Narrow-band imaging by use of interferometers

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Abstract

The principles of operation of imaging spectrometers based on the use of Fabry–Perot and Fourier transform interferometers are described. The advantages and disadvantages of the two techniques are discussed, and some examples are given of their application in space-borne instruments for astronomy and Earth observation.

Fabry–Perot interferometers

Principles of Fabry–Perot interferometry

A Fabry–Perot interferometer (FPI) is formed by two plane reflecting surfaces that are parallel to each other with an adjustable spacing. Interference can occur between the multiply reflected beams propagating perpendicularly through the plates.

In the ideal case of two elements with identical reflectivity $R$, separated by distance $d$, the fractional transmission of an FPI at wavelength $\lambda$ is given by the Airy formula (e.g., Born and Wolf 1999),

$$\frac{I_t}{I_0} = \left[1 + \frac{4R}{(1-R)^2} \sin^2 \left(\frac{\delta}{2}\right)\right]^{-1},$$

where $I_0$ and $I_t$ are the intensities of the incident and transmitted beams, and $\delta$ is the phase difference between the interfering waves:

$$\delta = \frac{4\pi d}{\lambda}. \quad (18.2)$$

The transmission is a maximum, and equal to unity, when $\delta = 2n\pi$, i.e.,

$$d = \frac{n\lambda}{2} = \frac{c_0 n}{2\nu}, \quad (18.3)$$

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where $n$, a positive integer, is the order of interference, and $c_0$ is the speed of light. It is remarkable that transmission of $I_t = I_0$ can be achieved through two highly reflecting surfaces. One way of visualising this is that a photon can tunnel through the potential barrier constituted by the device because in the space between the reflectors there is an allowed state with precisely the same energy as that of the photon. For a given thickness, the transmission as a function of wavelength is a series of peaks at wavelengths given by $\lambda = 2d/n$. The frequency difference between adjacent orders of interference is a constant, known as the free spectral range, given by

$$\Delta\nu_{\text{FSR}} = \frac{c_0}{2d}. \quad (18.4)$$

The FPI transmission as a function of frequency is thus a comb of narrow resonances spaced equally in frequency by $\Delta\nu_{\text{FSR}}$. Assuming that the reflectivity is high so that $(1 - R)^2 \ll R$, we can solve Equation 18.1 for the condition that $I_t/I_0 = 0.5$ to find an expression for the FWHM of the transmission peak:

$$\Delta\delta = \delta_1 - \delta_2 = \frac{2(1 - R)}{\sqrt{R}} \quad \text{or} \quad \Delta\nu_{\text{FWHM}} = \frac{(1 - R)c_0}{2\pi d \sqrt{R}}. \quad (18.5)$$

The finesse of the FPI is defined as the ratio of the free spectral range to the FWHM:

$$F = \frac{\Delta\nu_{\text{FSR}}}{\Delta\nu_{\text{FWHM}}} = \frac{2\pi}{\Delta\delta} = \frac{\pi \sqrt{R}}{(1 - R)}, \quad (18.6)$$

and is dictated by the reflectivity of the plates - high reflectivity means high finesse. The spectral resolving power of the FPI operating in order $n$ is given from Equations 18.3 and 18.5 by

$$\nu \Delta\nu_{\text{FWHM}} = \frac{c_0 n}{2d} \frac{2\pi d \sqrt{R}}{(1 - R)c_0} = nF. \quad (18.7)$$

High spectral resolution is thus achieved with high finesse and with operating in high order. The contrast ratio between maximum and minimum transmission is

$$C = 1 + \frac{4R}{(1 - R)^2} = \left(\frac{1 + R}{1 - R}\right)^2. \quad (18.8)$$

Figure 18.1 shows the relative transmission $I_t/I_0$ as a function of $\delta$ for various values of reflectivity. The transmission varies significantly with thickness or wavelength. As the reflectance of each surface approaches unity (increasing finesse), the widths of the high-transmission regions become very narrow.

The transmission of a practical FPI is less than one, due to finite absorptance of the plates. The shape of the transmission profile is unaffected, but since the device operates on the principle of multiple reflection, the peak transmission is very sensitive to the absorptance. For plates with reflectance $R$, transmittance $T$, and absorptance $A = 1 - T - R$, it can be shown (e.g., Hecht 1987) that the peak transmission is

$$\frac{I_{\text{max}}}{I_0} = \left(1 - \frac{A}{1 - R}\right)^2 = \left(\frac{T}{1 - R}\right)^2. \quad (18.9)$$
Figure 18.1: Fractional transmission of an ideal FPI as a function of $\delta$/rad for $R = 0.7$, 0.8, and 0.95, with higher $R$ giving narrower peaks.

For example, with $(R, T, A) = (0.95, 0.04, 0.01)$, the peak fractional transmission is 64%, for $(0.95, 0.02, 0.03)$ it is 16%, and only 4% for $(0.95, 0.01, 0.04)$.

To form a tuneable spectrometer, one of the plates is mounted on a translation stage to make the spacing adjustable. It is necessary to suppress all of the resonances except the desired one. This can be achieved using a diffraction grating or a secondary, lower-resolution FPI. The latter method has the advantage that there is no angular dispersion, so that two-dimensional imaging remains possible.

In addition to the reflectivity, the spectral performance of an FPI is sensitive to defects in the flatness or parallelism of the reflectors and to the spread of angles in the incident beam. These effects can be characterised by additional contributions to the overall finesse.

Departures from flatness or parallelism can be modelled by decomposing the FPI into many individual elemental FPIs, all with plane parallel reflectors, whose transmissions are then averaged to give the total transmittance of the FPI (Ulrich et al 1963; Davis et al 1995). The flatness finesse is given by

\[
F_F = \frac{\lambda}{2\Delta d},
\]

where $\Delta d$ is the rms surface deviation of the reflectors (due either to non-flatness or departure from parallelism of the plates). The requirements on flatness and parallelism are stringent if high finesse is to be achieved. For instance, a flatness finesse of 100 at 100 $\mu$m wavelength requires $\Delta d < 0.5 \mu$m.

The aperture finesse is determined by the spread of angles propagating through the interferometer, which results in a corresponding spread in phase differences between the interfering beams, as illustrated in Figure 18.2. If the half-angle of the beam in the FPI is $\theta$, corresponding to a solid angle $\Omega = \pi \theta^2$, then the additional path difference compared to a perfectly parallel beam is

\[
\Delta d = d \left( \frac{1}{\cos \theta} - 1 \right) = d \left( \frac{1}{\sqrt{1 - \sin^2 \theta}} - 1 \right).
\]
The solid angle is related to the focal ratio of the collimator, \( f \), by
\[
\Omega \approx \frac{\pi}{4f^2}.
\]  
(18.12)

For small \( \theta \),
\[
(1 - \sin^2 \theta)^{-\frac{1}{2}} \approx (1 - \theta^2)^{-\frac{1}{2}} \approx 1 + \frac{1}{2} \theta^2 \approx 1 + \frac{\Omega}{2\pi},
\]  
(18.13)
giving
\[
\Delta d = \frac{d \Omega}{2\pi}.
\]  
(18.14)

The corresponding phase difference is
\[
\Delta \delta = \frac{4\pi}{\lambda} \frac{d \Delta d}{\lambda} = \frac{2d \Omega}{\lambda} = \frac{n \Omega}{\lambda}.
\]  
(18.15)

We can define a corresponding finesse, known as the aperture finesse, as
\[
F_A = \frac{2\pi}{\Delta \delta} = \frac{2\pi}{n \Omega}.
\]  
(18.16)

For high finesse, we must therefore operate in high order and minimise the solid angle of the beam by having a collimator with a high \( f \)-number.

The overall finesse is given by
\[
\frac{1}{F_{\text{tot}}^2} = \frac{1}{F^2} + \frac{1}{F_F^2} + \frac{1}{F_A^2}.
\]  
(18.17)

The performance of the FPI interferometer is critically dependent on the properties of the reflectors. For optical and NIR wavelengths, FPIs are formed from pairs of highly-polished plane-parallel dielectric slabs (e.g., fused silica) with appropriate multi-layer coatings to provide high reflectivity over the desired band. In the far
infrared, this technique does not work well as the layers become thick and lossy, and problems arise with differential thermal contraction of the layers. The requirements for high reflectivity and low absorption are best met by metallic grids. The grids can be either free-standing or supported on a thin dielectric film (e.g., Ulrich 1967). The most common grid pattern has regularly-spaced square holes with grid spacing $g$, as shown in Figure 18.3 (left), forming an inductive grid, or the complementary capacitative structure shown in Figure 18.3 (right). An inductive grid can be free standing, but the capacitative grid requires a dielectric substrate on which the metal can be deposited. For efficient operation as an FPI, the wavelength must be $\geq 5g$, at shorter wavelengths the grid starts to behave as a diffraction grating. Fixed far-infrared and sub-millimetre filters can be constructed by combining metallic grids with suitable spacings, often in FPI configurations (Ade et al 2006).

An imaging Fabry–Perot spectrometer consists of:

1. a collimator to provide a parallel beam;
2. the FPI with adjustable spacing;
3. an additional element (often another, lower resolution, FPI) to select one order of interference;
4. an additional filter to act as a short-wavelength blocker;
5. a camera to create a focal plane image;
6. a suitable 2-D detector array.

At FIR wavelengths, the interferometer needs to be operated at cryogenic temperatures.
Advantages and disadvantages of Fabry–Perot interferometers

The main advantages of FPIs for the FIR are

1. the simple optical design (fore-optics, collimator and camera), readily suited to an imaging system, and

2. the capability to achieve high spectral resolving power with a compact instrument.

The chief disadvantages are

1. it is difficult to achieve high overall efficiency compared to grating or FTS spectrometers;

2. the broad wings of the instrument response function can present problems in the analysis of rich spectra;

3. the design provides no wavelength multiplexing — mechanical scanning is essential to cover a range of wavelengths;

4. it is difficult to obtain wavelength coverage of more than about an octave with a single device;

5. much attention and care must be paid to the practicalities of order sorting and short-wavelength blocking.

Examples of Fabry–Perot instruments

A number of imaging Fabry–Perot instruments have been built and used on ground-based and airborne telescopes. Most have been based on the tandem FPI concept, in which a low-order FPI is used to order sort a high-resolution FPI. The Far Infrared Imaging Fabry–Perot Interferometer (FIFI, Poglitsch et al 1991) was operated on the KAO and used three cryogenic tuneable FPIs in series giving spectral resolution up to $10^5$ in the $40\mu$m to $200\mu$m range, with a $5 \times 5$ detector array.

The Sub-millimetre and Far-InfraRed Experiment, SAFIRE, (Benford et al 2003) is a planned imaging tandem Fabry–Perot instrument for the SOFIA airborne observatory, the successor to the KAO. It will operate between $100\mu$m and $700\mu$m with spectral resolution up to 2000 over a field of view of $160'' \times 320''$, covered by a $16 \times 32$ array of superconducting bolometers. The South Pole Imaging Fabry–Perot Interferometer (SPIFI, Bradford et al 2002) is a ground-based astronomical spectrometer operating at sub-millimetre wavelengths, using a $5 \times 5$ array of bolometric detectors operating at 60 mK. It uses two cryogenic scanning FPIs and has spectral resolving power selectable between 500 and 10 000.

The Long Wavelength Spectrometer (LWS, Clegg et al 1996) on board ESA’s ISO incorporated two scanning FPIs, one for $45\mu$m to $90\mu$m and one for $90\mu$m to $180\mu$m, which were order-sorted by a grating and offered resolution ($\lambda/\Delta\lambda$) up to 10 000. The FPIs were located in a three-position interchange wheel, with the third position open so that the instrument could also be operated in grating-only mode for medium-resolution spectroscopy. The optical layout of the LWS is shown in
Figure 18.4: Left: optical layout of the ISO LWS focal plane instrument; right: photograph of the instrument.

Figure 18.4. The ISO Short-Wavelength Spectrometer (SWS, de Graauw et al 1996) used a similar grating-FPI arrangement to provide high-resolution spectroscopy in the 11 μm to 45 μm range.

FPI instruments can also be used to study the chemistry and dynamics of the Earth’s atmosphere. An example of such applications is the High Resolution Doppler Imager (HRDI) instrument (Hays et al 1993) on board the UARS. This instrument was designed to measure wind velocities using Doppler shifts of O₂ rotational lines in the 550 nm to 770 nm region, and contained a triple FPI system providing 0.05 cm⁻¹ resolution (equivalent to λ/Δλ ≈ 3 × 10⁵).

**Imaging Fourier transform spectroscopy**

**Principles of FT spectroscopy**

The essential features of a Fourier transform spectrometer (FTS) are illustrated in Figure 18.5, which shows the layout of a Michelson interferometer. In a Fourier transform spectrometer such an interferometer is employed as an autocorrelation spectrometer—one which compares the signal to a delayed version of itself over a range of delays. The beam from Port 1 is collimated and split 50:50 by the beam divider. One beam is reflected back by the fixed mirror and the other by the moving mirror. After reflection, the beams again divide at the beam divider and interfere. The beams from the two arms of the interferometer interfere because of the difference in path length of the two optical trains. A typical implementation of the basic Michelson interferometer depicted in Figure 18.5 uses intensity beam dividers and corner-cube reflectors to maintain alignment. On average, half of the power from Port 1 is directed to Port 2 and half goes back to Port 1; likewise, any emission from Port 2 will be divided equally between Port 1 and Port 2. The Michelson interferometer thus has two input and two output ports, but in the basic configuration of Figure 18.5 they are not spatially separated. In the configuration shown the interferogram represents the difference spectrum: Port 1 – Port 2. The Martin-Puplett (M-P) interferometer (Martin 1982; Lambert and Richards 1978)
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Figure 18.5: Essential features of a Fourier transform spectrometer.

uses polarising beam dividers and roof-top reflectors to achieve separation of the input and output ports (but at a cost of half of the available power).

For an optical path difference $\Delta$ the phase difference between the interfering beams is

$$\sigma = \frac{2\pi \Delta}{\lambda} = 2\pi k \Delta \; ,$$

(18.18)

where the wavenumber $k$ is $1/\lambda$.

For an intensity beam divider with input amplitude $A_0$ (intensity $I_0 \propto A_0^2$), the amplitude of the reflected and transmitted beams is $A_0/\sqrt{2}$ and on the second interaction, the amplitude is reduced by a further factor of $\sqrt{2}$ to $A_0/2$. The amplitude in the output port is therefore

$$A_{\text{out}} = \frac{A_0}{2} + \frac{A_0}{2} e^{i 2\pi k \Delta} \; .$$

(18.19)

The corresponding intensity as a function of optical path difference is

$$I_{\text{out}}(\Delta) = A_0 A_0^* = \frac{A_0^2}{4} [1 + e^{i 2\pi k \Delta}][1 + e^{-i 2\pi k \Delta}] = \frac{I_0}{2} [1 + \cos(2\pi k \Delta)] \; ,$$

(18.20)

which is recorded by the detector as the interferogram. For a monochromatic input, the interferogram is a cosine wave. For an arbitrary spectral input $S(k)$, the interferogram is the sum of the relevant monochromatic components:

$$I_{\text{out}}(\Delta) = \int_0^{\infty} \frac{S(k)}{2} [1 + \cos(2\pi k \Delta)] dk \; .$$

(18.21)

Application of the Fourier integral theorem gives:

$$S(k) = 4 \int_{-\infty}^{\infty} \left[ I_{\text{out}}(\Delta) - \frac{1}{2} I_{\text{out}}(0) \right] \cos(2\pi k \Delta) d\Delta \; .$$

(18.22)

The inverse Fourier transform of the interferogram thus gives the input spectrum. Perfect reproduction of the spectrum would require the optical path difference
range to be infinite. With a real interferometer, the interferogram will be measured over a finite range of path difference. If the range is $\pm \Delta_{\text{max}}$, the interferogram is truncated by a rectangular function equal to unity between these limits and zero outside:

$$T = 1 \quad \text{for} \quad -\Delta_{\text{max}} < \Delta < \Delta_{\text{max}} \quad \text{(18.23)}$$

$$= 0 \quad \text{otherwise} \ .$$

The Fourier transform of this truncation function represents the measured spectrum for a monochromatic input, i.e., the instrument response function, $R(k, \Delta_{\text{max}})$:

$$R(k, \Delta_{\text{max}}) = 2 \int_{-\Delta_{\text{max}}}^{\Delta_{\text{max}}} \cos(2\pi k \Delta)d\Delta = 2\Delta \left[ \frac{\sin(2\pi k \Delta)}{2\pi k \Delta} \right] . \quad \text{(18.24)}$$

Figure 18.6 shows the shape of this function. The spectral resolution is characterised by its FWHM, given by

$$\delta k = \frac{1.21}{2 \Delta} . \quad \text{(18.25)}$$

The secondary features in the instrument response function are due to the sharp cut-off in $T(\Delta)$ and can be suppressed in the course of data processing by multiplying the interferogram by a suitable apodisation function. A standard method, termed linear apodisation, is simply to taper linearly the amplitude of the fringes to zero at the maximum path difference. The new effective instrument response function can then be determined by Fourier transforming this triangular response, which gives

$$R(k, \Delta_{\text{max}}) = \left[ \frac{\sin(\pi k \Delta)}{\pi k \Delta} \right]^2 2\Delta . \quad \text{(18.26)}$$

This new effective instrument response is also shown for comparison in Figure 18.6. It is immediately apparent that the suppression of the sidelobes comes at some cost to the spectral resolution via broadening of the main peak by a factor of $\approx \sqrt{2}$. An additional feature of any real interferometer is that the interferogram is not sampled continuously but at discrete intervals $d\Delta$. According to Nyquist’s sampling theorem, the corresponding highest frequency that can be measured unambiguously, known as the Nyquist frequency, is

$$k_{\text{max}} = \frac{1}{2 d\Delta} . \quad \text{(18.27)}$$

Higher frequencies in the input spectrum are aliased into the measured spectral band (0 to $k_{\text{max}}$), contributing to false features overlaying the spectrum. In contrast to the FPI, a simple low-pass optical filter can be used to remove frequencies above the Nyquist frequency. A popular variant of the FT spectrometer is a scanning instrument, in which the mirror is translated continuously at constant speed so that the optical fringes appear as low-frequency audio components in the detector output. Nyquist filtering in this case can be achieved conveniently by appropriate electrical filtering in the detector readout.

As with the FPI, the performance of a Fourier transform interferometer is influenced by the parallelism of the beam. Departures from parallelism, which are
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Figure 18.6: Normalised FTS instrument response function for $\Delta_{\text{max}} = 1$, un-apodised (blue dotted line) and with linear apodisation (red solid line).

Figure 18.7: Path difference for off-axis rays.

inevitable when viewing an extended object, result in phase shifts which cause distortions to the interferogram when the beams interfere. The geometry for an off-axis angle $\theta$ is depicted in Figure 18.7, from which one can show that the optical path difference $z$ between the two rays at the off-axis angle $\theta$ is given by $z = \Delta \cos \theta$.

The interferogram (Equation 18.20) is thus modified to

$$I_{\text{out}}(\Delta) = I_0 \left[ 1 + \cos(2\pi k \Delta \cos \theta) \right].$$  \hspace{1cm} (18.28)

Whereas on-axis rays produce a spectral feature at wavenumber $k$, the off-axis rays produce a feature at $k \cos \theta$. The corresponding resolution limit is

$$\delta k = k(1 - \cos \theta) \approx \frac{k \theta^2}{2}.$$  \hspace{1cm} (18.29)
for small $\theta$. The corresponding limit on resolving power is

$$
\frac{\delta k}{k} = \frac{\theta^2}{2} = \frac{\Omega}{2\pi},
$$

(18.30)

where $\Omega$ is the beam solid angle.

It should be noted that in comparison to the FPI the efficiency of the FTS is very high because there is no loss in order-sorting filtering, and the inherent relative efficiency of the beam division can approach 100%.

**Advantages and disadvantages of FTS instruments**

The main advantages of FTS instruments are

1. broad instantaneous spectral coverage, often allowing many spectral features to be observed simultaneously;

2. well-defined peak of the response function and the ability to match the response function to the scientific objectives by choice of a suitable apodisation function;

3. suitability for direct imaging at high spectral resolution with a compact instrument;

4. adjustable spectral resolution (dictated by the choice of maximum optical path difference);

5. high overall optical efficiency.

The main disadvantage compared to monochromator-based spectrometers such as the grating or Fabry–Perot is that in background-limited regime the wide instantaneous bandwidth contributes additional photon noise, leading to lower sensitivity as the price paid for broad wavelength coverage.

**Examples of space-borne FTS instruments**

FTS instruments are particularly useful in applications that require broad wavelength coverage, and they have been widely used in astronomy and Earth-observing satellite missions. A detailed review of remote sensing instruments is given by Persky (1995). Here we provide brief details of some instruments recently flown and currently planned.

The Composite Infrared Spectrometer (CIRS, Flasar et al 2004) is an instrument on board the Cassini satellite mission to the Saturnian system. CIRS contains two FT spectrometers using the same actuator, covering 7 $\mu$m to 17 $\mu$m and 17 $\mu$m to 1000 $\mu$m and providing spectral resolution between (0.5 and 15.5) cm$^{-1}$. The long-wavelength band is covered by a Martin-Puplett interferometer, using 2 $\mu$m spacing metal-grid polarisers and two thermopiles as detectors, each with the same 0.4 mrad field of view (FOV). The spectrometer for the shorter wavelength band mid-infrared interferometer is a Michelson with a KBr intensity beam-splitter and corner-cube retro-reflectors, and two $1 \times 10$ linear photodetector arrays, with each
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Figure 18.8: Opto-mechanical layout of the Herschel-SPIRE Fourier Transform Spectrometer.

detector having a 0.3 mrad FOV. CIRS has observed the atmospheres of Jupiter, Saturn and Titan, characterising temperature, gas composition, and atmospheric aerosols with vertical and horizontal resolution from tropospheric to stratospheric altitudes. The Tropospheric Emission Spectrometer (TES, Beer et al 2004) is an imaging FTS operating on NASA’s EOS satellite. TES covers wavelengths between 3.2 µm and 15.4 µm and carries out global measurements of O₃, H₂O, CO, CH₄ and other important species as a function of altitude in the Earth’s troposphere. The TES optics feature back-to-back corner-cube reflectors with a common translator mechanism to vary the optical path difference (OPD). One input port views the atmosphere while the other views an internal calibration source. The optics are cooled to 180 K to reduce the thermal background on the detectors and to provide high contrast between the Earth’s atmosphere and the instrument background. Two focal planes are located at the two output ports and are each split into two channels by dichroic beam dividers. Four 1 × 16 arrays of photovoltaic detectors operate at 65 K and view spatially equivalent pixels.

The Spectral and Photometric Imaging Receiver (SPIRE) instrument (Griffin et al 2008) is currently flying on the Herschel Space Observatory, launched by ESA on 14 May 2009. SPIRE contains a three-band sub-millimetre camera and an imaging FTS which covers 194 µm to 672 µm. The FTS (Figure 18.8) has an approximately circular field of view of 2.6′ diameter and spectral resolution adjustable between 0.042 cm⁻¹ and 2 cm⁻¹ (λ/Δλ = 20 to 1000 at 250 µm). To minimise the background on the detectors, the entire SPIRE instrument is cooled, with temperature levels of ≈5 K for much of the optics, 2 K for the final optics, and 0.3 K for the bolometric detector arrays. The FTS uses two broadband intensity beam splitters in a Mach–Zehnder configuration, with a single back-to-back scanning roof-top fold mirror serving both interferometer arms. All four ports are independently accessible as in the M-P polarising FTS, but the throughput is a factor of two higher than for the M-P as none of the incoming radiation is rejected,
and there is no sensitivity to the polarisation of the incident radiation. A thermal calibration source at the second input port allows the background power from the telescope to be matched. The amplitude of the interferogram central maximum is proportional to the difference in the radiant power from the two ports, so this allows the large telescope background to be nulled, reducing the dynamic range requirements for the detector sampling. Two detector arrays are placed in the two output ports to accommodate the whole wavelength range in two sections with overlapping bands. The SPIRE FTS is used to characterise the physics and chemistry of interstellar dust and gas in our own and nearby galaxies.

An FTS spectrometer is also proposed for Herschel’s successor, the Japanese Space Infrared telescope for Cosmology and Astrophysics (SPICA) mission. The SAFARI instrument (Swinyard et al 2008) for SPICA is based on an adaptation of the SPIRE FTS design, to operate in the 30 μm to 200 μm range with much improved sensitivity provided by the cold (4 K) telescope and the use of improved far infrared detectors. Future far infrared interferometer mission concepts such as SPECS (Harwit et al 2007), SPIRIT (Leisawitz et al 2007) and FIRI (Helmich and Ivison 2009), propose to carry out high angular resolution imaging spectroscopy using a double Fourier spatial and spectral interferometric technique (Mariotti and Ridgway 1988; Elias et al 2007).

Bibliography