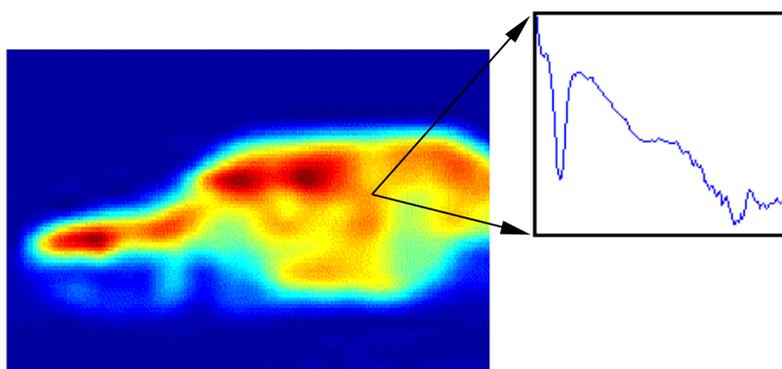


Frans Lundberg

The design of ScanSpec – a scanning imaging FTIR spectrometer



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Abstract <p>This report describes the ScanSpec project at the Department of IR Systems at the Defense Research Establishment (FOA) in Linköping, Sweden. The purpose of the project was to build an imaging spectrometer. It has been done by connecting a narrow-angle telescope to a fast FTIR spectrometer and by rotating a mirror in front of the telescope. This way, spectra of IR-radiation from different directions are acquired. The mirror is used to scan a scene to acquire a spectral image, that is, an image for which each pixel consists of a whole spectrum.</p> <p>The report includes an overview of imaging spectrometers for the IR-region and of the military use of spectral images. The development of the ScanSpec imaging spectrometer is described and the first measurements are presented.</p> <p>The report is written for anyone interested in spectral images and imaging spectrometers and specifically the ScanSpec imaging spectrometer. The reader is assumed to have some university level knowledge about physics in general.</p>		
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Sammanfattning <p>Denna rapport beskriver ScanSpec-projektet vid Institutionen för IR-system på Försvarets forskningsanstalt i Linköping, Sverige. Syftet med projektet var att bygga en bildalstrande spektrometer. Detta har gjorts genom att montera ett långt teleskop på en snabb FTIR-spektrometer och genom att rotera en spegel framför teleskopet. På detta sätt samlas spektra från olika riktningar in. Spegeln används till att skanna av en scen för att samla in en spektral bild, det vill säga en bild där varje pixel består av ett helt spektrum.</p> <p>Denna rapport innefattar en översikt av bildalstrande spektrometrar för IR-området och av den militära användningen av spektrala bilder. Utvecklingen av den bildalstrande spektrometern ScanSpec beskrivs och de första mätningarna presenteras.</p> <p>Rapporten är skriven för den som är intresserad av spektrala bilder, bildalstrande spektrometrar och speciellt den bildalstrande spektrometern ScanSpec. Läsaren antas ha en del allmän fysikkunskap på universitetsnivå.</p>		
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1 Introduction

Imaging spectrometry has developed rapidly the last years and has applications in many fields of science. The military applications include measuring optical signatures, surveillance, and targeting. The ScanSpec imaging spectrometer described in this text is designed to be able to measure optical signatures of backgrounds and potential military targets.

This report will tell the reader about the ScanSpec project which was done at the Department of IR systems at the Defense Research Establishment (FOA) in Linköping, Sweden. The goal of the project was to build an imaging spectrometer based on a fast non-imaging spectrometer. This has been done by connecting a narrow-angle telescope to the spectrometer and by turning a mirror in front of the telescope. In this way the infrared radiation from different directions can be collected. By scanning the mirror around two rotation axes a whole *spectral image* can be acquired. A spectral image is an image in which each pixel consists of a spectrum. The imaging spectrometer is named ScanSpec and the finished construction can be seen in Figure 1.

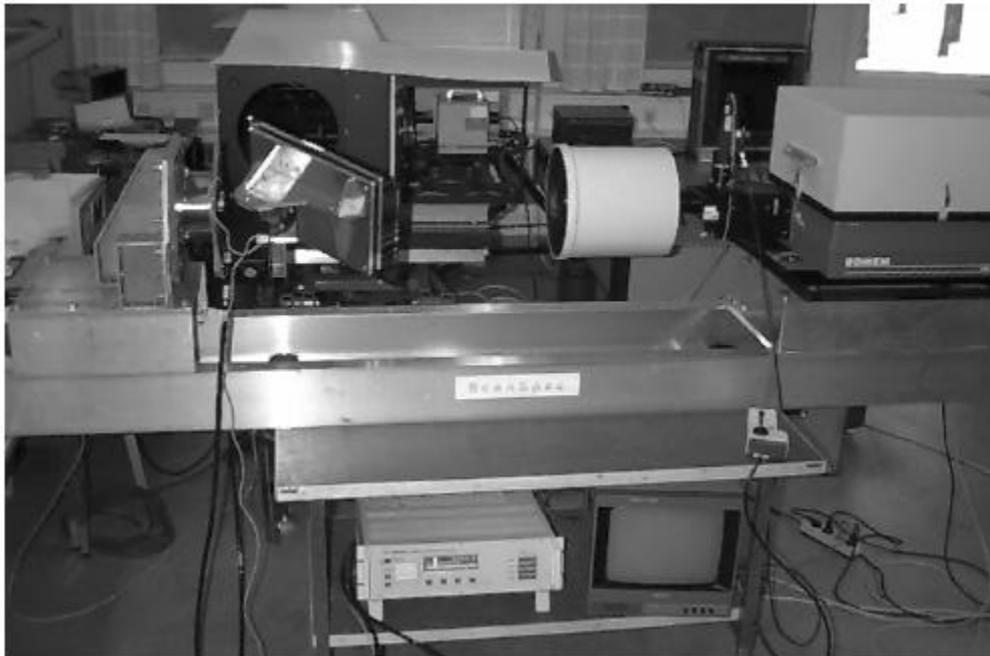


Figure 1- ScanSpec.

The system is based on a fast FTIR spectrometer (Fourier-transform infrared spectrometer) from Bomem Inc. The spectrometer is capable of collecting 65 spectra/s at the highest speed and lowest spectral resolution.

The report is divided into three parts plus this introduction and the conclusions chapter. *Part I - Spectral images*, explains what a spectral image is, its history and how spectral images can be acquired. *Part II - Building ScanSpec*, will tell the reader how ScanSpec was built and the last part, *part III - What ScanSpec can see*, will present what ScanSpec can be used for and its performance. That part also presents the initial measurements including the world's probably first hyper-spectral image of a Volvo 440!

This project is the last part of my masters degree at the University of Umeå, Sweden.

Before we will learn more about spectral images in the next chapter, I would like to take the opportunity to thank all the very helpful people at FOA in Linköping, who have contributed to this project, especially Pär Nilsson and Claes Nelsson.

2 Spectral images and their military use

2.1 What is a spectral image?

People view the world in color, and draw conclusions about objects due to the color of the object. Human eyes or a normal color video camera produce spectral images (defined below) with very low spectral resolution, only three frequency bands. It is easier to recognise objects on a color TV compared to on a black and white TV, that is, objects are easier to detect if the light¹ from many frequency bands is recorded. Compared to a color video camera or human eyes with only three frequency bands, an imaging spectrometer can increase the number of recorded frequency bands to thousands or more. The human eye covers less than 10 per cent of the spectral region available to imaging spectrometers [Breckinridge 1996]. Imaging spectrometers will provide us with further information in many fields of research, ranging from studying outer space to looking at microscopic objects.

The definition of what a spectral image is can vary slightly. My definition of a spectral image is

a three-dimensional data entity that describes the spectral radiance of a scene as a function of two spatial variables and one spectral variable. The two spatial variables should tell where the spectral radiance is measured and the spectral variable should tell for what frequency/wavelength it is measured.

The spatial variables can be distances or angles. The spectral variable is either frequency or wavelength. For ScanSpec, the spatial variables are angles and the spectral variable is frequency. The spectral radiance L_{spec} is often defined as

$$L_{spec,\lambda} = \frac{dL}{d\lambda} \quad (\text{Equation 1})$$

where L is the radiance and λ is the wavelength [Physics p. 264, Pedrotti p. 265]. But, when the frequency f is used as the spectral variable, the following definition can be used,

$$L_{spec,f} = \frac{dL}{df} \quad (\text{Equation 2})$$

There are several reasons why I have chosen to use frequency as the spectral variable when acquiring the spectral images. The most important reason is that the spectrometer in the ScanSpec system (Bomem MR254) records spectral radiance according to equation 2. It is also often easier to work with frequency instead of wavelength, since the energy difference between two photons with a fixed frequency difference is always the same. Also, unlike the wavelength, the frequency of the electromagnetic radiation is independent of the medium the radiation is propagating in.

A spectral image can be seen as an image where each pixel is a radiance spectrum instead of just a gray-scale value as it is in an ordinary black and white image.

¹ Throughout this report, the word "light" will be used for both the visible and the infrared electromagnetic radiation.

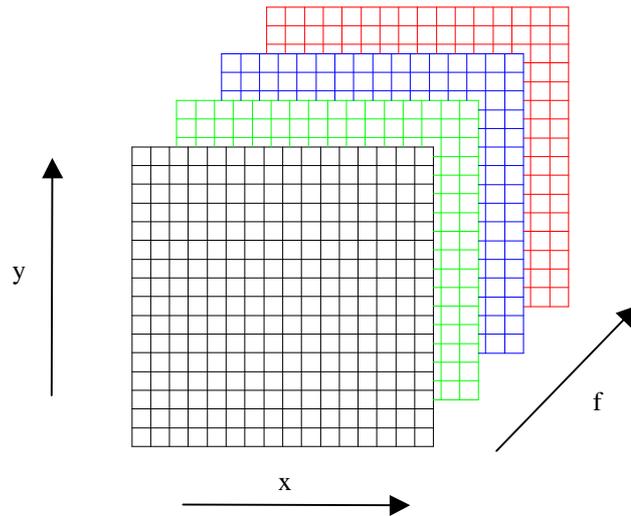


Figure 2- This figure depicts how a spectral image can be seen as a collection of several gray-scale images, one for each frequency for which the spectral radiance has been recorded.

An alternative way of mentally visualizing the data of a spectral image is as a collection of many ordinary gray-scale images, one for each frequency for which the spectral radiance was recorded. This way of visualizing a spectral image is depicted in Figure 2 and has been the basis for the presentation of the data collected by ScanSpec.

From now on we will concentrate on spectral images in the infrared part of the electromagnetic spectrum which can be divided into the following bands.

NIR, near infrared	0.7-1.1 μm
SWIR, short wavelength infrared	1.1-2.5 μm
MWIR, mid-wavelength infrared	2.5-7 μm
LWIR, long wavelength infrared	7-15 μm
FIR, far infrared	>15 μm

The definition of these frequency bands differ in the literature. I have followed the definition by [Holst]. ScanSpec covers the whole region from NIR to FIR, but it is less sensitive in the NIR and the FIR region.

2.2 The history of spectral images

The astronomer George Ellery Hale is credited with being the first person to create a spectral image. At the turn of this century he realized how important it was to study both the spectral and the spatial variations of the light from the sun. He designed a spectrometer that would only let through light at a specific wavelength. A solar telescope was placed so that the focal plane of the telescope coincided with the entrance slit of the spectrometer. The light that passed through the spectrometer was recorded on a photographic plate. By moving the slit with a constant velocity over the disc of the sun and keeping the photographic plate at the same position, Hale was able to record the intensity of the light for a specific wavelength in one spatial dimension. To record the intensity for another wavelength, he had to adjust the spectrometer and make another scan. [Breckinridge]

The idea of recording both spatial and spectral variations of radiation has been around for a century or so. However, it is only the last decade or two that complete systems that can record a spectral image with two spatial dimensions and one spectral dimension have been built.

Not until the last few years have imaging spectrometers been available commercially for the MWIR and the LWIR regions, and the market seems to be limited to only a few products. I believe that the development of new imaging spectrometers for the MWIR and the LWIR regions will be rapid the coming few years, due to the increased size and performance of 2D-arrays of IR-detectors. See [internet: Rockwell] and [internet: Sensors] for commercially available 2D-arrays of IR-detectors.

2.3 The military use of infrared spectral images

Infrared spectral images are important in military research to measure optical signatures of backgrounds and potential targets. The measurements can be used to build models of the IR-radiation from vehicles and other objects of military interest.

Apart from research, spectral images can be used for surveillance and targeting. Radar sensors provide a wide area coverage, but "for a given detection probability, they currently have unacceptably high false alarm rates" [Eismann]. Therefore, the use of visible and infrared sensors must be considered to decrease false alarm rates. Other disadvantages with radar compared to passive optical sensors are that a radar transmitter is easier to detect than a passive optical detector, and a radar can be jammed. During the day, the visible and the near infrared parts of the spectrum are interesting, but when it gets dark MWIR and LWIR sensors become more important. Broad-band infrared imaging sensors for MWIR or LWIR (IR-cameras) have been used successfully to detect hot targets in cold backgrounds. For example, a person in a cold background is easy to detect. Camouflaged targets in warm backgrounds are harder to detect with broadband IR-sensors. For such targets, spectral as well as spatial information about the radiation is needed in order to distinguish the target from the background. [Eismann], [Eismann and Schwartz]

2.4 Spectral resolution and frequency range needed for target detection

Eismann, Schwartz, Cederquist, Hackwell and Huppi have investigated which wavelength bands that are most effective in detecting targets. A number of target/background combinations of military interest in forest and desert environments were investigated using data from a non-imaging spectral database [Eismann3, Eismann4 and Schwartz2 in Eismann]. The result was that a small number of spectral bands can provide good target detection performance if the bands are chosen appropriately. Further, the optimal spectral bands tend to be in the region from 8.5 μm to 11 μm (or even 10.5 μm). The database was also used to estimate the minimal spectral resolution needed for an imaging spectrometer to detect military targets in the IR-region. The result was that a resolution of 250 nm is acceptable, but 100 nm can be set as a goal for an imaging spectrometer in order to be sure that the spectral resolution of the instrument will be adequate. Of course, the optimal frequency region for target detection in Swedish environments could be somewhat different from the one mentioned above. [Eismann]

When discussing the spectral resolution that is needed to detect targets, we will divide infrared spectral sensors into three groups: multi-spectral, hyper-spectral and ultra-spectral sensors, according to [Breckinridge].

Multi-spectral instruments able to record only a few spectral bands are called multi-spectral. For example the human eye is a multi-spectral sensor. A spectral resolution of $\Delta\lambda/\lambda \approx 0.1$ can be used for terrain classification.

Hyper-spectral instruments. A spectral resolution of $\Delta\lambda/\lambda \approx 0.01$ is used with hyper-spectral sensors. At this resolution the radiation from solid and liquid surfaces reveals details of the chemical composition.

Ultra-spectral instruments that can record spectral information in a large (1000 to 10000) number of spectral bands are called ultra-spectral. The spectrometer used with ScanSpec is ultra-spectral if the highest spectral resolution is used. With such a high spectral resolution the chemical composition of gases can be studied.

According to Breckinbridge's computations [Breckinbridge] a resolution of 10 nm approaches the optimum when studying solid objects in the range 0.4 to 2.5 μm . For comparison, the Bomem MR254 FTIR spectrometer used in the ScanSpec system has a maximum spectral resolution of 0.1 nm at 1 μm and 10 nm at 10 μm . Breckinridge also explains that "lower resolution is needed for solids than for gases because the atoms and their electronic transitions which form the lines are more tightly bound in the solid lattice and thus give much broader spectral features than those spectral features produced by gases". [Hackwell] states that "a resolving power ($\lambda/\Delta\lambda$) of 200 resolves any spectral features seen in a solid or liquid surface".

2.5 Conclusion

IR-cameras can detect hot targets in a cold thermal background, but in order to detect targets with a temperature not much different from the background, imaging spectrometers are necessary. The best wavelength bands for a high target/background contrast fall in the range 8.5 to 11 μm . A spectral resolution of 100 nm in that region is enough to detect military targets. The Bomem MR254 spectrometer has a higher resolution than necessary for this application. It is therefore possible to use it to investigate what the lowest spectral resolution needed is in order to detect military targets in typically Swedish backgrounds. This is important to know if a spectral imager with higher speed and higher spatial resolution will be bought or constructed at FOA in the future.

3 Imaging spectrometers

3.1 Introduction

The definition of an imaging spectrometer (or spectral imager) in this report is simply:

an instrument able to collect a spectral image.

There are other definitions, for example:

"... an instrument capable of simultaneously registering the spectrum components AND the spatial location" [internet: Specim].

I believe there is no instrument today that can simultaneously register both the spectrum and the two spatial dimensions of the radiation. In order to do that a three-dimensional array of radiation sensors is needed (or a 2D-array of 1D-arrays or a 1D-array of 2D-arrays).

2D-arrays of sensors for IR-radiation is in a phase of rapid development. The advent of large 2D-arrays of IR-sensors has led to the development of various types of imaging spectrometer designs. Some of the possible designs will be discussed in this report.

The data recorded by an imaging spectrometer can be viewed as a data cube of numbers of the spectral radiance in three dimensions: two spatial dimensions, x and y , and one spectral dimension f . A 2D-array of IR-sensors can, obviously, record only *two* of these three dimensions at the same time. The third dimension, the spectral or one of the spatial ones, must therefore be sampled temporally. If a 1D-array of IR-sensors would be used, two of the three dimensions would have to be sampled temporally. If only one sensor is used (as is the case with ScanSpec) all the three dimensions of the data cube must be temporally sampled. Since the performance of 2D-arrays of IR-sensors have recently been improved much and is being improved rapidly, I have no doubt that currently the best way of constructing imaging spectrometers is with a construction based on a 2D-array of IR-sensors. Therefore the following text will only treat imaging spectrometers based on such sensors.

There are basically three different ways of extracting spectral information from infrared radiation.

1. filtering
2. using dispersive instruments
3. using Fourier transform instruments

These three ways can all be used when designing an imaging spectrometer and will be exemplified. I will not try to give a complete summary of what different types of imaging spectrometers there are and their advantages and disadvantages. The following should be seen as examples of the instruments that exist today and the fundamental principles of their construction. The development of imaging spectrometers is very rapid at the moment and the situation in, say, five years will be completely different. More imaging spectrometers will be on the market and they will have better performance and probably cost much less than today.

One factor that limits the performance of the imaging spectrometers of today is the huge data rate that would be produced by a fast imaging spectrometer with high spatial and spectral resolution. For example, assume that we wish to produce spectral images with 500x500 pixels and 1000 spectral

bands. Further, assume that we want to record 25 spectral images per second and that each value of the spectral radiance is recorded with 2 bytes. This would demand a data rate of

$$500^2 \text{ pixels/spectral band} \cdot 1000 \text{ spectral bands/spectral image} \cdot 25 \text{ spectral images/s} \cdot 2 \text{ bytes/pixel} = 12.5 \text{ Gbyte/s!}$$

I do not think there is any way of taking care of all that data with the current technology at least not for a reasonable price, but if the speed of digital data storage units and processors increase as it has been in the past, who knows? Real-time data compression could possibly be used to reduce the enormous data flow.

3.2 Imaging spectrometers based on filtering

One easy way of constructing an imaging spectrometer is to use band-pass optical filters. For example a filter-wheel or a tunable Fabry-Perot filter can be placed in front of an IR-camera. Filtering is not a new technique, but it should not be underestimated compared to the various new approaches, especially as new filters develop. Conceptually, the design is simple, the instrument can be built small and light-weight and is not too expensive.

3.3 Imaging spectrometers based on dispersion

As we will see, there are several completely different ways of designing a spectral imager based on dispersion. Gratings or prisms can be used to spread out the wavelengths in space. I will not try to give a complete description of all different approaches that exist. I will merely give a few interesting examples. The examples will include commercially available imaging spectrometers.

Simple imaging spectrometers based on dispersion

The simplest type of imaging spectrometer, based on a 2D-array of light detectors, uses lenses, an entrance slit and a diffractive optical element. The diffractive element diffracts the light in one direction. The other direction is left for spatial imaging. The array of light detectors can simultaneously record the spectra in one direction and one spatial dimension in the other direction of the array. The second spatial dimension has to be temporally scanned. This can be achieved by turning a mirror in front of the spectrometer, by turning the whole spectrometer, or by moving it in one direction, for example by using it from an airplane.

One of the first of these instruments to be built is the Fluorescence Line Imager (FLI), designed and constructed in Canada in 1981. It uses a CCD-camera covering the visible and near infrared part of the spectrum. The first entrance lens for the FLI forms an image on a slit. The second lens collimates the light. Then the light passes through a transmission grating and the last lens before it is detected by a 2D-array of light sensors. [Gower]

There are imaging spectrometers for the infrared region that are based on the same basic principles as the FLI above, for example SEBASS. SEBASS works in the MWIR and the LWIR regions. More information about SEBASS can be found in [Hackwell] and [Eismann].

An imaging spectrometer that disperses the light along the optical axis

Pacific Advanced Technology Inc. (California, USA) has used a new approach to dispersive imaging spectrometry that has been patented¹. A single optical element is used, see Figure 3. That element performs both the imaging and the dispersion. An 2D-array of light sensors is moved as indicated in the figure. Only one specific wavelength of light is focused on the sensor array at a time. The optics is designed so that the depth of focus is very shallow, allowing for high spectral resolution.

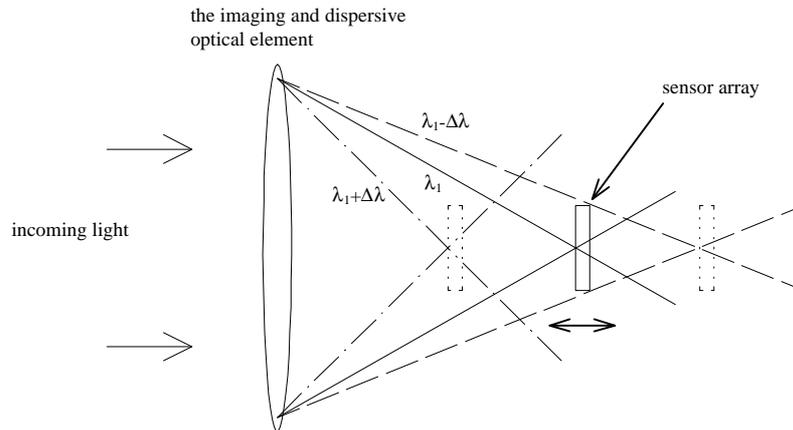


Figure 3 - The principle of the Pacific Advanced Technology imaging spectrometer. Light of longer wavelength will be refracted more in the optical element than that of shorter wavelengths. Only light with a specific wavelength will be focused at the sensor array. As the sensor array moves as indicated a spectral image can be recorded.

The collected spectral image needs advanced digital image processing to increase the spatial and the spectral resolution. Non-linear deconvolution algorithms have been developed for this.

The advantage of this approach over a conventional dispersive spectrometer is that the whole aperture can be used to collect light instead of only a narrow slit that has a low throughput. It also has an advantage over a Fourier-transform spectrometer. The photon noise (shot noise) is lower, since only light from a small frequency band is measured at a time, not the entire bandpass of the instrument as is the case for a Fourier transform spectrometer. However, the spectral resolution of a Fourier-transform spectrometer is generally higher.

Pacific Advanced Technology offers an MWIR instrument with the following parameters:

Spectral range	3.0 - 5.0 μm
Nominal Spectral resolution	$\Delta\lambda/\lambda = 0.0025$ (0.01 μm at 4 μm)
F-number	f/2.5 at 4 μm

A turn-key system including IR-camera and computer would cost around 95000 USD. This instrument could be used with an existing IR-camera and a computer which would reduce the cost to 45000 USD. They also sell a new product covering the range 8 to 10 μm which is a bit more expensive. [email: Hinnrichs]

¹ US Patent 5,479,258 issued Dec. 26, 1995



Figure 4 - The imaging spectrometer from Pacific Advanced Technology.

Their instrument is shown in Figure 4. More information can be found at their web site [internet: Patinc].

[Hinnrichs]

ImSpector N17

The Finnish company Specim, Spectral Imaging Ltd., sells a spectral line imager based on dispersion. See [internet: Specim]. The N17 costs 4700 USD and 19000 USD together with a suitable InGaAs IR-camera [email: Parameter].

3.4 Imaging spectrometers based on Fourier-transform methods

Fourier-transform spectrometry (FTS)

For readers not familiar with Fourier-transform spectrometry I will briefly explain the main idea.

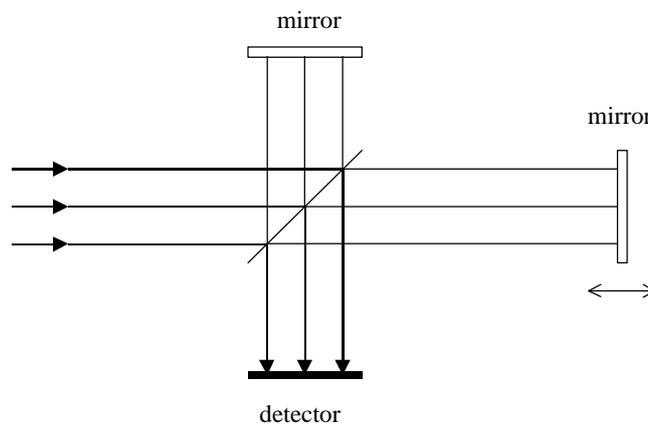


Figure 5 - The basic principle of Fourier-transform spectrometry.

The basic principle of Fourier-transform spectrometry (FTS) is shown in Figure 5. The optical layout can vary, but the principle is the same. Light enters from the left in the figure, a beam-splitter

reflects 50 per cent of the light towards the top mirror and the rest of the light hits the mirror to the right. The light is reflected on the mirrors and the light from the two optical paths are reunited at the beam-splitter. The light from the vertical and the horizontal optical paths interfere with each other and hit the infrared detector (or a two-dimensional array of IR-detectors). By moving the right mirror and simultaneously studying the interference pattern of the light at the detector an *interferogram* can be acquired. There is a one-to-one correspondence between this interferogram and the spectrum of the light. This relationship will not be derived here, but it involves a Fourier-transform, hence the name of this method. I refer to [Pedrotti] for a more detailed discussion of the subject.

Infrared imaging spectrometers based on Bomem Spectrometers

Bomem Inc. has been involved in the development of imaging spectrometers based on the Bomem MB-series of FTIR spectrometers. The imaging spectrometers DREV IISR 0, IISR I and IISR II were developed for the Defense Research Establishment at Valcartier (DREV), Canada. These imaging spectrometers are especially interesting for FOA since they are based on the same type of spectrometer as the one used in the ScanSpec system. The principle of the design of those spectrometers is rather simple. Instead of using only one detector to record one interferogram (see Figure 5), a 2D-array of IR-detectors is used. Each detector will then record interferograms from different spatial locations. The arrangement can be seen as many independent Fourier-transform spectrometers that use the same optics.

The development of the first Infrared Imaging Spectral Radiometer (IISR) based on a Bomem FTIR spectrometer started in 1988. It was based on the largest InSb detector array commercially available at the time (4x8) and is called DREV IISR 0. It was a bench top proof of concept instrument and it was followed by DREV IISR I that was able to acquire valuable data. The next version, DREV IISR II, is an improved field instrument.

Eglin IISR is a newer (1996) instrument also based on a Bomem FTIR spectrometer. It is a compact prototype for airborne use.

These are some of the specifications for the Eglin IISR:

Spectral range	3.5 - 5 μm (compatible to LWIR also)
Spectral resolution	1, 2, 4, 8, 16, 32, 64, 128 cm^{-1} (computer selectable) ¹
Spatial resolution	8x8 pixels
Frame rate	60 frames/s at 4 cm^{-1} resolution
Maximum recording time	15 s at 4 cm^{-1} resolution

My conclusions of the Eglin are that it is very fast and still has a high spectral resolution. The speed and the spectral resolution combination of such an imaging spectrometer surpasses all other imaging spectrometers I have read about, but the low spatial resolution of 8x8 is, of course, a drawback of the instrument. The short maximum recording time is also a limitation of the instrument.

[Villemaire], [presentation: Villemaire]

¹ The unit most widely used for frequency in spectrometry is the a *kayser* (k). The word "kayser" is not widely used, usually substituted with "reciprocal centimeters". 1 cm^{-1} equals $2.9979 \cdot 10^{10}$ Hz \approx 30 GHz. [Beer].

Spatial Fourier-transform spectrometry

For the Eglin imaging spectrometer above, the interferograms are sampled in time, this way of acquiring interferograms is called *temporal FTS*. There is another fundamentally different way of acquiring the interferograms - *spatial FTS*. For spatial FTS, one axis on the 2D IR-detector array is used to sample the interferogram while the other axis is used to acquire spatial information in one dimension. The other spatial dimension has to be sampled in time. There are several different optical designs for imaging spectrometers based on spatial FTS, see [Sellar]. One example of a possible design will be described below.

A spectrometer using a grating to achieve path differences

This type of spectrometer is called a digital array scanned interferometer (DASI). It is based on a Michelson interferometer using the principle shown in Figure 5, but it has no moving parts. A grating is used, not to disperse light, but to achieve the optical path difference necessary for the interferogram to be recorded. This can be seen in Figure 6. The interferograms and one spatial dimension can be recorded simultaneously by the 2D detector array. The other spatial dimension necessary to form a spectral image has to be scanned with a mirror or by moving the whole spectrometer.

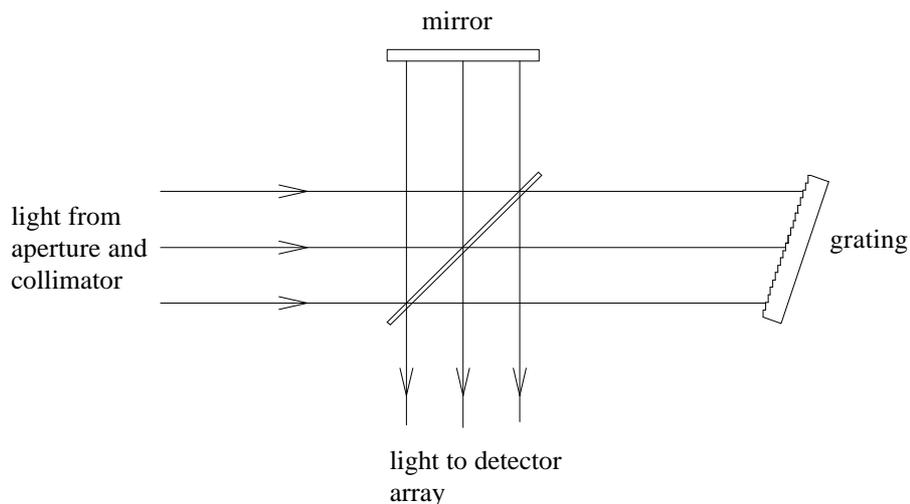


Figure 6 - An interferometer where a grating is used to produce the optical path difference necessary to produce the interferogram. The 2D detector array records interferograms in one direction and a spatial dimension in the other direction.

According to [Hammer], "a DASI has the potential of achieving higher spectral resolution at a specific signal-to-noise level than do equivalent aperture grating-based instruments".

[Hammer]

4 The goals of the project

4.1 The goals

The goal of the ScanSpec project was to build an imaging spectrometer using an existing non-imaging spectrometer (Bomem MR254) with a narrow angle telescope. This was to be done by using a large mirror in front of the telescope that can be turned around two rotation axes to acquire spectra from different spatial locations. The spectrometer used is briefly described in chapter 5.1.

The main performance design goal of ScanSpec was that the existing Bomem spectrometer should, when possible, limit the total performance of ScanSpec. By "when possible" is meant when possible within the given time and money resources of the project (see chapter 4.2 below).

The minimum performance requirement of ScanSpec was that it should be able to acquire a spectral image with the spatial resolution of 10x10 pixels within one minute.

An extra desirable feature was the target-following feature. That feature is the possibility to continuously measure the IR-radiation from a moving object by turning the mirror. In order to be able to follow an airplane, the line of sight of ScanSpec must turn 20° per second or more. Also, it is desirable to cover a large part of the sky by turning the mirror. The coverage of the sky of an elevation angle of -4° to 50° and an azimuthal angle of ±90° would be sufficient for this target-following feature.

ScanSpec should be documented so that it can be used with no further information than the User's manual. There should also be a report describing the project (this report).

Both the hardware and the software should be constructed to make it easy to modify for other new applications.

4.2 The resources

The ScanSpec was to be built, tested and documented using 20 weeks of work for one person and within a total time of 24 weeks.

The cost of the project could not exceed approximately 200 000 SEK not including my salary.

5 The overall design of ScanSpec

5.1 The Bomem MR254 FTIR spectrometer

To understand the design of ScanSpec, a few things need to be known about the Bomem MR254 spectrometer. Only the information needed to understand the rest of this report is provided here. For further information, please refer to [Bomem1] and [Bomem2].

The Bomem MR254 is an FTIR spectrometer (Fourier-transform infrared spectrometer) with changable spectral resolution. The spectral resolution of 1, 2, 4, 8 or 16 cm^{-1} can be chosen. The standard programs of ScanSpec use a resolution of 4 or 16 cm^{-1} . The spectral range of the spectrometer itself is from 0.7 to 20 μm , but the usable range depends on what detectors that are used. The Bomem spectrometer used for ScanSpec is equipped with two IR-detectors, an InSb- and an MCT-detector. The optical layout of the spectrometer makes it possible to use both the detectors simultaneously. The spectrometer has a built-in cold black-body source used to optically subtract the internal radiation of the optics in the MR254. Both of the detectors and the black-body source are cooled with liquid nitrogen. The MCT-detector is called Detector A and the InSb-detector is Detector B.

The spectrometer has three apertures: one between the telescope and the spectrometer, and one in front of each of the two detectors. There are seven settings of the diameter of the apertures: 6.4, 4.5, 3.2, 2.2, 1.6, 1.1 and 0.8 mm. ScanSpec is currently designed to be used with all apertures set to 6.4 mm, but it can be used with other aperture settings.

The MR254 in the ScanSpec system uses a narrow angle telescope, also from Bomem. Bomem specifies the field of view¹ of the telescope to 0.27°, but measurements at a distance of 60 to 90 m show that the field of view is closer to 0.20°, see appendix 1.

The spectrometer is controlled by a PC-computer (called the FTIR-computer) and a program developed by Bomem called Acquire. While the spectrometer is collecting interferograms, the data is sent from the spectrometer to an acquisition board in the FTIR-computer via an optical fiber. The memory of the acquisition board is limited to 64 Mbyte which is the maximum amount of data that can be collected by the spectrometer. Each point of each interferogram is stored with 2 bytes, so a maximum of approximately 32 million interferogram points can be acquired. When the acquisition of the interferograms is finished, the data is sent from the acquisition board to the RAM-memory of the FTIR-computer. With Acquire the user can then produce calibrated spectra from the acquired data and calibration files. The calibrated data is stored in a special file format that can be read by the ScanSpec software.

Unfortunately, the Acquire program cannot be controlled from another program. The user has to interact with Acquire to produce the calibrated spectra from the acquired data, so this process cannot be automated.

If the resolution 16 cm^{-1} is chosen, a maximum of 65 spectra can be acquired per second. For the resolution 4 cm^{-1} the spectrometer can acquire 31 spectra/second. The spectrometer can add many interferograms to reduce noise before the data is sent to the acquisition board in the FTIR-computer.

¹ The field of view of the telescope is the angle of the circular cone from which the telescope gathers light. It is abbreviated FOV.

Each spectrum gets a time stamp when it is acquired, based on the system clock of the FTIR-computer. It is not specified in the documentation from Bomem Inc. [Bomem1], [Bomem2] if the time stamps mark the beginning, the middle or the end of the time period while the spectrum is being acquired.

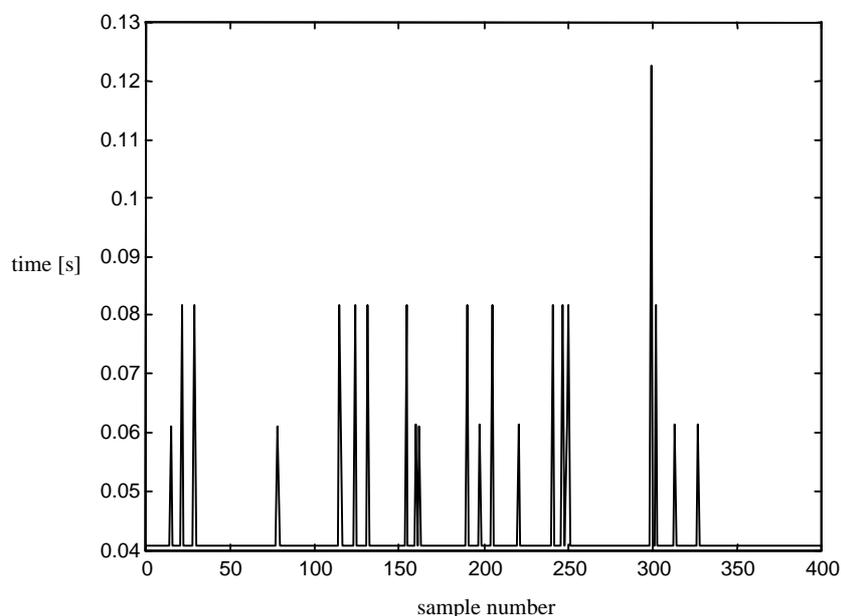


Figure 7 - The time between two consecutive spectra. 21 of the 400 times are not what they should be. The resolution 8 cm^{-1} was used, two interferograms were added per measurement, oversampling was on and both detectors were used.

Unfortunately, the times when the spectra are acquired cannot be controlled at all. When the acquisition has started, the spectrometer cannot be controlled by any external events. Another timing problem is that if the spectrometer is, for example, set at the resolution 8 cm^{-1} and set to add two interferograms per measurement it should be able to acquire 25 spectra/s. Usually it does, but not always! In most cases the time between two consecutive spectra is $1/25\text{ s}$ but sometimes that time is $1.5/25$, $2/25$ or even $3/25\text{ s}$. Figure 7 shows what it can look like.

This irregularity and the fact that the spectrometer is independent of external events once it has started has made the signal processing much more complex than what it could have been.

5.2 Main design

To build an equipment that complies with the target-following feature, explained in chapter 4.1, the first type of construction considered was the one in Figure 8.

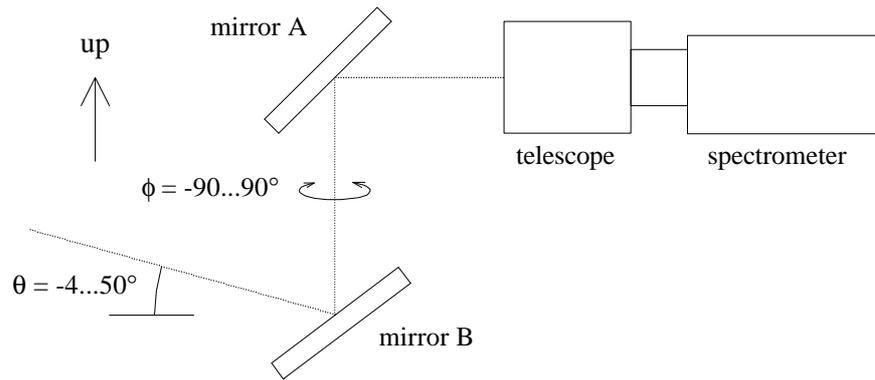


Figure 8 - Main construction Alternative 1. The mirror A is fixed at a 45° angle with the optical axis of the telescope. The mirror B can be rotated $\pm 90^\circ$ around the vertical axis as indicated and it can also be rotated around a horizontal axis through the surface of the mirror.

The advantage of this construction is that the system would cover a large part of the sky, and that the target-following feature would be provided for. The disadvantages are that two mirrors must be used and that the supporting construction for the mirrors and the spectrometer would be more complicated than for the alternatives below that use only one mirror.

The target-following feature could also be realised with only one mirror (Alternative 2) as shown in Figure 9.

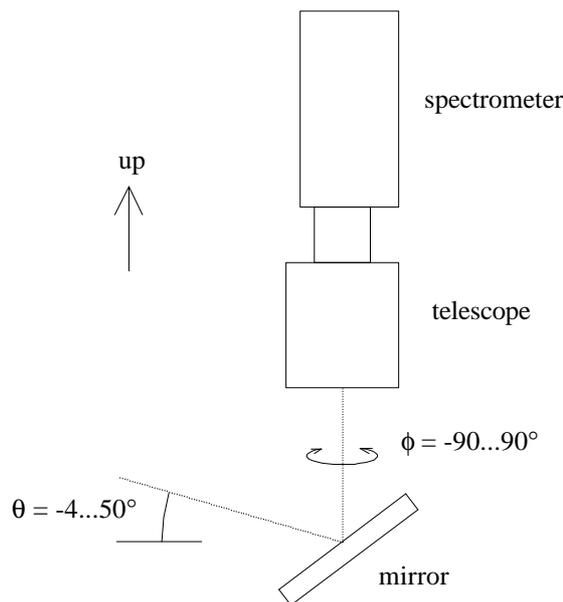


Figure 9 - Main construction Alternative 2. The elevation angle can be between -4° and 50° and the azimuthal angle from -90° to $+90^\circ$ from straight forward.

Alternative 2 has the advantage that it only uses one mirror which increases the performance. On the other hand, the standing arrangement is harder to stabilize to the ground since the center of gravity of such a system would be much higher above the ground than for Alternative 1. There is also another problem. The spectrometer itself works well in a vertical angle as in Figure 9, but the IR-detectors are cooled with liquid nitrogen and the dewars for the nitrogen are not made for vertical use of the

spectrometer. It is possible, but costly to make new dewars designed specifically for the vertical use of the spectrometer. Paul Coulson at Bomem Inc. guessed the cost for such dewars to be "in the order of 30 000 - 40 000 USD" [email: Coulson]. This cost would be way too high, but the existing dewars could probably be modified to work vertically.

The construction that was finally chosen (Alternative 3) is depicted in Figure 10. It is capable of collecting spectral images, but the ranges of q and f are not adequate for the target-following feature, explained in chapter 4.1. The construction can be easily modified to Alternative 1 or 2. When the chosen construction has been tested it could be further built to work vertically. If the Alternative 1 construction would be preferred later, the rotating mirror must be replaced with a fixed 45° -mirror and the rotating mirror must be placed below the 45° -mirror.

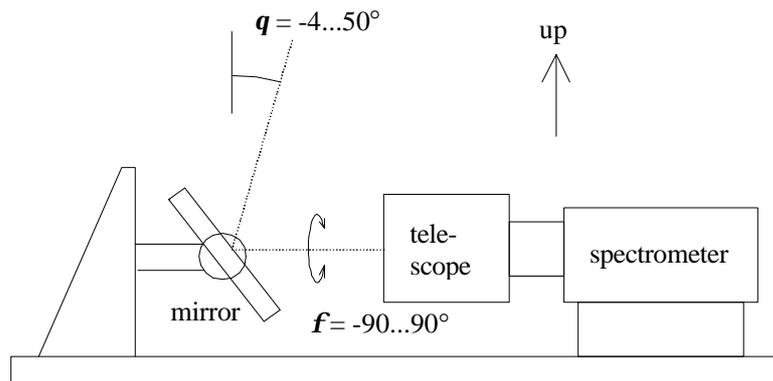


Figure 10 - Main construction Alternative 3. The spectrometer and the support for the mirror turning system are standing on two beams. This construction can be modified to main construction Alternative 1 or 2.

To sum up, if the chosen construction would be modified in the future to the standing arrangement (Alternative 2) no extra work has been done compared to choosing Alternative 2 from the beginning. If the chosen construction would be modified to Alternative 1 in the future there is a little bit of extra work compared to choosing Alternative 1 from the start. But, if the target-following feature will never be used, choosing Alternative 1 from the start would have been a waste of time and money. Also, it is doubtful if the construction according to Alternative 3 could be realized with the available resources of the ScanSpec project (see chapter 4.2).

5.3 Definition of angles

The definition of the following angles will make it easier to explain the scan pattern of the mirror treated in chapter 5.4.

f and q are defined in Figure 10.

f_2 and q_2 are defined as: $f_2 = q$, $q_2 = 90^\circ - f$. When f_2 and q_2 are close to zero they approximate the azimuthal and the elevation angle for the chosen construction. f_2 is zero when the line of sight and the optical axis of the telescope are orthogonal. f_2 is positive if these angles are acute. q_2 is the elevation angle when $f_2 = 0$. The rotation axis of the mirror-turning system that changes the f_2 -angle will be called the f_2 rotation axis. The other rotation axis will similarly be called the q_2 rotation axis.

x and y are defined as: $x = \mathbf{f}_2 / 2$ and $y = \mathbf{q}_2$. These angles are the mechanical angles that the mirror-turning system must turn the mirror to accomplish a line of sight with the angles \mathbf{f}_2 and \mathbf{q}_2 . The "2" in the expression above is because the mirror only has to turn the angle $D\mathbf{f}_2 / 2$ around the \mathbf{f}_2 -axis to change \mathbf{f}_2 with the angle $D\mathbf{f}_2$.

5.4 The scanning of the mirror

The specifications of the mirror-turning system depend on how the mirror is scanned to acquire a spectral image. There are basically two different ways of doing this. One way is to let the mirror go to the desired starting position and stop. Then the spectrometer gathers one spectrum and the mirror moves to a position corresponding to the next pixel in the spectral image and stops. Then the spectrometer would gather the next spectrum, and so on. This way of step-scanning would require enormous accelerations of the mirror if the scanning should be so fast that the speed of the spectrometer limits the time of acquiring a spectral image. Another problem with this type of scanning is that the spectrometer cannot be synchronized with the step motion.

The other way of scanning the mirror, which was chosen in this project, is to continuously scan the mirror over one line of the image at a time. By scanning all the lines all the data for the spectral image can be acquired. The drawback with continuous scanning is the motion blur due to the fact that the mirror is moving during the acquisition of the spectra. Note that a Fourier-transform spectrometer gathers data for all the frequencies at the same time (the Fellgett or multiplex advantage [Pedrotti]), so that all frequencies will be recorded from the same field of view. The motion blur is not such a serious problem since the mirror will never move more than one pixel distance during the acquisition of one spectrum. Also, since the angular speed of the mirror is known, the motion blur could be compensated for in the signal processing of the data. However, this has not been done since motion blur has shown to be a minor problem.

According to measurements (see Appendix 1), the field of view of the telescope is approximately circular with a diameter of 0.20° when the largest apertures (diameter = 6.4 mm) are used. Assume that we would like to scan the mirror so that one spectra will be recorded for every 0.20° . Since the spectrometer acquires 65 spectra/s in the fastest mode the mirror has to turn with the speed of $13^\circ/\text{s}$ if the scanning is done by turning the mirror around the \mathbf{q}_2 rotation axis. If the scanning is done around the the \mathbf{f}_2 rotation axis only half of that speed is needed, $6.5^\circ/\text{s}$. The minimum speed needed for the target-following feature is $20^\circ/\text{s}$ for the \mathbf{q}_2 rotation axis and $10^\circ/\text{s}$ for the \mathbf{f}_2 rotation axis. Those speeds determines how fast the tables should be.

The needed acceleration of the tables is another important issue. The goal that the spectrometer should limit the performance of ScanSpec means, in this case, that the time when the spectrometer is not acquiring useful information (the time while the mirror is not moving with a constant velocity to scan a line in the spectral image) should be small compared to the total acquisition time.

One question that arises when deciding on the scan pattern is what the spatial sampling frequency should be. The angular sensitivity of the InSb-detector and the MCT-detector together with the narrow-angle telescope has been measured (see appendix 1). The field of view of the telescope sets an upper limit of the spatial frequencies that can be measured with the scanning system. The telescope works as a low-pass filter for the spatial frequencies. Appendix 1 contains figures showing the magnitude of the Fourier-transform of the angular sensitivity¹ functions (the MTF's) for the two detectors together with the narrow angle telescope. Note that these measurements were performed

¹ The magnitude of the Fourier-transform of the angular sensitivity is commonly called the MTF, the modulation transfer function. See [Holst] for a thorough discussion of MTF.

without the mirror that ScanSpec uses. The mirror also affects the angular sensitivity functions. The figures of the Fourier-transforms in Appendix 1 show that spatial frequencies above 5 cycles/degree will be almost totally destroyed by the low-pass filtering feature of the telescope. Thus, spatial frequencies above 5 cycles/degree are not possible to acquire. According to the Nyquist criterion a sampling frequency of 10 cycles/degree is enough to reproduce a signal that is limited to frequencies below 5 cycles/degree. This sampling frequency is used with ScanSpec, that is a spectrum is acquired every 0.1° .

One figure of merit when quantifying the amount of aliasing is to see how much of the total power of the MTFs that falls within the frequency band that can be reconstructed (within 5 cycles/degree in this case) [Watson]. Crude estimates show that that figure is above 88% for the InSb-detector and above 82% for the MCT detector, so aliasing should not be a problem if the sampling frequency is 10 samples/degree.

The scan pattern first implemented was the one in Figure 11. The effective scan lines goes both in the right and the left direction.

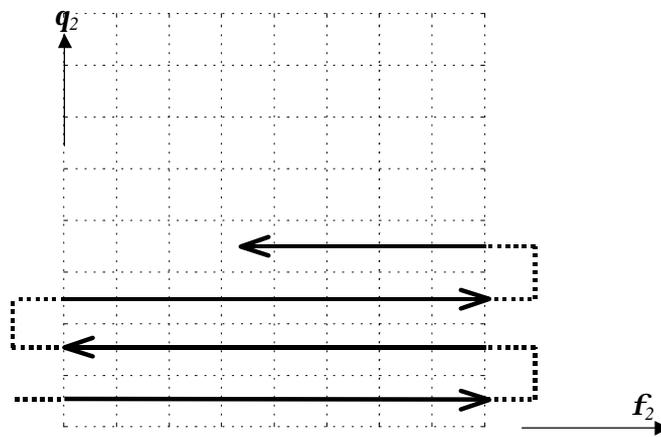


Figure 11 - Scan pattern. The effective scan movements are marked with thick line. The background grid shows the locations of the pixels in the spectral image.

That type of scan pattern showed to work poorly because of timing problems. Instead, the scan pattern shown in Figure 12 was used with better results. Note that when the dotted parts of the path in Figure 12 is traced, the mirror moves as quickly as possible. For most scan programs¹, the ineffective scan time is small compared to the effective scan time. The ineffective scan time is the time when the line of sight traces the dotted part of the path, and the effective scan time is the time when the line of sight is tracing the part of the path marked with thick arrows.

¹ The user can choose a "scan program" which consists of parameters that control the scanning of the mirror such as image size and spectral resolution.

6 The ScanSpec hardware

6.1 The mirror

When choosing a mirror for IR applications there are some important parameters of the mirror to consider: reflectance, flatness, protective coating, size and shape, weight, and price.

Reflectance

The reflectance of a mirror that will be used for IR-applications is important in two ways. Firstly a high reflection is needed to keep most of the radiation that will be studied. Secondly and often more important, a high reflection is needed to decrease the amount of thermal emission from the mirror. This emission of IR-radiation from the mirror is especially harmful; it is hard to calibrate the spectrometer so that this radiation will be compensated for, since it might not be possible to keep the temperature of the mirror constant.

Gold-coated mirrors have best reflectance in the IR-region of the spectrum. Silver- and aluminum-coated mirrors also have good reflectance in this region and they have higher reflectance than gold in the visible region.

Flatness

The flatness of the mirror is not very crucial in this case. The mirror will only collect light for *one* pixel of the image at a time. The flatness is much more important for an imaging system that collects a whole image at a time. One problem when buying a mirror is that different manufacturers define flatness differently.

Protective coating

A surface coating is needed to protect the surface from scratches and oxidation. A bare aluminum or gold surface must not be touched at all.

Size and shape

The mirror size depends on the range of the angles f and q . It also depends on how close the rotating axes will be to the surface of the mirror. See Appendix 2 for the calculation of the required mirror size. The size of the mirror chosen is 438 by 290 mm (rectangular). The weights and prices below are based on approximately that size.

Weight

For the ScanSpec application the mirror has to be accelerated quickly it is important to keep the weight low. In our case this means the same as not choosing a mirror that is unnecessary thick.

There are however (very expensive) mirrors where weight has been reduced by not making them solid. The bending rigidity of such a mirror is much higher than that of a solid mirror with the same weight.

Price

The price of mirrors varies a considerably, especially with the flatness parameter. The price can be reduced a lot if an off-the-shelf mirror can be bought instead of one specially designed for just this application. If the flatness does not have to be very high, float glass¹ can be used, and then the price of the glass substrate is low since float glass is not polished. For a specially designed mirror the two main costs are the price of the glass substrate (if float glass is not used) and the cost of coating the glass. The choice of surface coating material is less important for the price.

Alternatives

Three different alternatives for the mirror were thoroughly investigated.

1. A gold-coated mirror with a high surface flatness (0.75 μm). Spectrogon could deliver such a mirror in 10 to 12 weeks for between 60 000 and 70 000 SEK [phone: Spectrogon 980618]. Also Melles Griot could make such a mirror for around 65 000 SEK [phone: Melles Griot 980626]. Such a mirror would be between 30 and 40 mm thick and weigh 10 to 13 kg with the size specified above.
2. A thinner mirror with a medium flatness. A flatness of around 9 μm can be obtained with normal float glass about 15 mm thick. Spectrogon could deliver a 15 mm aluminum coated mirror for 28 600 SEK in about 6 weeks after order [fax: Spectrogon 980625]. Bernard Halle could sell an aluminum coated mirror with the mentioned flatness and thickness for 2100 DEM [fax: Bernard Halle 980710] which is a much better deal. The weight of a mirror with the given dimensions is about 5 kg.
3. A thin off-the-shelf mirror. Edmund Scientific (New Jersey, USA) sells a 408 \times 609 \times 6 mm aluminum coated float glass mirror for 200 USD. The flatness is 6 to 8 μm according to [phone: Edmund Scientific 980624], but these figures are not guaranteed by Edmund Scientific. The mirror is too large, but since it is so thin it can be cut with an ordinary glass cutter. The weight after it is cut to the desired size is 1.9 kg. The delivery time is less than 2 weeks.

A 10 mm thick float glass mirror at the IR-department at FOA was tested in front of the telescope. The CCD camera on the spectrometer showed an image that was not much blurred by the mirror. Unfortunately, the mirror was not large enough for this application. But, the result shows that the flatness of a float glass mirror can be sufficient for this application. A normal bathroom mirror (about 4 mm thick) was also tested, but gave a very blurred image from the CCD camera. Not surprisingly, such a mirror is not flat enough for this application.

Alternative 1 was discarded, since the flatness of a float glass mirror is sufficient. Also the price for such a mirror is much higher than for the other alternatives. The weight would require much from the mirror turning system, and the delivery time is unacceptably long.

¹ Float glass is "flat glass produced by solidifying molten glass on the surface of a bath of molten tin" according to [internet: Webster].

It was decided to order a mirror from Edmund Scientific according to Alternative 3. The stated flatness is good enough, but there was a question of whether the thickness of 6 mm gives enough bending rigidity to keep the mirror flat when forces act on the mirror due to angular acceleration and the mass of the mirror. If the mirror, according to Alternative 3, would not be sufficient for the application there is no big loss, since that mirror is inexpensive and the delivery time short. A mirror according to Alternative 2 could then be bought. The mirror-turning system is designed for the Alternative 3 mirror, but it also works for the Alternative 2 mirror even though it will then be a bit slower.

The mirror from Edmund Scientific was tested with the telescope and the CCD camera on the spectrometer. The results showed that the flatness of the mirror is good enough. The image recorded by the CCD camera was not perfectly sharp (not as sharp as when the 10 mm float glass mirror was tested), but not so blurred that it matters much for this application.

6.2 The mirror mounting

When choosing the way to mount the mirror I considered essentially five requirements:

1. The mirror mounting should not introduce unnecessary forces on the mirror which causing the mirror to bend.
2. The mounting should be so stiff that the angles between the surface of the mirror and the mirror-turning system do not change more than 0.01° during the rotations.
3. The mounting should be made so that bending due to angular accelerations and the mass of the mirror is minimized.
4. The strength of the mounting should be enough to carry the weight of the mirror and other forces.
5. Thermal expansion should be considered.

It is almost impossible to try to support the mirror with something flatter than the mirror itself. So the mirror has to support its own weight and it must also handle the forces due to angular acceleration without bending too much.

Requirement 1 can be obtained by mounting the mirror at only three points. Theoretically no moments can then act on the mirror due to the mounting. In reality there are no ideal points, but the the points should be made as small as possible. Also an elastic material (rubber) can be used to minimize moments acting on the mirror through the mounting points. The construction of one of these three mounting points can be seen in Figure 13. I chose to use adhesives to fasten the mirror. Another way would have been to use clips around the edges. The adhesive method has the advantage that the mirror can be fastened anywhere on the backside of the mirror, not only at the edges. The drawback is that once glued, nothing can be changed.

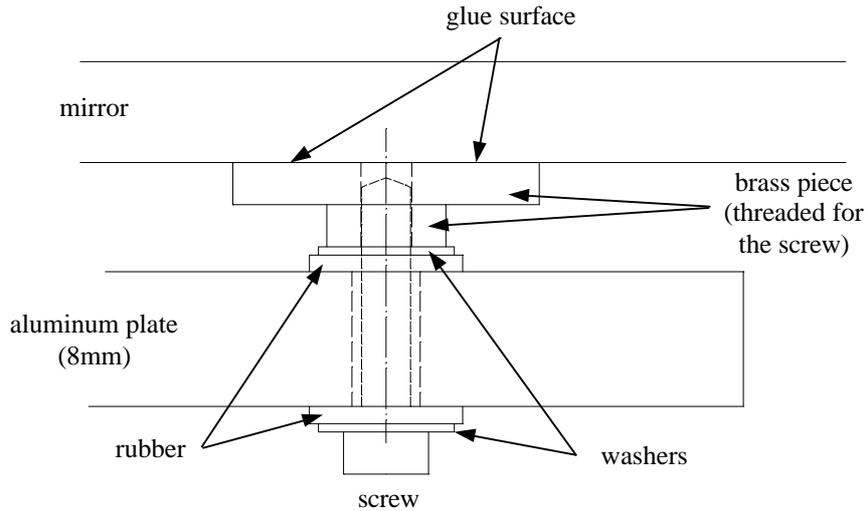


Figure 13 - A drawing of one of the three mirror mounting points

Requirement 2 has been proved to be fulfilled with this construction and the scan pattern used.

Requirement 3. The three mounting points must be located to minimize the bending of the mirror caused by forces. This is a problem that has not been treated in detail. An analytic calculation was made on the one-dimensional case (bending of a beam), but it might not be valuable for this case. The problem is well defined though and could be solved numerically with finite element methods (FEM).

Requirement 4 is fulfilled. The strength of the three mounting points is good, in fact, many times better than necessary.

Requirement 5. The mounting should not introduce forces on the mirror due to changes in temperature. If the mirror mounting should be able to work between $-25\text{ }^{\circ}\text{C}$ and $35\text{ }^{\circ}\text{C}$ the temperature range ΔT is 60 K. The linear thermal expansion coefficient for aluminum is $23.2 \cdot 10^{-6}\text{ K}^{-1}$ (average between 0 and $100\text{ }^{\circ}\text{C}$) and for common glass it is $8 \cdot 10^{-6}\text{ K}^{-1}$ [Physics]. The mounting points will not be more than 0.53 m (the diagonal of the mirror) apart. The difference in thermal expansion between aluminum and glass on that distance and the given ΔT is $(23.2 \cdot 10^{-6}\text{ K}^{-1} - 8 \cdot 10^{-6}\text{ K}^{-1}) \cdot 60\text{ K} \cdot 0.53\text{ m} = 0.00047\text{ m} \approx 0.5\text{ mm}$. The holes for the screws in the aluminum plate should be made larger than the diameter of the screw to compensate for this.

The choice of adhesive

Two different adhesives were tested, Loctite 406 (cyano acrylate) and a two-component epoxy adhesive called Araldit 2012. The Araldit has superior strength with the tested brass-glass combination and it was used for the ScanSpec mirror. I will not describe in detail the tests that were made, but I will state some conclusions. The cleaning of the surfaces is very important, as is the roughness of the surfaces. The brass surface should be made rougher with a file. The strength of the glue specified by the producer is very optimistic and their testing must have been done under very optimum conditions. Those figures cannot be used, testing is necessary! The tests show that the used mirror mounts holds at least 300 N each which is well enough for the application. This figure corresponds to a stress of 4 MPa ($= 4\text{ N/mm}^2$). The producer of the Araldite 2012 stated a figure of 15 MPa.

6.3 The mirror-turning system

This section will serve as a brief description of why the chosen mirror-turning system was favored and also serve as some advice for someone who intends to buy similar equipment. The most important parameters for the mirror-turning system follows.

- Speed. At least $10^\circ/\text{s}$ for dx/dt and $20^\circ/\text{s}$ for dy/dt provide for the target-following feature.
- Acceleration. The faster the better. An acceleration of $100^\circ/\text{s}^2$ is adequate for ScanSpec.
- Angular precision. The field of view of one pixel in the spectral image is 0.10° . We want the maximum error of the angles f_2 and q_2 to be 20% of a pixel (0.02°). Then the maximum error of the angle x must be $0.02 / 2 = 0.01^\circ$ and the maximum error of y must be 0.02° .
- Control. It must be possible to easily control the mirror-turning system from a PC.
- Torque. The torque must be high enough to turn the mirror so quickly that the turn-around time for the mirror is low compared to the effective scan time.
- Range. The system must cover the range of f and q as shown in Figure 8, page 21.
- Delivery time. As soon as possible, but not longer than 8-10 weeks.

The first approach was to find a complete system to buy which would be as complete as possible only leaving me with the mirror mounting to do. But, finally separate parts were bought, since there was no complete mirror-turning system that met the requirements above and at the same time was within the budget of the ScanSpec project. Many alternatives were considered more or less in detail. Some of them are briefly described below. Generally, the companies are well represented on the internet and references to the internet addresses are given.

Alternative Sagebrush

Sagebrush [internet: Sagebrush] offers a gimbal system (Model-20 Pan & Tilt Gimbal) that is inexpensive (around 80 000 SEK), but unfortunately the torque is too low for the ScanSpec application. Their gimbal with a camera mounted is shown in Figure 14. Sagebrush is working on a new larger gimbal, but it was not available for sale in June 1998.



Figure 14 - The gimbal system from Sagebrush.

Sagebrush could also design a custom made gimbal for the performance needed, but they said they could not possibly deliver such a system within the desired delivery time.

Alternative Daedal

Contacts were made with Östergrens elmotor, (a Swedish representative of Daedal Inc.) regarding the making of a custom-designed gimbal system for our needs. They tried to design a system, but failed to do so before the very last possible date for an order from FOA. Daedal does not have an off-the-shelf product that matches our needs. One possible way would be to buy separate parts from Daedal, but for the alternative with separate parts, Newport had better products to match our specifications.

Other alternatives

Products from other companies have also been studied. Aerotech [internet: Aerotech] offers a complete gimbal system shown in Figure 15. The weight of more than 100 kg was way too much and the price is probably not even close of matching the budget.

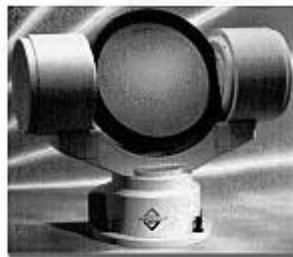


Figure 15 - Gimbal system from Aerotech.

Other companies that have similar products as the ones above include Ball Aerospace & Technologies Corp. [internet: Ball] and Anorad [internet:Anorad].

Alternative Newport (the chosen alternative)

Newport could offer a complete gimbal system for our needs, but it would have to be custom built and the price would be closer to 200 000 DEM than the required maximum cost of 200 000 SEK. However, Newport sells separate parts that suit our application. They sell both rotary tables and cradles. Some of their products are shown in Figure 16.



Figure 16 - Rotary tables (left) and cradles (right) from Newport.

The rotary tables have better accuracy than the cradles. Therefore two rotary tables were bought. One rotary table plus a cradle was also considered as an alternative.

The two rotary tables RV120PP and RV160PP were bought with stepper motors controlled by the motion controller MM4005. From now on the motion controller MM4005 will be called MM.

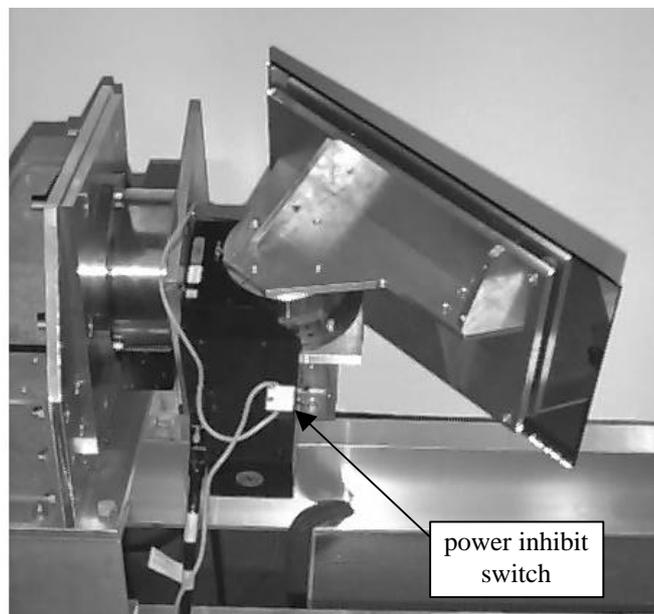


Figure 17 - A photo of the mirror-turning system of ScanSpec. One of the two power inhibit switches is marked. The other parts of the mirror-turning system are labeled in Figure 18.

How the two rotary tables are mounted can be seen in Figure 17 and Figure 18. The mirror-turning system has two emergency motor power inhibit switches (one shown in Figure 17) that protect the tables from rotating too far which would cause serious damage to the construction.

The use of AutoCAD

AutoCAD was used when making the construction of the mirror-turning system and the rest of the ScanSpec hardware. The dimensions of the rotary tables from Newport were known in advance so by using CAD (Computer Aided Design) everything could be constructed before the rotary tables arrived. This was almost a prerequisite to be able to finish the project on time. Making this design

using only paper and pen instead of by modeling of solids would have been very much harder. Another advantage with AutoCAD is the the program has built-in functions to compute the moments of inertia which were needed in order to check the torque needed from the rotary tables for a certain angular acceleration.

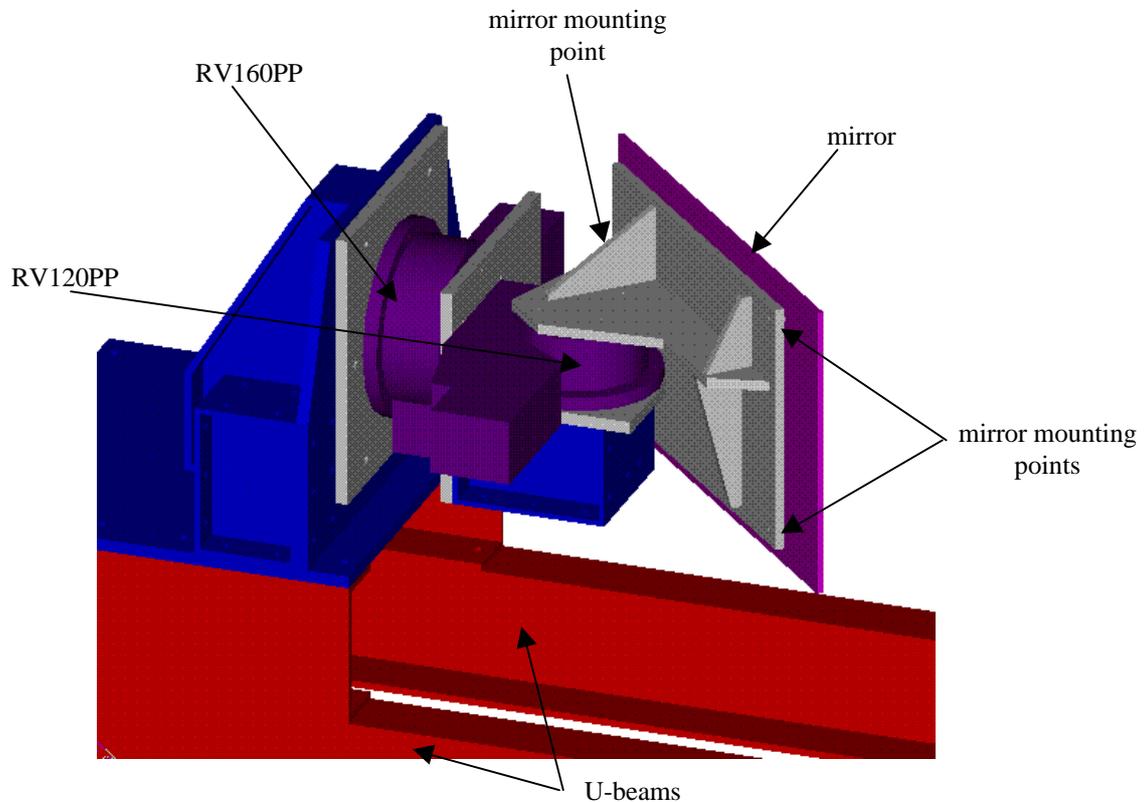


Figure 18 - AutoCAD model of the mirror-turning system

The mirror-turning system of the AutoCAD model is shown in Figure 18. The placement of the three mirror mounting points are also shown.

The complete AutoCAD drawings are available on the CD [CD: ScanSpec98:1].

6.4 The support construction

The support construction, that keeps the mirror-turning system and the spectrometer in place, is based on aluminum U-beams with the dimensions 7 x 140 x 60 mm. The whole construction can be seen in Figure 19.

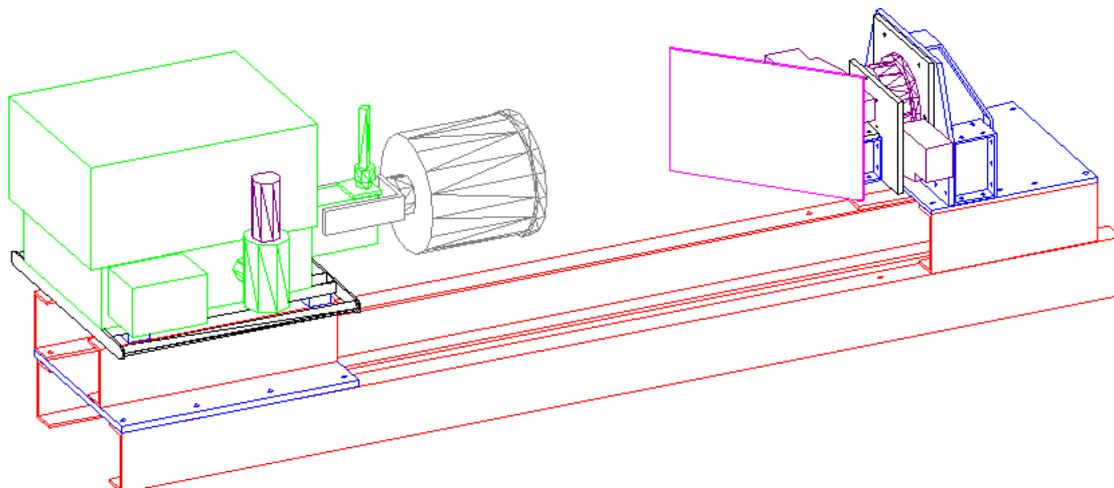


Figure 19 - AutoCAD drawing of the complete construction.

The distance between the beams is large enough to make it easy to modify the current construction to the main construction Alternative 1 as depicted in Figure 8, page 21.

6.5 Communication between ScanSpec parts

The communication between the different parts of the ScanSpec system will be described in this section. The information paths of the ScanSpec system are shown in Figure 20. The physical information paths (the wires) between the MM (the motion controller MM4005) and the rotary tables (RV120PP and RV160PP) and between the MM and the joystick were already supplied. The only paths implemented by me are marked with thick arrows in the figure. The wiring for the hardware switches is very simple. It is only a circuit that is closed as long as none of the hardware switches is activated. If one of the switches is activated the motor power for both motors is immediately turned off.

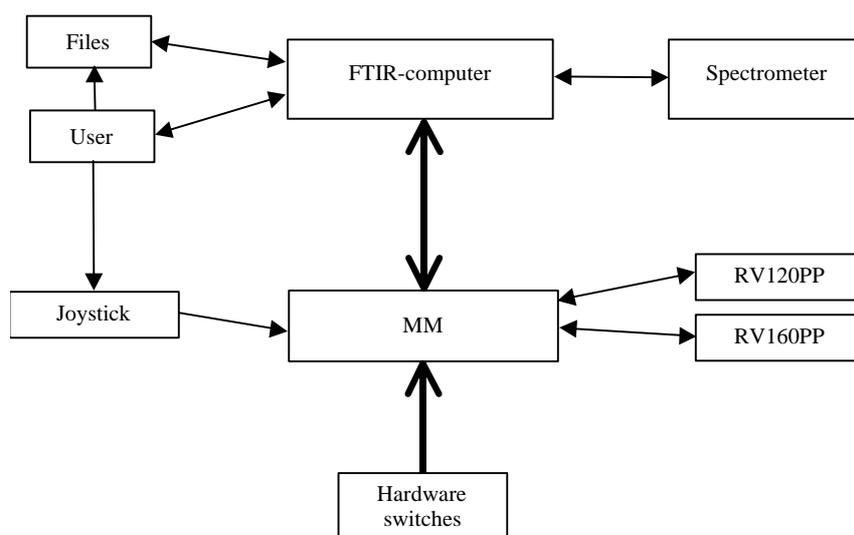


Figure 20 - The flow of information in the ScanSpec system. The two (electrical) information paths marked with thick arrows were made by me.

The other thick arrow that goes between the MM and the FTIR-computer demands some explanation. The wiring which is shown in Figure 21. For a definition of the pins on the MM and the PIO12 see [MM] and [PIO].

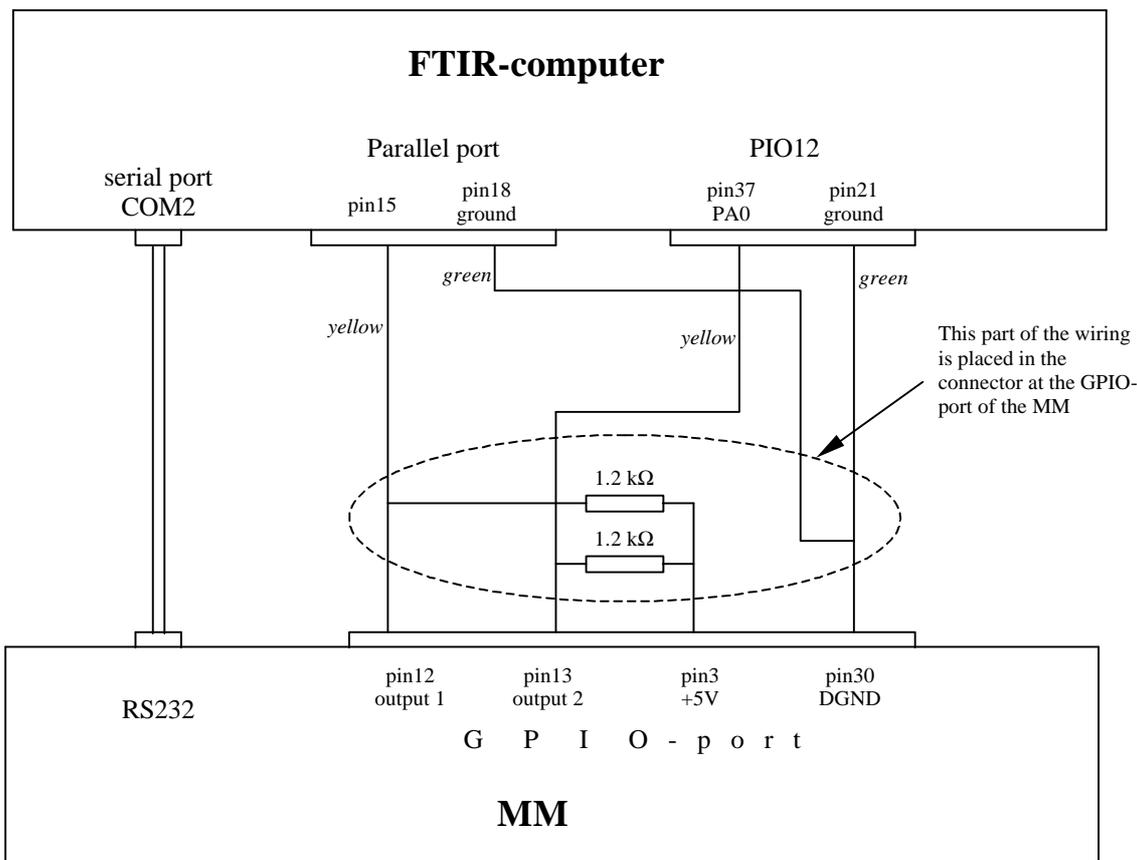


Figure 21 - The wiring between the FTIR-computer and the MM motion controller.

The connection between the serial port of the FTIR-computer and RS232 port of the MM is used to send commands or whole motion control programs to the MM from the FTIR-computer. The FTIR-computer receives information about recorded positions from the MM over the same wire.

The wire from output 1 of the MM to the pin5 of the parallel port of the FTIR-computer is used to send a trigger pulse from the MM to the FTIR-computer to synchronise the events between the FTIR-computer and the MM. The parallel port of the FTIR-computer is read by a C++ program written by me.

The wire from output 2 of the MM to pin37 of the PIO12 acquisition board of the FTIR-computer is used to send a trigger signal from the MM to the FTIR-computer when the acquisition of spectra should start. The PIO12 board is read by the Acquire software.

7 The ScanSpec software

7.1 General

The software for ScanSpec is based on the Matlab programming language because it is easy to program. It has good tools for graphical presentation of data and the staff at the department of IR systems at FOA know the language and will be able to make modifications in the code for the ScanSpec software. However, the C and C++ programming languages have been used for communicating with external hardware. Matlab does not currently have the ability to communicate with a serial port of a computer, for example. C has also been used once when the corresponding Matlab code executed much too slowly. A special motion control programming language from Newport has been used to control the two rotary tables. A few parts of the Matlab code rely on the Matlab Signal Processing and Image Processing toolboxes.

The details of the implementation will not be covered here. Please, refer to the comments in the code and to the Software manual (filename: "Software manual.txt") provided with the ScanSpec software for detailed information. The first release of the ScanSpec software (version 98:1) is available on a CD, complete with documentation [CD: ScanSpec98:1]. There is also a FOA internal report [manuals] which contains a print-out of the Software manual and the User's manual for ScanSpec.

The software consists of three modules, briefly described below.

Module 1 - Acquiring data

This module lets the user choose a scan program and start angles. There are eleven standard scan programs for different image sizes, spectral resolution, spatial oversampling (will be explained later) and number of spectra added per measurement. The module writes a motion control program which is sent to the MM and executed there. Together with Acquire, this module collects all the data necessary to compute the spectral image. The spectral data is saved in files with the Acquire program. The positions of the rotary tables are sampled by the MM with a constant time interval. These positions are sent from the MM to the FTIR-computer, when the scanning of the mirror is finished, and then they are saved in a file to be used by module 2.

Module 2 - Computing the sim

This module uses the collected data to create the spectral image. The spectral image is saved as the file current.sim (sim stands for spectral image). The file format of a spectral image file is defined in the Software manual [CD: ScanSpec98:1]. This module includes signal processing that will be described in some detail below in chapter 7.2.

Module 3 - Looking at the sim

The purpose of this module is to present the spectral image to the user in an efficient way. The User's manual (filename: "User's manual.txt" in [CD: ScanSpec98:1]) describes the functions of this module. The module is implemented using a Matlab GUI (Graphical User Interface) which is a convenient way to produce user interfaces. In the chapter "The first measurements" (chapter 8) there are examples of what this GUI can look like.

There are eleven standard scan programs defined in ASCII-text files. The most important parameters in those files and the ones needed to understand the signal processing are the following:

- Image size. The spatial size of the spectral image can be chosen to be 8x8, 16x16, 32x32 or 64x64 pixels.
- Number of interferograms that should be added for the acquisition of one spectrum. The more interferograms added per spectrum the higher is the signal to noise ratio.
- Spatial oversampling. If the spatial oversampling is N , N spectra are acquired per pixel field of view (per 0.10°) when the mirror is turned around the f_2 -axis.
- Spectral resolution. The spectral resolution can be chosen to 1, 2, 4, 8 and 16 cm^{-1} . The standard scan programs uses 4 and 16 cm^{-1} . The lower resolution the more spectra per second can be acquired.

7.2 Signal processing

The positions of the rotary tables, sampled by the MM with a certain frequency, are first saved in the memory of the MM. After the acquisition is finished the data is transferred to the FTIR-computer via a serial connection. The maximum number of samples is limited to 4000 by the MM. Also, it takes a long time to read the positions recorded by the MM when the scanning of the mirror is finished. One reason why it takes so long to send the data from the MM is that the positions can, for some strange reason, only be sent to the FTIR-computer as ASCII-text which increases the amount of data many times compared to sending it as binary data. The number of samples of the positions of the rotary tables should not be too high. Approximately 6 positions of both the rotary tables are sampled per scan line.

The spatial oversampling parameter mentioned in section 7.1 demands further explanation. Generally, the errors of the measured spectra from a Fourier-transform spectrometer can be significantly reduced by averaging several interferograms for each spectrum to reduce the random noise. This is also the case for the Bomem MR254 spectrometer. This can be done by choosing to average several interferograms in the Acquire program. But if only one spectrum is acquired per pixel field of view, the image will be smeared out because the mirror is moving continuously during the acquisition of the spectrum causing motion blur. To handle this another way to reduce the noise has been implemented. If the spatial oversampling parameter is set to N , N spectra are acquired per pixel in the spectral image. How the noise will be reduced by this method will be described.

Module 1 creates the following data.

- The sampled positions from the MM.
- The file(s) current.raa and/or current.rab. Current.raa contains the acquired spectra from detector A and current.rab the spectra from detector B. It also contains a time for each spectrum.
- Some parameters that describe the size of the image, the spectral resolution, the start angles et cetera.

The signal processing in module 2 can be divided into two separate parts. Part I computes the positions of the rotary tables at each time a spectrum was recorded by the spectrometer. Part II computes the spectrum for each pixel in the spectral image.

Part I - Computation of the positions of the measured spectra

The lower part of the scan pattern of a 8x8 spectral image is shown in Figure 22. The points for which the MM might have recorded positions are marked.

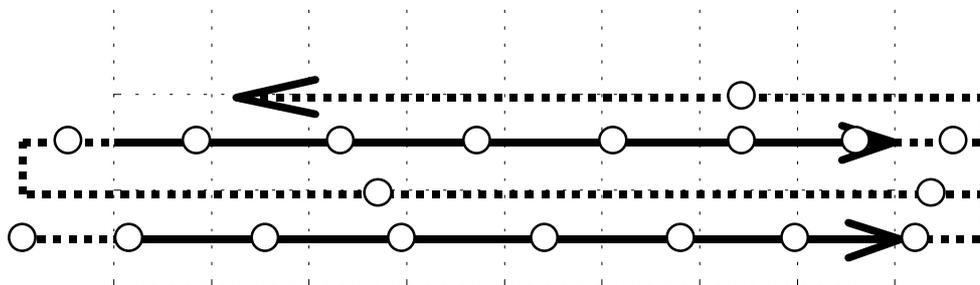


Figure 22 - The lower part of the scan pattern for a 8x8 spectral image. The circles mark the locations of the positions sampled by the MM. Only two scan lines out of eight are shown.

The speed is constant when the thick arrows are traced by the line of sight, but not otherwise. Let us consider time as a function of position. We can then extrapolate linearly (using the two samples closest to the edge) to find the times at the beginning and the end of each of the eight scan lines (each of the eight thick arrows). When we have found these times we can throw away the information from the spectra not sampled on a scan line.

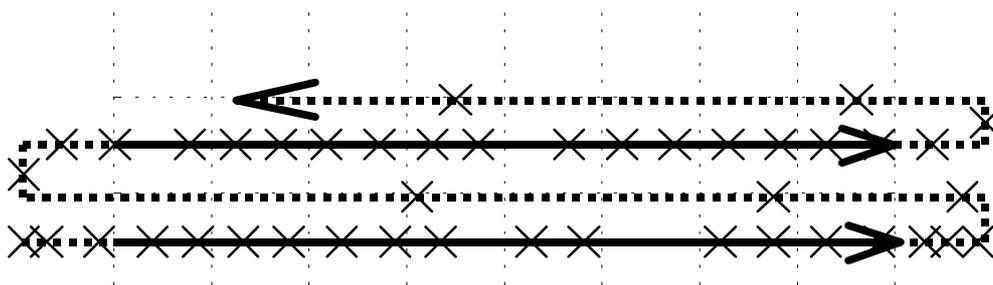


Figure 23 - The first part of the scan pattern for a 8x8 spectral image. The crosses mark the positions of the tables each time a spectrum is acquired. Only two scan lines out of eight are shown.

The next step is to estimate the positions of the tables when each of the spectra on the scan line was acquired by the spectrometer. If the position is seen as a function of time, this can be done by linear interpolation and extrapolation using the positions recorded by the MM. Linear interpolation and extrapolation is well justified in this case, since the speed of the motion is constant while the line of sight is on a scan line. An example of what the positions of the spectra can look like is seen in Figure 23. The positions of the spectra which were not acquired on a scan line are also marked even though they are never estimated in the signal processing. A spatial oversampling of 2 has been used in the example in Figure 23. Normally there are two samples per pixel, but not always due to the irregularity of the times between the spectra as exemplified in Figure 7, page 20.

Part II - Computation of the spectra in the spectral image

From part I of the signal processing we have the positions of all the spectra acquired on a scan line. These positions will generally not coincide with the positions of the center of the pixels in the spectral image. We want to estimate the spectra in those points. Let us consider the spectral radiance of one specific scan line and frequency. That spectral radiance will then be a function of only f_2 as depicted with a stem plot in Figure 24 A. Note that at two places one spectral radiance value is missing and at another place two radiance values are missing. This is because of the irregularity of the times between the spectra. In Figure 24 the spatial oversampling is 4 and the size of the spectral image is 8x8 pixels. Part A of the figure shows the spectral radiances recorded. The radiance, at the positions on the f_2 -axis that are marked with blue lines, will be estimated by linear interpolation and extrapolation. Linear interpolation and extrapolation was chosen since this signal processing has to be quite fast. Note that the procedure described here for only one scan line and frequency must be repeated for all frequencies and scan lines.

Now, we have radiance values at all the positions marked with blue lines in Figure 24, but we only need values at the positions marked with red lines which are the centers of the spectral image pixels. We know that the telescope works as a low-pass filter on the spatial frequencies of the studied scene. Very roughly the telescope destroys all the spatial frequencies above 5 cycles per degree (see Appendix 1), therefore we know that all the frequencies in the measured radiance signal above 5 cycles per degree is due to noise. Let us remove those frequencies with a filter to reduce the noise.

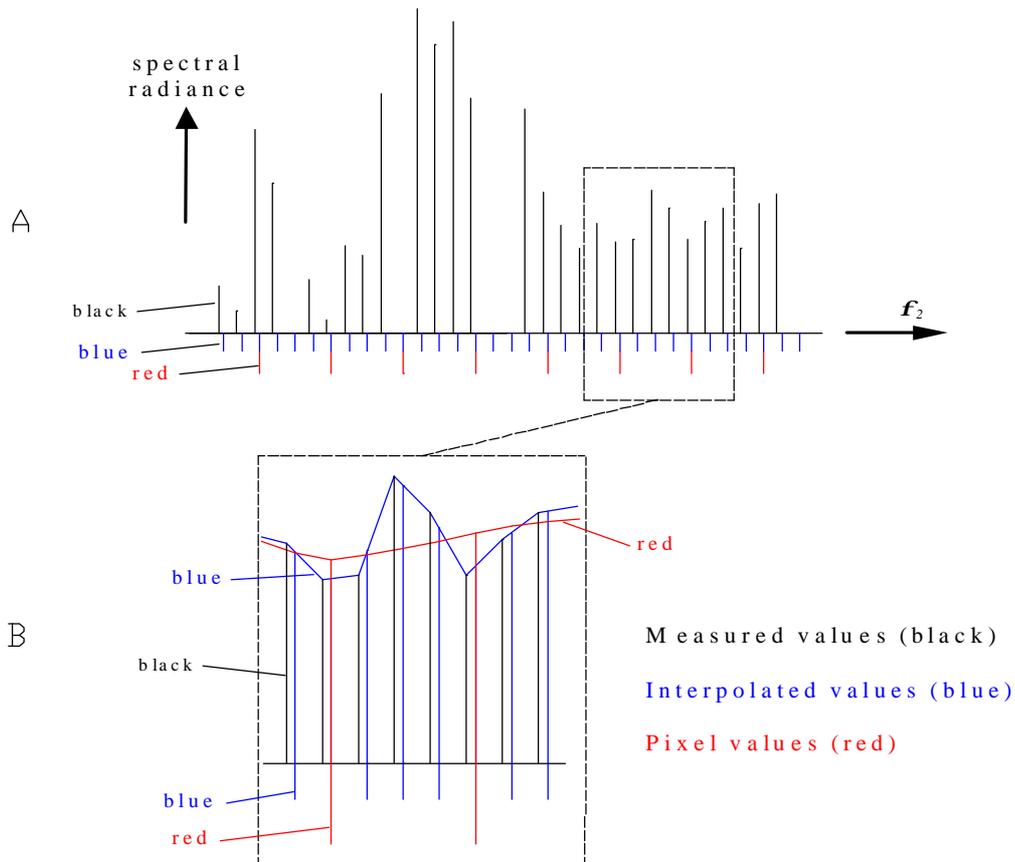


Figure 24 - The measured and interpolated spectral radiance values.

Figure 24 part B shows an enlarged section of part A. The black values are the measured values. The blue values are the interpolated values and the red values are the final pixel values. The blue function is filtered with a low-pass filter with a cut-off frequency of 5 cycles per degree. The filter

was implemented with the Matlab Signal Toolbox function `fir1`. The filter is a finite impulse response filter made with the window method. The window is a Hamming window. The order of the filter is two times the spatial oversampling.

This way of reducing the noise is better than just averaging four radiance values, in the sense that the motion blur is reduced. It can be discussed, though, if the motion blur is so serious that this rather complicated signal processing is necessary. Initial testing shows that the motion blur if no spatial oversampling is used, is not as serious as anticipated.

7.3 Testing, reliability, and the timing problem

Testing

Since there are so many different combinations of input parameters for the ScanSpec software system, there is no way of testing for bugs for all possible cases of input to the programs. Instead, the eleven standard scan programs have been chosen and tested. All the standard programs work, but the timing problems discussed below are worse for certain scan programs.

Reliability

There are four things that affect the reliability of the system:

1. Bugs in the software written by me. The software has been tested with the standard programs with no bugs found.
2. The reliability of the software Acquire. Acquire has a tendency to crash when large amounts of data are collected, especially when over about 32 Mbyte of data is stored at the Bomem acquisition board.
3. Problems with data transfer to the MM. On some occasions, the data transfer from the FTIR-computer over the serial cable to the MM has been malfunctioning. When the standard scan programs were tested with the final software version 98:1, there was no problem with the data transfer.
4. The timing problem. This problem is described in the next section.

The timing problem

The MM is synchronized with the FTIR-computer by a trigger signal sent from the MM to the parallel port of the FTIR-computer. The parallel port is checked with a C++ program written by me. There are of course certain delays when sending the trigger and reading it. However, initial testing shows that the timing error can be as large as ± 0.05 s varying from time to time and this is probably not only because of these delays. Since many programs must be run on the FTIR-computer at the same time (at least Acquire, Matlab, the C++ program to check the parallel port, and the operating system Windows 95) I believe the probable cause of the timing problem is that the Pentium processor of the FTIR-computer is not necessarily running the C++ program at the moment when the trigger signal is sent to the parallel port. It might take a few hundredths of a second before the processor starts executing the C++ program again. Maybe the problem could be solved by using the interrupts of the Pentium processor.

The scan pattern was chosen so that the system can tolerate some timing error. The slow standard scan programs (Program 1, 2, 7, 8, 9, 10, and 11, see Appendix 3) are not affected by this timing problem. If the timing error is too large for the fast-scanning programs (Program 3, 4, 5, and 6) the data for the spectral image can be recalculated with a time correction given by the user.

8 The first measurements

All the data from the measurements described below are available on the CD [CD: ScanSpec98:1] in the directory ScanSpec\data.

8.1 Measurements with the standard scan programs

The very first measurements made with ScanSpec were performed on a collimator target. The collimator at the Department of IR systems at FOA can be used to simulate a target at an infinite distance and with a certain temperature and angular extent. All the eleven scan programs were tested on the same target. One example of the result for a four-bar target is shown in Figure 25, page 44. It is made with scan program 6 that acquires a 32x32 spectral image with a spectral resolution of 16 cm^{-1} in about 30 seconds. No spatial oversampling or averaging of interferograms was used. The temperature difference between the target (the four bars) and the background was 10°C.

The left image in Figure 25 shows the spectral radiance of the test target averaged between 687 and 764 cm^{-1} and the right image is averaged between 1875 and 1975 cm^{-1} . The radiance is shown using a linear gray-scale. The unit of the spectral radiance is $\text{W}/(\text{cm}^2 \text{ sr cm}^{-1})$ in the figure, but SI-units ($\text{W}/(\text{m}^2 \text{ sr Hz})$) can also be displayed.

To make it possible to study the repeatability four measurements were done on the same target with the same scan program, see the directory "ScanSpec\data\Repeatability test sims" in [CD: ScanSpec98:1]. The repeatability of the ScanSpec has not been studied much, but the repeatability for the test case is much higher than anticipated.

8.2 MRTD measurements

The minimum resolvable temperature difference (MRTD¹) has been estimated. If many interferograms are added per measured spectrum, the MRTD is around 0.2 °C. Figure 26 shows a test measurement with a target/background temperature difference of 0.2 °C where I consider the target to be resolved. 256 interferograms were added per spectrum and two times spatial oversampling was used when scanning the image. Note that the radiance has been averaged in the frequency intervals best in resolving the target.

If the standard scan programs are used, the MRTD is closer to 1 °C than 0.2 °C. The MRTD depends on how many interferograms that are averaged, the spatial oversampling, and what frequency band is considered. A thorough investigation of how the MRTD depends on these factors has not been made.

¹ The minimum resolvable temperature difference is the minimum temperature difference between a test target and a background (both black bodies) for which the target is perceived [Holst, page 7].

8.3 Measurements of a Volvo 440

The first real object measured with ScanSpec was a Volvo 440. The distance between the car and ScanSpec was 70 m. One spectral image of the car is shown in Figure 27. As an example of how different features of the car are predominant in different frequency bands, a band where almost only the headlights can be seen was chosen.

The car including the exhaust is seen in Figure 28. The exhaust emits a lot of IR radiation around the frequency 4100 cm^{-1} . The original 32×32 image has been interpolated using splines to create a 125×125 image.

If the calibration of the spectrometer is done carefully someone with knowledge about spectrometry could get much of information from images like this. For example the gas contents of the exhaust could be studied and probably some conclusions about the features of the headlights could be drawn from the data.

8.4 Calibration

The calibration of the ScanSpec system is a bit tricky since the entrance optic is large. There is a large area blackbody source at the Department of IR systems at FOA, that can be heated, but not cooled. To study cold winter backgrounds a blackbody that can be cooled to at least $-20\text{ }^{\circ}\text{C}$ would be desirable when calibrating the system. A black-body that keeps the same temperature as the surrounding environment could also be adequate when measuring cold targets.

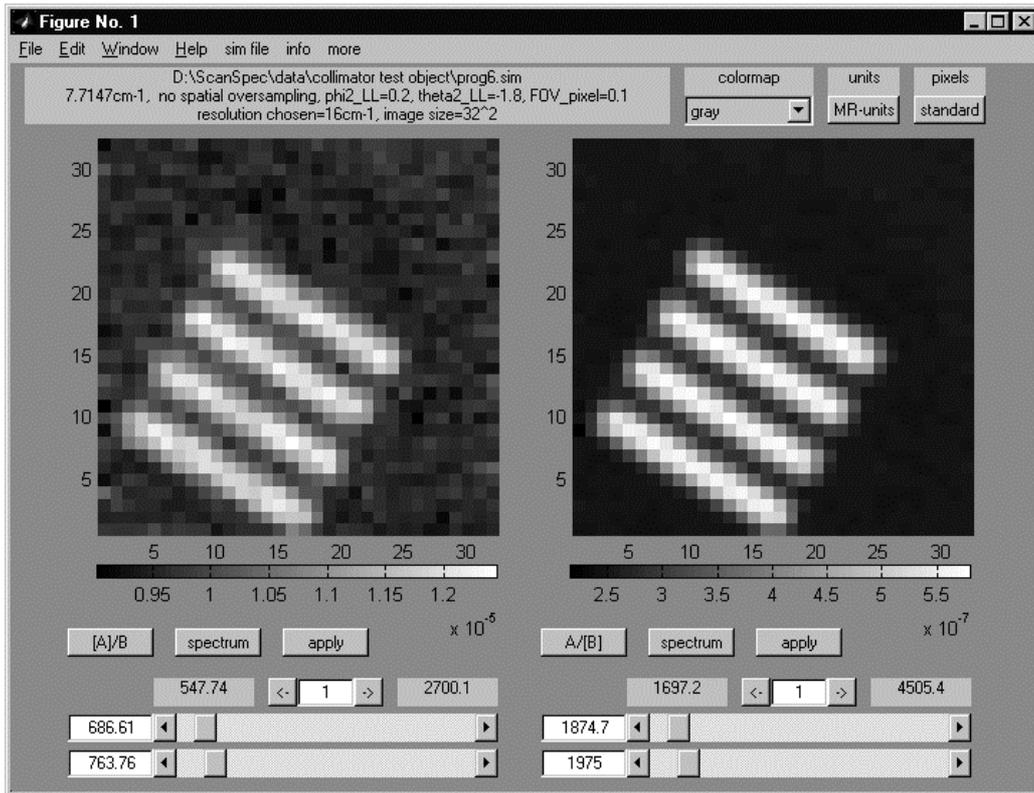


Figure 25 - The collimator test object acquired with standard scan program 6.

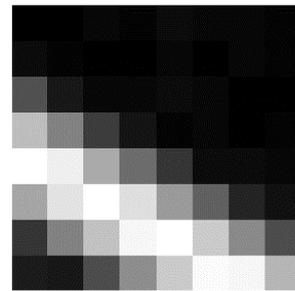
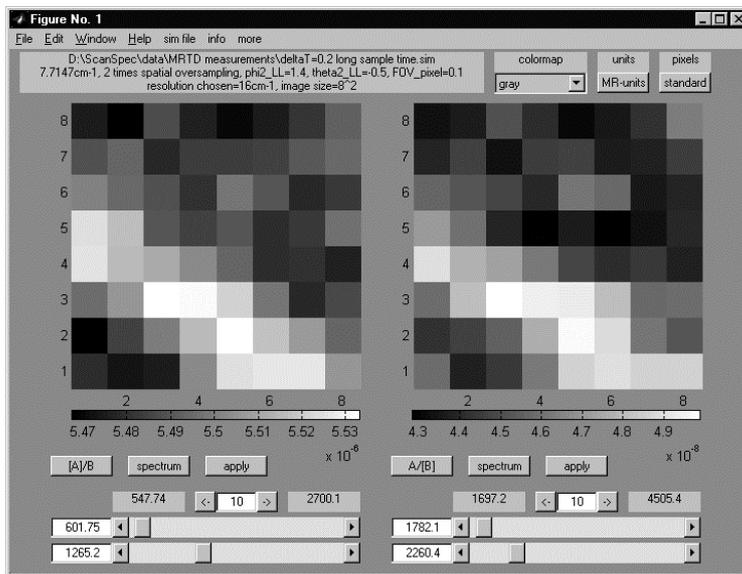


Figure 26 - Minimum resolvable temperature difference (MRTD) measurement. The temperature difference between the target and the background was 0.2 °C. 256 interferograms were averaged per measured spectrum. Two times spatial oversampling was used. The image to the right shows a similar measurement when the temperature difference was 20 °C.

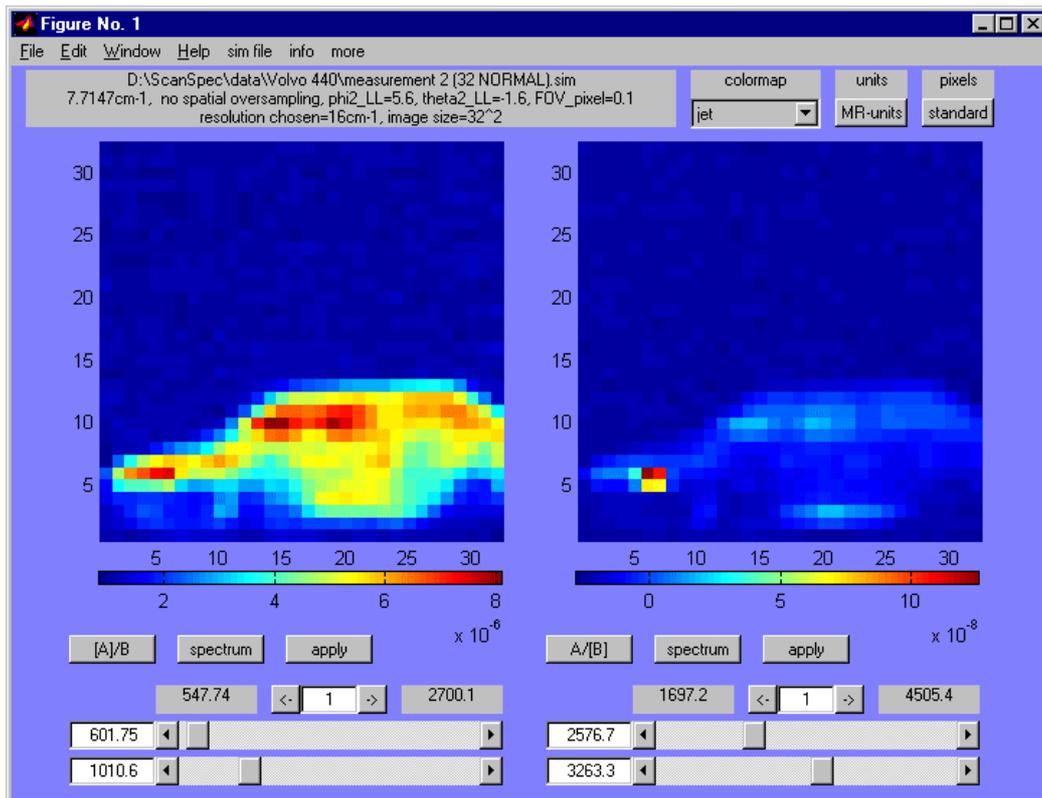


Figure 27 - The Volvo 440 seen in two different frequency bands. The car was running and the fan was on. In the right window the headlights are the most dominant feature.

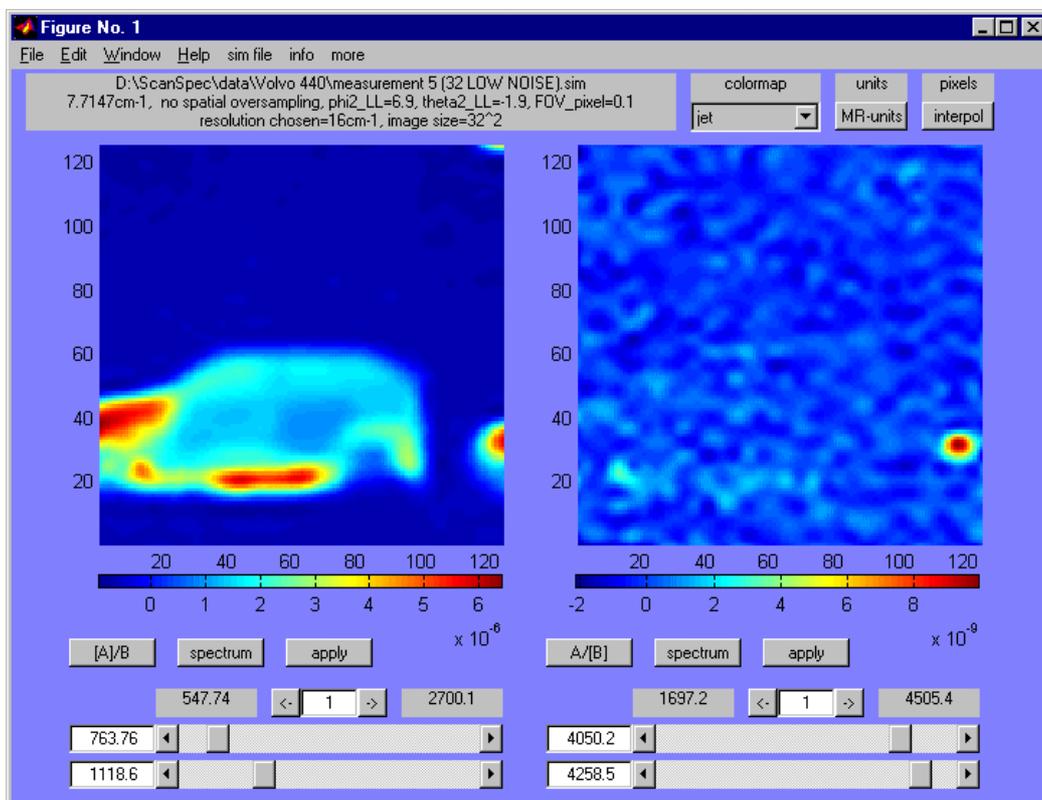


Figure 28 -This figure shows the Volvo after the window was opened. In the right image only the exhaust emissions can be seen.

9 Results and possible improvements

9.1 Distortion

The ScanSpec imaging system is not free from image distortion, but when the angle f_2 is kept close to zero the distortion will be low. It is recommended to use f_2 -angles less than 25° . If that recommendation is followed there should be no problems with distortion unless very low distortion is needed. The distortion is known exactly and depends only on the start q_2 - and f_2 -angles, therefore the distortion could be corrected for.

Most of the distortion could be avoided with some changes in the software that governs the scan pattern. This issue is briefly discussed in the Software manual section "Improvements and changes" [CD: ScanSpec 98:1].

9.2 Are the goals of the project met?

The main goal of the ScanSpec project was to make an imaging spectrometer from an existing non-imaging spectrometer and that the existing spectrometer would limit the performance of the total system using the resources available.

The Bomem spectrometer is limiting the total performance in the most important parameters such as: spectral resolution, spatial resolution, image size, time to post-process the data and time to acquire the spectral image. The ScanSpec software (and maybe the MM) limits how low the image distortion could be. The ScanSpec hardware limits the range of the sky that can be measured, but it is built to be easily changed to cover a larger part of the sky. The reliability of the system is limited by both the spectrometer (Acquire often crashes for large amounts of data) and the other parts of the system (the timing problem and problems with data transfer to the MM, see chapter 7.3, page 40).

The minimum performance goal of being able to acquire a 10x10 spectral image within a minute at the lowest resolution of the Bomem spectrometer is met and far surpassed. ScanSpec can acquire an image with 10 times more pixels (32x32) in around 30 s.

Any software system can be improved. The software for ScanSpec has been written to be easy to use and change. Possibility of re-using the code has not been considered since the application is very specialized with only very few parts that could be used in other software systems. The error checking is not at all complete, but is still a significant part of the code. The software limits the total performance of the system to a number of fixed image sizes and a pixel field of view of 0.10° . It can only look "one way", not both to the right and the left of the spectrometer. The software could have been made more general, but not within the time goal of the ScanSpec project. That would also have meant more code and code harder to maintain. More code is not desirable since the code already consists of 4300 lines (127 000 characters).

The hardware and the software have been constructed with consideration to possible future changes.

The costs of the project except for my salary are

Two rotary tables with motion controller	160 000 SEK
The mirror	2 000 SEK
The support beams	2 000 SEK
Workshop cost	30 000 SEK
Other expenses	<3 000 SEK

Which sums up to around 200 000 SEK which was the approximate budget of this project, so the economic goal was met.

The goal of finishing the project within 20 weeks of work for one person and within a total time of 24 weeks was not accomplished. It took 23 weeks of work within 28 weeks.

The reader can judge if the project has been well documented in this report and in [CD: ScanSpec98:1].

9.3 Possible improvements, changes and new applications

ScanSpec is ready to be used in field measurements, but important improvements could be made. Some of them are mentioned below. The possible improvements of the software have already been discussed.

The system could be more prepared for transportation and field use to make it more practical to make measurements.

The system can be modified for totally new applications. For example, the noise levels for different frequencies and signal levels could be measured automatically with ScanSpec. This can be done by moving the line of sight from a hot to a cold target and for each position several spectra can be acquired. By computing the average and the variance of the measured radiance values the signal to noise ratio for different frequencies and signal levels can be estimated.

The modulation transfer function (MTF) could also be measured automatically. This can be done by measuring the spectral image of a point source. But the spatial sampling frequency should then be higher than the two samples per 0.20° that is currently used with ScanSpec. The MTF of the system for a certain frequency is the Fourier-transform of the radiance image for that frequency.

Another application would be background subtraction. For example, when flares from airplanes are measured the flare could be followed with the mirror of ScanSpec using the joystick. The positions of the line of sight would be recorded and when the flare has burned out the mirror could trace the line of sight backwards to measure the radiation of the background without the flare. The background radiation could then be subtracted from the measurements.

10 Conclusions

An imaging spectrometer, ScanSpec, has been developed from a non-imaging FTIR spectrometer from Bomem Inc. The ScanSpec project has been successful in that ScanSpec widely increases the capabilities of the FTIR spectrometer.

Other imaging spectrometers for the IR-region have been developed, but there is not much commercially available on the market that covers the MWIR and the LWIR regions. The performance of ScanSpec is good compared to other imaging spectrometers in the MWIR and LWIR regions when it comes to spectral resolution and sensitivity, but it is slow and the image size is limited. The advent of large 2D-array of IR-detectors has led and will lead to the development of various new types of imaging spectrometer designs.

For the most important parameters such as acquisition time, spectral resolution, spatial resolution, data post-processing time, and maximum image size, the spectrometer limits the total performance of ScanSpec.

Improvements of ScanSpec can be made, but are probably best to do later after some measurements have been done, to see what features that are most important to improve. The system has been made to be easy to change. The mirror and the mirror-turning system can be used for other important applications, not only to acquire spectral images.

ScanSpec is suitable to measure the infrared radiation from backgrounds or anything that does not move. Together with IR-cameras with higher spatial resolution ScanSpec can be used for measurements to build a data base of IR-signatures of backgrounds and potential military targets.

11 References

A note on the referencing system in this report

A reference within a sentence applies for that sentence only and a reference directly after the last sentence of a paragraph applies for that whole paragraph. If the reference is placed on a separate line it is for the whole text between the last headline and that reference. The name within brackets [] is a keyword used to find the reference in this section. If the reference is not a reference to printed material there is also a word before the keyword describing the type of the source.

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CD

ScanSpec98:1, The software of ScanSpec version 98:1 (First version) is available on a compact disc from the FOA Department of IR systems, Linköping, Sweden. The CD includes all the programs written for ScanSpec, the data from the first measurements discussed in this report, and the complete documentation of the system, including User’s manual, Software manual, the FOA report [manuals] and this report.

Email

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Spectrogon 980618, phone call from Kurt-Erik Lundquist, Spectrogon (Täby, Sweden), to me 18 June 1998.

Edmund Scientific 980624, phone call to Edmund Scientific (+1-609-573 6250), 24 June 1998.

Presentation

Villemaire, André Villemaire (Bomem Inc.), Jean Giroux (Bomem Inc.) and Ron J. Rapp (Air Force Wright Laboratories), "An Imaging Fourier-transform Spectrometer", *Third workshop on Infrared Emission Measurements by FTIR*, Quebec, Canada, February 1996.

Appendix 1 -

Measurements of field of view, angular sensitivity and focusing range

Introduction

This text describes measurements performed in September 1998 with the Bomem MR254 spectrometer together with the narrow angle telescope (SMY02). The sensitivity of the InSb and the MCT detectors has been studied for different angles off the optical axis of the telescope. The focusing range of the telescope and the field of view of the telescope/detectors have also been measured. Only the data from the measurements are presented, without conclusions.

How the measurements were done

The narrow angle telescope (Bomem SMY02) were mounted on the spectrometer. A blackbody source was set at 1200°C at a distance ranging from about 40 to 90 m from the telescope. A grid was drawn on a piece of cardboard with a hole. The grid was put up in front of the blackbody source and the hole was aligned with the aperture. The spectrometer was standing on a tripod that could be panned and tilted. The CCD camera of the spectrometer was connected to a monitor. A mark was made on the screen of the monitor. The spectrometer could then be turned up, down, left, and right. The grid in front of the blackbody source together with the screen could be used to measure the angles the spectrometer was panned and tilted. The mark on the screen was made in the center of the visual field of view through the CCD camera when Aperture AB (see next paragraph) was set at 1.1 mm.

The spectrometer has three apertures: one directly after the telescope (will be denoted Aperture AB), and one for each of the two detectors. The aperture for the MCT detector will be denoted Aperture A and the one for the InSb detector will be called Aperture B. There are several diameters of each aperture: 6.4, 4.5, 3.2, 2.2, 1.6, 1.1, and 0.8 mm.

The temperature in the room was about 20 °C and the temperature around the edges of the aperture of the blackbody source was not very much higher. The temperature of the blackbody did not change more than 3 K during the same measurement. According to Wien's radiation law, the total radiation emitted by a blackbody is proportional to T^4 . This means that a temperature change of 3 K will change the measured values with approximately $3 \cdot 4 / (1200+273)$ which is less than 1 per cent.

The spectrometer was set at alignment mode with a spectral resolution of 4 cm^{-1} . This way the total radiation could be measured. The gain for the detectors was never changed during a measurement.

Figure 1 shows the equipment that was used. The angle of interest Df can be approximated with $\arctan(h/(d-a))$ to a very high accuracy since $h \ll d$ ($h < 0.20 \text{ m}$ and $d > 35 \text{ m}$).

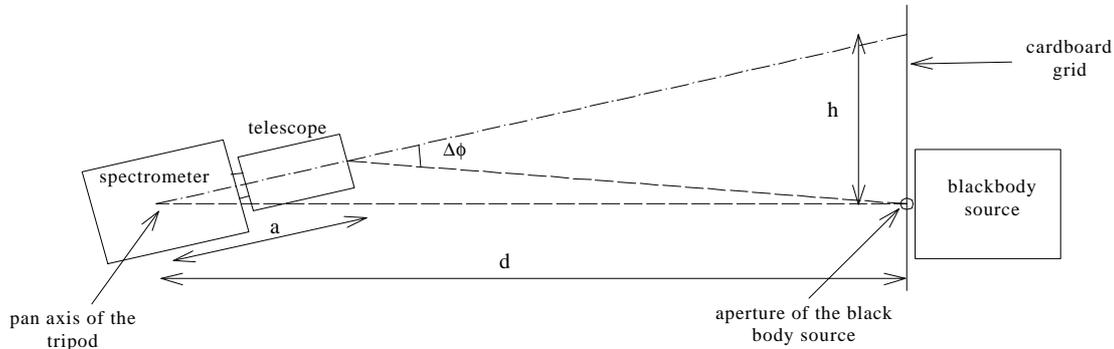


Figure 1 - The equipment for the measurements seen from above.

The distance a is the distance from the pan axis of the tripod to the primary optics of the telescope (not to the front end of the telescope). a was measured to be 0.55 m .

Measurement 1 - The focusing range

The CCD camera was used to measure the shortest distance an object can be focused at by the telescope. The result was $37 \pm 1 \text{ m}$ from the front end of the telescope. According to Bomem [1994] this distance is supposed to be 30 m .

Measurement 2 - Angular sensitivity

These were the parameters for the measurements:

- Aperture A: fully open
- Aperture B: fully open
- Aperture AB: 6.4 mm
- aperture of the blackbody: 12.5 mm
- blackbody temperature: $1212 \text{ }^\circ\text{C}$
- distance $d - a$ (according to Figure 1): 59.1 m

The radiation was measured for different angles of Df and Dq . The angle Df is shown in Figure 1. This angle is positive if the blackbody aperture is on the right hand side of the optical axis of the telescope. Dq is the elevation angle. If the blackbody aperture is above the optical axis of the telescope, Dq is positive.

The measurements were performed for both detectors at every crossing of a $20 \times 20 \text{ mm}$ grid on the cardboard in front of the blackbody. This corresponds to measurements at every 0.019° for the angles Df and Dq . 13×13 values were acquired for both detectors. The background level was subtracted from the result. The data were then normalized so the maximum value is 1.00 . (The

absolut values are of no interest for these measurements.) The results for the MCT and the InSb detector can be seen as contour plots in Figure 2 and 3.

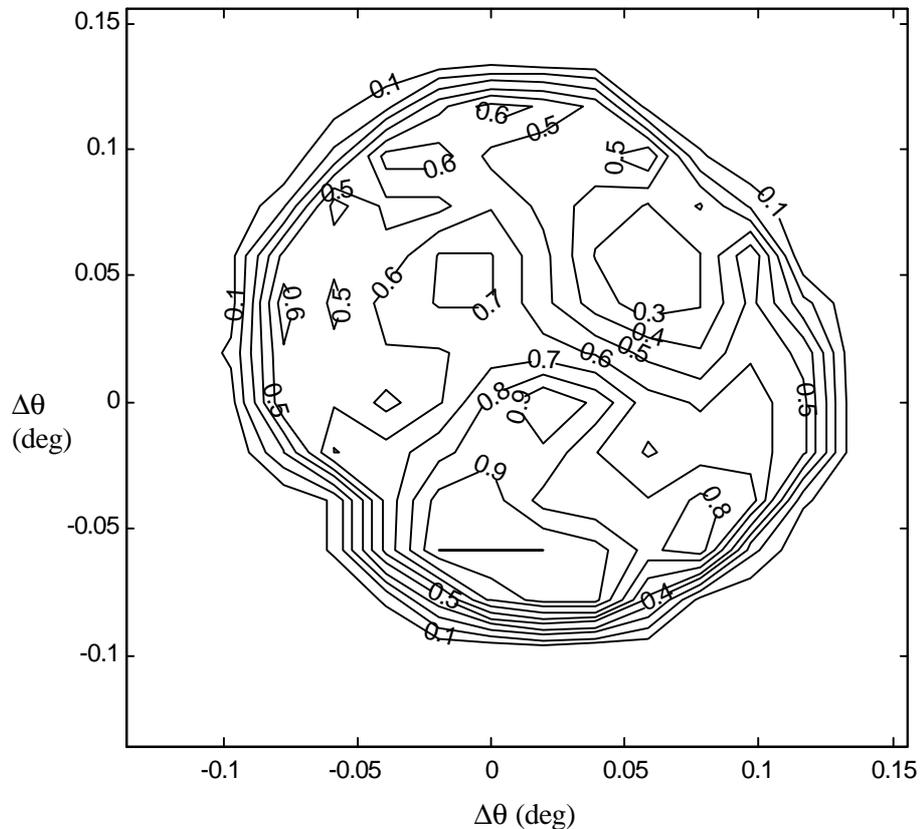


Figure 2 - The normalized sensitivity of the spectrometer within the field of view. The narrow angle telescope and the MCT detector were used.

Figure 2 shows the sensitivity of the MCT detector which is used to detect longer wavelengths. The region for which the spectrometer is sensitive is nearly circular, but the sensitivity within that circle varies from 1.0 to 0.3 (arbitrary units).

The sensitivity within the field of view of the InSb detector, that is shown in figure 3, is much more uniform. The sensitivity within the central part of the circular field of view varies between 1.0 and 0.75 (arbitrary units).

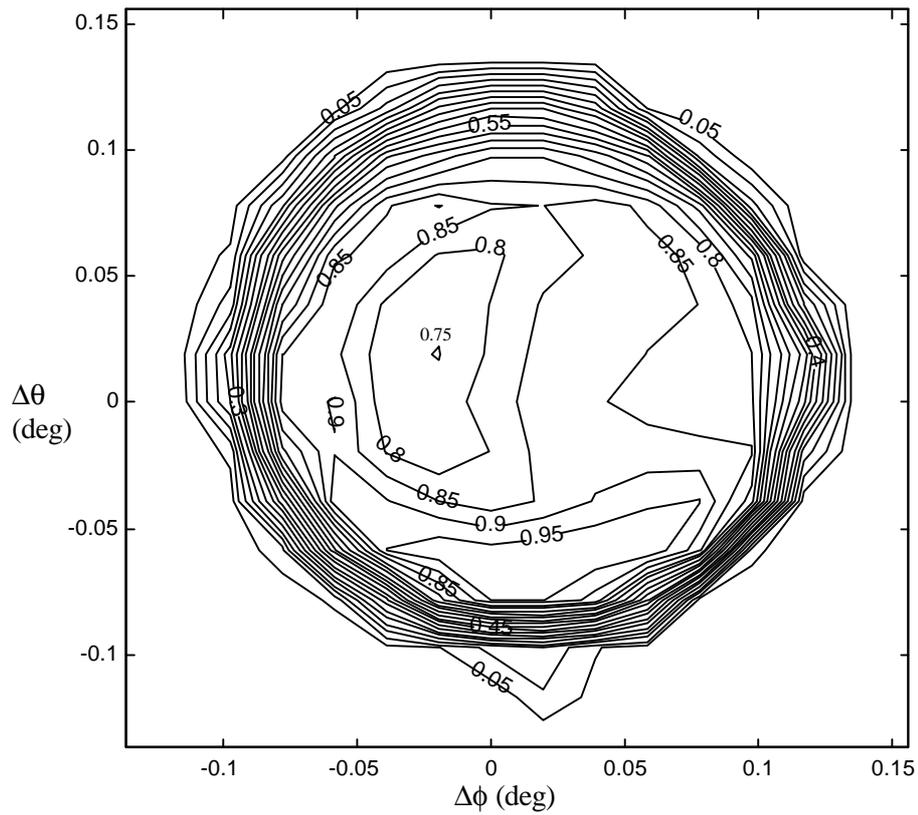


Figure 3 - The normalized sensitivity of the spectrometer within the field of view. The narrow angle telescope (Bomem SMY02) and the InSb detector were used.

Figure 4 and 6 show the magnitude of the Fourier-transforms of the angular sensitivity functions in Figure 2 and 3. Figure 5 is the scale for those figures.

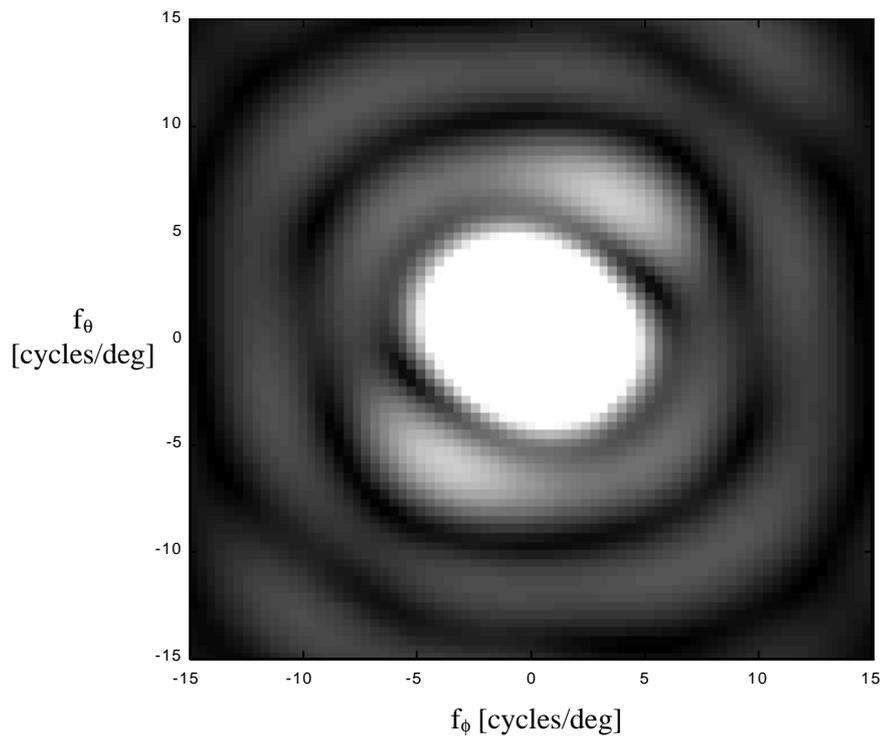


Figure 4 - The magnitude of the two-dimensional Fourier transform of the angular sensitivity (the MTF) for the MCT detector. The values are normalized so that the maximum value equals 1.

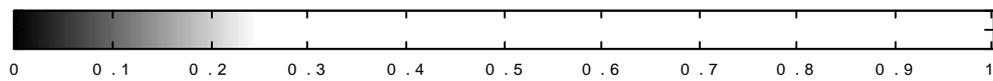


Figure 5 - Scale for figure 4 and 6.

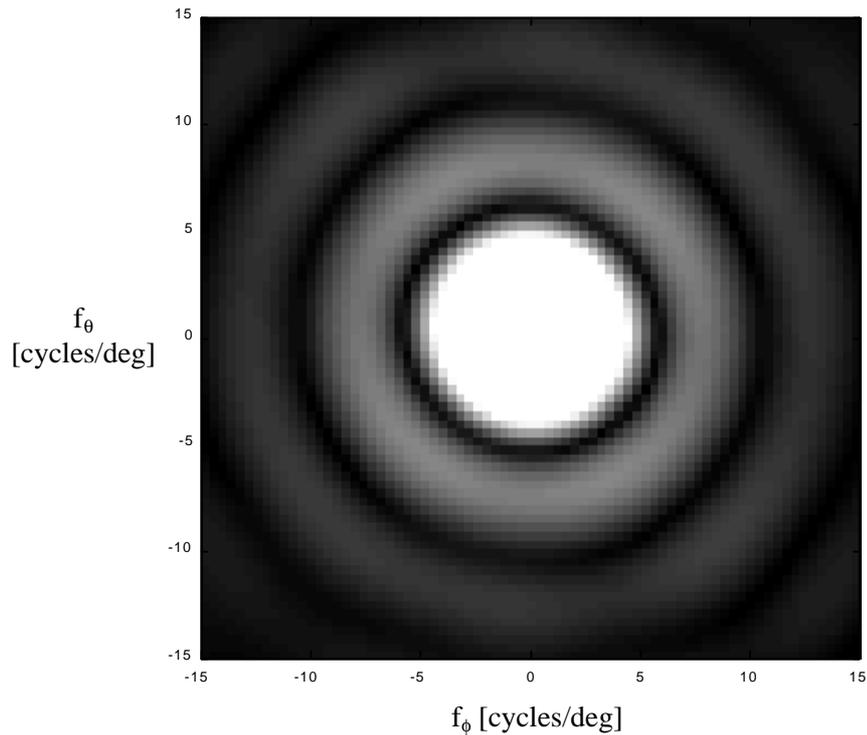


Figure 6 - The magnitude of the two-dimensional Fourier transform of the angular sensitivity (the MTF) for the InSb detector. The values are normalized so that the maximum value equals 1.

Errors

The statistical errors in the measurements were estimated by measuring the sensitivity for the same part of the field of view three times. The part measured was Df ranging from 0 to 0.16° for $Dq = 0$. To incorporate most of the errors the telescope was defocused and focused again and the angle Dq was changed and set back to 0° between each of the three measurements. Also, some time passed between the measurements in order to incorporate the temperature fluctuations of the blackbody source. The background radiation was subtracted from the result and the values were then normalized to a range between 0 and 1 (arbitrary units) as with the previous measurements. Figure 7 and 8 show the results of these measurements.

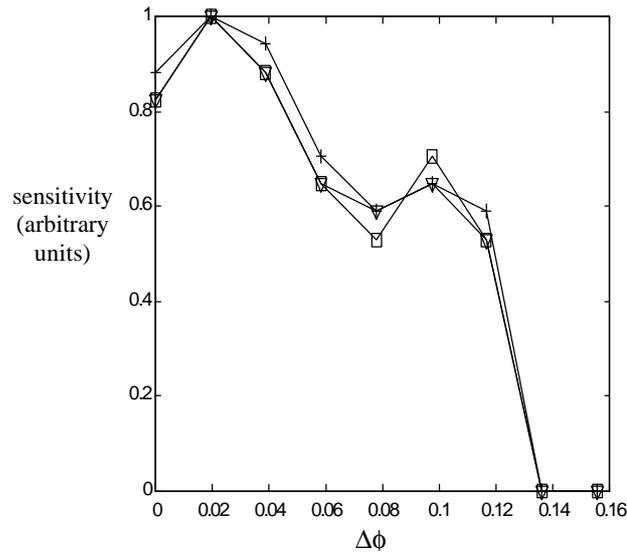


Figure 7 - Three measurements of the sensitivity of a part of the field of view for the MCT detector.

The difference between the three measurements for the MCT detector is at up to 6% of the maximum measured value.

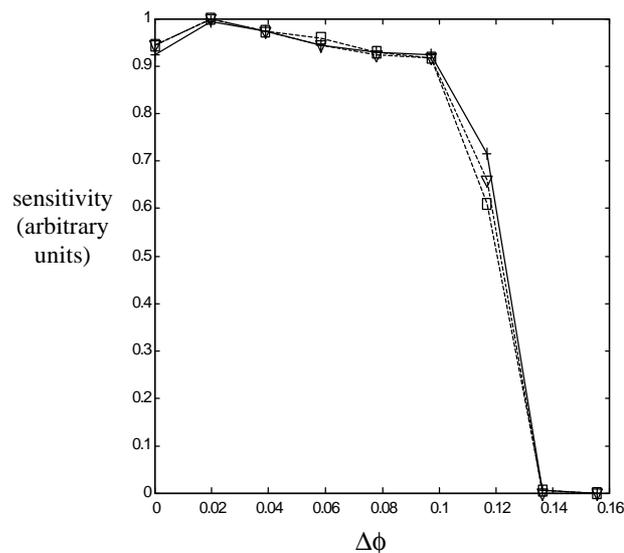


Figure 8 - Three measurements of the sensitivity of a part of the field of view for the InSb detector.

The difference between the measurements of the sensitivity of the InSb detector is up to 1.4% of the maximum value except at one point, for $Df = 0.117^\circ$ the difference is 10%. This is due to the uncertainty in the determination of Df which affects the results when the sensitivity changes with Df rapidly. The error of Df is estimated to $\pm 0.005^\circ$.

Measurement 3 - The field of view for different aperture settings

The definition of field of view and how it was estimated

Let us assume that the contour of the 0.5 sensitivity as in figure 2 and 3 is almost circular. This assumption is good for the InSb detector, but a poor one for the MCT detector.

Four angles were measured each time the field of view was to be determined. These angles a_1 , a_2 , a_3 , a_4 are depicted in Figure 9. Since the center of the field of view do not necessarily have to be exactly the same as the center of the visual field of view of the CCD camera, the field of view was estimated the following way. The position of the center of the field of view was estimated by $((a_1+a_2)/2, (a_3+a_4)/2)$ in the coordinate system in Figure 9. Then half of the field of view is estimated as the average of the four distances from the center of the field of view to the end of the arrows.

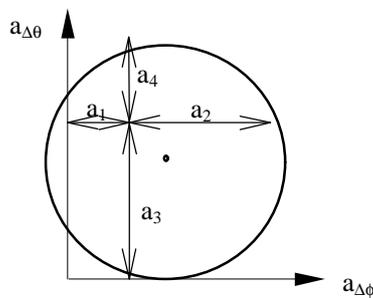


Figure 9 - How the field of view was estimated.

The measurements

Measurement 1

Parameters

aperture A: fully open
 aperture B: fully open
 aperture AB: 6.4 mm
 aperture of the blackbody: 12.5 mm
 blackbody temperature: 1212° C
 distance $d-a$: 59.1 m

Measurements

(To obtain the corresponding angles a_1 , a_2 , a_3 , a_4 multiply by $9.70 \cdot 10^{-4}$ °/mm)

MCT detector:	$a'_1 = 85$ mm,	$a'_2 = 125$ mm,	$a'_3 = 125$ mm,	$a'_4 = 90$ mm
InSb detector:	$a'_1 = 92$ mm,	$a'_2 = 125$ mm,	$a'_3 = 120$ mm,	$a'_4 = 93$ mm

Result

MCT detector with aperture fully open and distance $d-a = 59.1$ m:	FOV = 0.209°
InSb detector with aperture fully open and distance $d-a = 59.1$ m:	FOV = 0.210°

Measurement 2Parameters

Same as for measurement 1 except:
distance $d-a$: 88.2 m

Measurements

(To obtain the corresponding angles a_1, a_2, a_3, a_4 multiply by $6.50 \cdot 10^{-4}$ °/mm)

InSb detector: $a'_1 = 145$ mm, $a'_2 = 195$ mm, $a'_3 = 190$ mm, $a'_4 = 140$ mm

Result

InSb detector with fully open aperture and distance $d-a = 88.2$ m: FOV = 0.220°

Measurement 3Parameters

Same as for measurement 1 except:
distance $d-a$: 40.1 m
aperture of the blackbody: 6.2 mm

Measurements

(To obtain the corresponding angles a_1, a_2, a_3, a_4 multiply by $1.429 \cdot 10^{-3}$ °/mm)

InSb detector: $a'_1 = 62$ mm, $a'_2 = 81$ mm, $a'_3 = 74$ mm, $a'_4 = 158$ mm

Result

InSb detector with fully open aperture and distance $d-a = 59.1$ m: FOV = 0.198°

Measurement 4Parameters

aperture B: 3.2 mm
aperture AB: 6.4 mm
aperture of the blackbody: 12.5 mm
blackbody temperature: 1209 °C
distance $d-a$: 59.1 m

Measurements

(To obtain the corresponding angles a_1, a_2, a_3, a_4 multiply by $9.70 \cdot 10^{-4}$ °/mm)

InSb detector: $a'_1 = 71$ mm, $a'_2 = 63$ mm, $a'_3 = 60$ mm, $a'_4 = 73$ mm

Result

InSb detector with aperture = 3.2 mm and distance $d-a = 59.1$ m: FOV = 0.130°

Measurement 5Parameters

aperture A: 3.2 mm

aperture AB: 6.4 mm
 aperture of the blackbody: 12.5 mm
 blackbody temperature: 1209 °C
 distance $d-a$: 59.1 m

Measurements

(To obtain the corresponding angles a_1, a_2, a_3, a_4 multiply by $9.70 \cdot 10^{-4}$ °/mm)

MCT detector: $a'_1 = 72$ mm, $a'_2 = 70$ mm, $a'_3 = 57$ mm, $a'_4 = 79$ mm

Result

MCT detector with aperture = 3.2 mm and distance $d-a = 59.1$ m: FOV = 0.136°

Measurement 6

Parameters

aperture B: 1.6 mm
 aperture AB: 6.4 mm
 aperture of the blackbody: 12.5 mm
 blackbody temperature: 1209 °C
 distance $d-a$: 59.1 m

Measurements

(To obtain the corresponding angles a_1, a_2, a_3, a_4 multiply by $9.70 \cdot 10^{-4}$ °/mm)

InSb detector: $a'_1 = 29$ mm, $a'_2 = 30$ mm, $a'_3 = 23$ mm, $a'_4 = 36$ mm

Result

InSb detector with aperture = 1.6 mm and distance $d-a = 59.1$ m: FOV = 0.058°

Appendix 2 - Calculation of the mirror size

The diameter of the entrance optics of the narrow-angle telescope for the Bomem MR254 spectrometer is 250 mm. The field of view of the telescope is 0.28° according to Bomem. Assume that the mirror will be used so that the length of the optical path from the telescope to the mirror is less than 2 m. For ScanSpec 98:1 this distance will be much less than 2 m, but there might be later modifications in the future that require a longer distance. The diameter of the infinite cone from which the telescope collects light at 2 m from the telescope is

$$(250 + 2000 \cdot \tan 0.28^\circ) \text{ mm} \approx 260 \text{ mm}.$$

Since the angle of incidence i is not zero, the mirror has to be larger than 260 mm. Figure 1 shows the situation. The angle of incidence i will vary between 20° and 47° which gives a range of the f_2 angle of between 50° and -4° .

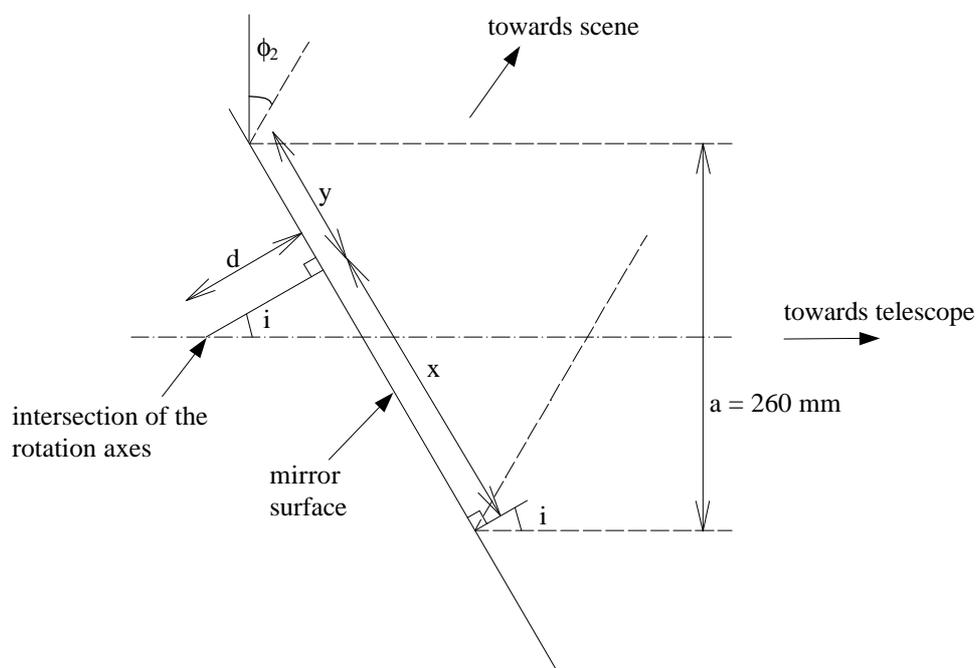


Figure 1

Geometry gives that

$$y(i) = \frac{a}{2 \cos i} - d \tan i$$

and

$$x(i) = \frac{a}{2 \cos i} + d \tan i.$$

We know the distance a . The distance d depends on the rotary table and how the mirror is mounted. We assume that d will be between 80 and 100 mm (which it is in the realized construction). The maximum values of $y(i)$ and $x(i)$ when i varies between 20° and 47° and d varies between 80 and 100 mm are

$$y_{max} = 110 \text{ mm}, x_{max} = 298 \text{ mm}.$$

15 mm have been added to these values so there will be a 15 mm border around the edges of the used area to compensate for misalignment. The other dimension of the mirror only needs to be $260 + 2 \cdot 15$ mm = 290 mm. The dimensions of the mirror are shown in Figure 2.

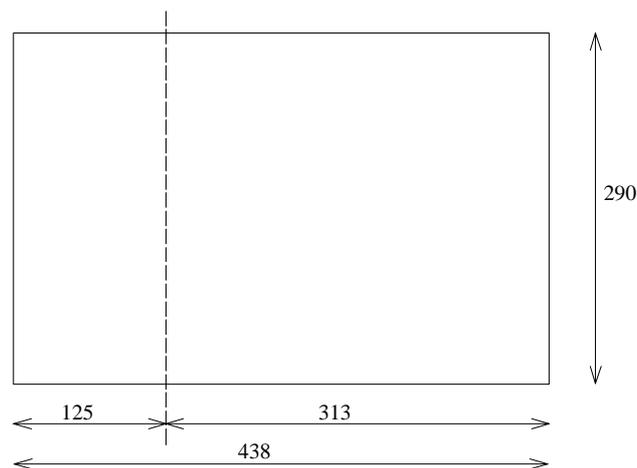


Figure 2 - The dimensions of the mirror

Appendix 3 - The standard scan programs

This is a list of the parameters of the eleven standard scan programs. The first two parameters are spectral resolution and image size.

Standard scan program 1 - NORMAL 8

16cm⁻¹, 8x8, 4x spatial oversampling, 1/2 scan per spectrum

Standard scan program 2 - NORMAL 16

16cm⁻¹, 16x16, 4x spatial oversampling, 1/2 scan per spectrum

Standard scan program 3 - NORMAL 32

16cm⁻¹, 32x32, no spatial oversampling, 2 scans per spectrum

Standard scan program 4 - FAST 8

16cm⁻¹, 8x8, no spatial oversampling, 1/2 scan per spectrum

Standard scan program 5 - FAST 16

16cm⁻¹, 16x16, no spatial oversampling, 1/2 scan per spectrum

Standard scan program 6 - FAST 32

16cm⁻¹, 32x32, no spatial oversampling, 1/2 scan per spectrum

Standard scan program 7 - LOW NOISE 8

16cm⁻¹, 16x16, 2x spatial oversampling, 16 scans per spectrum

Standard scan program 8 - LOW NOISE 16

16cm⁻¹, 16x16, 2x spatial oversampling, 16 scans per spectrum

Standard scan program 9 - LOW NOISE 32

16cm⁻¹, 32x32, no spatial oversampling, 16 scans per spectrum

Standard scan program 10 - HIGH RES. AND LOW NOISE

4cm⁻¹, 8x8, 2x spatial oversampling, 16 scans per spectrum

Standard scan program 11 - HIGH RES. 16

4cm⁻¹, 16x16, 4x spatial oversampling, 1/2 scan per spectrum

Furthermore, these settings are used with all standard scan programs: scan_mode=1, use_A_detector=1, use_B_detector=1, oversampling_mode_A=0, oversampling_mode_B=0, aperture=1, pixels_per_FOV=2, telescope=1. See a standard program-file in [CD: ScanSpec98:1] for exact definitions of these parameters.