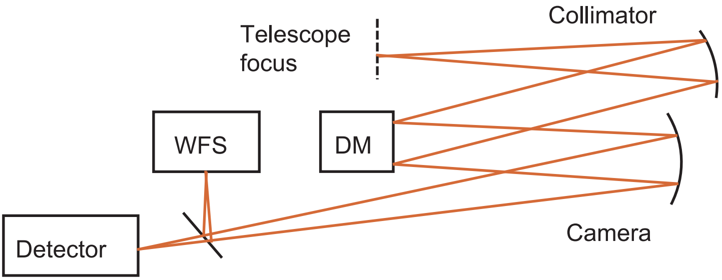
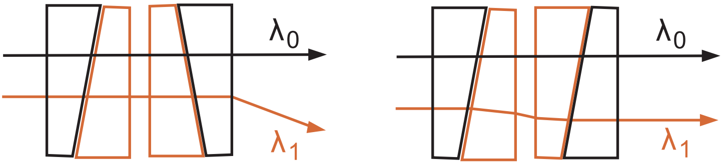
High-Resolution Imagers

High-resolution imagers look at very small fields of view with diffraction-limited angular resolution. As the field is small, intrinsic aberrations are negligible and parabolic mirrors, often used off axis, provide diffraction-limited collimation, magnification, and focusing independent of wavelength. As atmospheric seeing is typically the limiting factor, high-resolution imagers include **adaptive optics**.



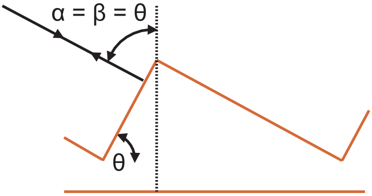
High-resolution imaging requires the correction of the **atmospheric dispersion**, which is induced by the differential refraction of air and depends on the wavelength, the zenith angle of the object, the temperature, the pressure, and the humidity. An **atmospheric dispersion corrector** (ADC) compensates for this variable dispersion. The most common ADC design employs two identical prism combinations that rotate against each other to adjust the amount of correction. Each prism combination consists of two prisms made from different materials such that the central wavelength is not deviated.



The longitudinal or **linear ADC** design consists of two wedge plates where one is close to the focus and the other is moved along the optical axis to adjust the amount of correction.

Echelle Spectrometers

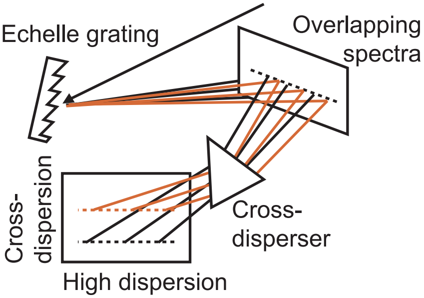
According to the grating equation $\frac{d\beta}{d\lambda} = \frac{m}{a \cos \beta}$, one can obtain high dispersion by either operating the grating at very high diffraction orders ($m \geq 50$), or decreasing the factor $a \cos \beta$, which requires high groove density (small groove spacing a, while a must be larger than λ) and large angles of incidence ($\beta \to 90$ deg). Gratings operated under large angles of incidence are called **Echelle gratings**.



For high efficiency, the incoming and the reflected ray should have about the same angle ($\alpha \approx \beta \approx \theta$). Under these conditions, the spectrometer operates in **Littrow configuration** and the grating equation becomes $m\lambda_B = 2a \sin \theta$.

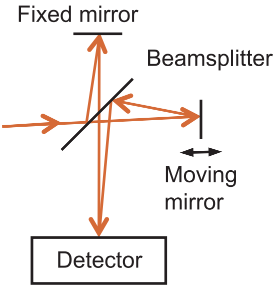
A fundamental quantity of spectrometers is the **free spectral range** (FSR), which is the maximum $\Delta\lambda$ for which successive orders do not overlap and is given by

$$\lambda_{fsr} = \frac{\lambda_{max}}{m + 1}$$



At high orders m, λ_{fsr} becomes too small. However, the spectral overlap can be avoided by spatially separating the diffraction orders by means of a so-called **pre-disperser**, a low-dispersion prism or grating. Since the pre-dispersion direction is perpendicular to that of the primary disperser, it is also called a **cross-disperser**. The design must ensure that the spectral overlap of the orders at their ends is sufficient to reconstruct a continuous spectrum. Echelle spectrometers uniquely provide high spectral resolution and efficient use of detector pixels, but their more complex optics yields more scattered light and lower efficiency.

Fourier Transform Spectrometer



A **Fourier transform spectrometer** (FTS) is a classical Michelson interferometer with a variable path length L and detectors and beamsplitters appropriate for the considered spectral range. The change in path length occurs with constant velocity or by stepping, the latter enabling imaging FTS instruments. Hence, an FTS measures one Fourier component of the spectrum at a time.

For a source with a spectrum $B(k)$ between k_1 and k_2 and wave number $k = 2\pi/\lambda$, the intensity at the output of the FTS as a function of the path-length difference x between the two arms is

$$I(x) = I_0 + \frac{1}{2}\int_{k_1}^{k_2} B(k)\cos(kx)dk \qquad I_0 = \frac{1}{2}\int_{k_1}^{k_2} B(k)dk$$

The FTS output has a constant offset I_0, an intensity that is averaged over the spectrum, and a term that is modulated by the path-length difference. The spectrum $B(k)$ is recovered from the Fourier transform of $I(x) - I_0$.

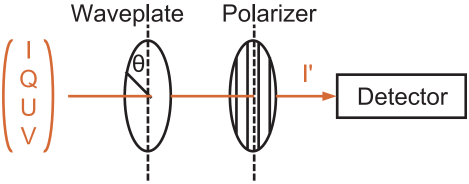
An FTS yields **absolute wavelength** measurements, limited only by the accuracy of the path-length difference measurement. The **spectral resolution** R of an FTS is determined by its largest path-length difference L and given by:

$$R = \frac{2L}{\lambda}$$

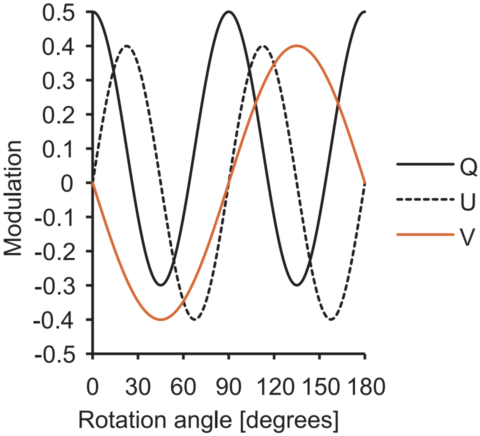
It is independent of the size of the entrance aperture. An FTS has high throughput and can provide spectral information on multiple sources within the field of view simultaneously.

Rotating Waveplate Polarimeters

Many different types of polarimeters have been built for different applications. The simplest polarimeters are **rotating waveplate polarimeters**, where a rotating waveplate is followed by a linear polarizer or a polarizing beamsplitter. The measured intensity I' as a function of waveplate retardance δ and rotation angle θ for an incoming beam with Stokes vector (I, Q, U, V) is



$$I' = \frac{I}{2} + \frac{Q}{4}[(1+\cos\,\delta) + (1-\cos\,\delta)\cos\,4\theta] + \frac{U}{4}(1-\cos\,\delta)\sin\,4\theta - \frac{V}{2}\sin\,\delta\sin\,2\theta$$



A waveplate with $\delta = 126.8$ deg at the wavelength of interest has equal modulation amplitudes and sensitivity for Q, U, and V. The rotation can be continuous with eight equally long integrations per rotation or stepped to four or more discrete angles.

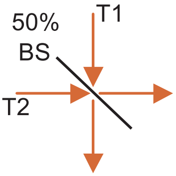
The signals S produced by a polarimeter with a modulator having states 1 and 2 followed by a polarizing beamsplitter producing images l and r can be combined in the **dual-beam exchange** equation to remove effects due to transmission changes, detector gain variations, and image motion:

$$\frac{1}{4}\left(\frac{S_1^l}{S_2^l}\frac{S_2^r}{S_1^r} - 1\right) = \frac{1}{2}\left(\frac{V_1}{I_1} + \frac{V_2}{I_2}\right)$$

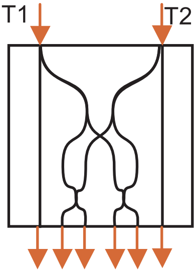
Beam Combiners

There are several ways to combine coherent optical beams from different telescopes in interferometry.

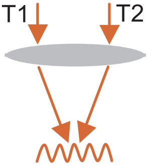
A **coaxial beam combiner** uses a 50% beamsplitter mirror to combine two coherent pupils from different telescopes, creating two beams with varying intensity, depending on the phase difference between the incoming beams. This is similar to a Michelson interferometer.



Photonic integrated circuits, or integrated optics, allow optical systems to be made more compact and with higher performance than with discrete optical components. Beam combiner chips are directly fed by single-mode fibers from each telescope, providing instantaneous pairwise combination of all baselines for multiple telescopes, including phase shifting.



Coherent optical beams can be combined under an angle, creating an **interference pattern**. The pupils of multiple telescopes are reimaged side by side, and all pupils together form an image on a single camera. It is possible to combine multiple telescopes by carefully selecting the distances between the pupils of all telescopes.



A **Fizeau interferometer** works in a similar way, but here the size and distance of the pupils resemble the physical layout of the telescopes. Therefore, the Fizeau interferometer can produce images directly.