits input light based on polarization with a nominal separation angle $\alpha_s$ between beams. The straightness optics then consists of two mirrors configured in a 180-$\alpha_s$-deg angle. If the straightness optics displaces, both optical paths change equally. If the straightness optics laterally shifts, one interferometer arm gets longer, while the other gets shorter. This optical path change is then detected and converted to straightness.

$$z_p = 2\Delta x \sin\left(\frac{\alpha_s}{2}\right)$$
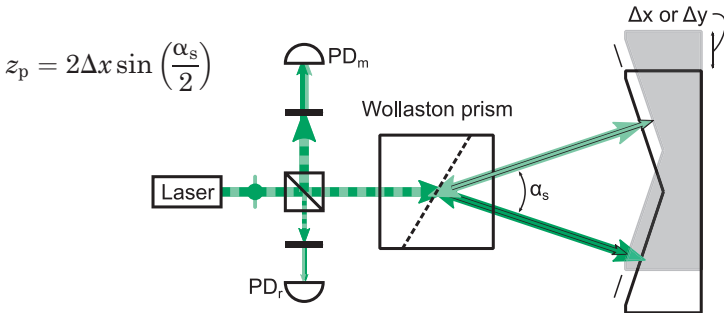
The output angle in the Wollaston prism is typically small, between 0.1 and 2 deg, leading to a straightness sensitivity of between ~0.005$\Delta x$ and ~0.035 $\Delta x$.

**Straightness interferometer advantage:**

- Insensitive to displacement changes.

**Straightness interferometer disadvantages:**

- Low-sensitivity measurement, often dominated by refractive index fluctuations.
- Large straightness optics needed for longer distances.
- Straightness reference determined by mirror flatness symmetry deviation amplified by 1/sensitivity.