ScanSpec: an imaging FTIR spectrometer

Claes Nelsson[*a], Frans Lundberg[*b], Pär Nilsson[a], Mattias Berglund[c]

[a]Defence Research Establishment, P.O. Box 1165, SE-581 11 Linköping, Sweden
[b]Computer Vision Laboratory, Linköping University, SE-581 83 Linköping, Sweden
[c]Swedish Armed Forces - Norrland Signals, P.O. Box 9108, SE-961 19 Boden, Sweden

ABSTRACT

The demand for hyperspectral imagers for research has increased in order to match the performance of new sensors for military applications. These work in several spectral bands and targets and backgrounds need to be characterized both spatially and spectrally to enable efficient signature analysis. Another task for a hyperspectral research imager is to acquire hyperspectral data to be able to study new hyperspectral signal processing techniques to detect, classify, and identify targets. This paper describes how a hyperspectral IR imager was developed based on an FTIR spectrometer at the Defence Research Establishment (FOA) in Linköping, Sweden. The system, called ScanSpec, consists of a fast FTIR spectrometer from Bomem (MR254), an image-scanning mirror device with controlling electronics, and software for data collection and image forming. The spectrometer itself has not been modified. The paper also contains a performance evaluation with NESR NEDT, and MRTD analysis. Finally, some examples of hyperspectral results from field trials are presented: maritime background and remote gas detection.

Keywords: background, FTIR, hyperspectral, imaging, MRTD, NEDT, NESR, scanning, ScanSpec, signature

1. INTRODUCTION

Hyperspectral optical imaging techniques have become increasingly important for military applications as sensor technology has evolved and as techniques for low observables have improved. The technique has been used for several years in remote sensing applications from satellites and airborne platforms. Today hyperspectral imaging techniques are moving into operational military sensor systems for surveillance and target recognition. Another application is the detection of gases, both combustion products and chemical warfare agents. A common definition of a hyperspectral system is that the spectral resolution is / 0.01. The number of spectral bands can vary, and for a certain application the entire spectral region does not need to be covered with overlapping bands. What is important, is that the bands used are carefully selected.

As a result, the demand for hyperspectral imaging research and investigation tools has increased. Targets and backgrounds need to be characterized both spatially and spectrally to enable efficient signature analysis. The target signatures must be carefully adapted to the backgrounds in a wide spectral range and with a high spectral accuracy. The same applies for counter-measures where decoys must be spectrally and spatially correct. Another application for a hyperspectral imager in research is to enable the acquisition of hyperspectral data for the study of new hyperspectral signal processing techniques for target detection, classification, and identification. With this type of data, the important bands can be selected.

A hyperspectral imager produces data in the form of a data cube. Two of the axes correspond to the x- and y-dimensions of the scene. The third dimension contains the spectral information. 2D-arrays for IR-radiation are in a phase of a rapid development and the availability of large 2D-arrays of IR-detectors has led to the development of various designs for hyperspectral imagers. Two of the dimensions are then mapped onto the array and the third is collected over time. The dimension collected over time could be either the spectral dimension or one of the spatial dimensions. Three classes of systems can be identified: **Filtering systems**, where the spectral information is acquired over time as a filter wheel is rotating or some other filtering component changes pass band over time, **Dispersive instruments**, where the spectral content of the incoming radiation is spread out in space (The 2D-array registers the two spatial dimensions or one spatial and the spectral), and **Fourier Transform (FTIR) techniques**, where an interferogram is acquired instead of a spectrum. The spectra are then

---

[*] Correspondence: Claes Nelsson: clanel@lin.foa.se; www.foa.se; Phone: +46 13 378284
Frans Lundberg: frans@isy.liu.se; www.isy.liu.se/cvl; Phone: +46 707 601861

calculated at a later stage. All these techniques have found their applications and they have been described previously[1,9]. The FTIR-technique is the one with the highest spectral resolution.

This paper describes how a somewhat different approach was used to develop a hyperspectral IR imager called ScanSpec. At the Department of IR Systems at the Defence Research Establishment (FOA) in Linköping, Sweden, an FTIR spectrometer, MR254, from ABB Bomem is available for spectral signature characterization, see Section 2.1. An add-on system was appended to the spectrometer consisting of an image-scanning mirror device with controlling electronics, and software for data collection and image forming. The aim has been not to alter the spectrometer so it still can be used for other applications. The budget of the project was limited and this work shows how the capacity of an FTIR spectrometer can be improved in a very efficient way. Commercial hyperspectral imaging systems are in general a lot more expensive. Also presented in this paper are results from evaluation measurements with the system as well as some results from the first field experiments.

2. DESIGN AND CONSTRUCTION

2.1. The ABB Bomem spectrometer MR254

The ScanSpec system is based on a spectrometer from ABB Bomem called MR254. It is shown in Figure 1. To understand the design of ScanSpec a few things need to be known about the spectrometer. The MR254 is a high-speed, high-end FTIR spectrometer designed for both laboratory and field use. The Bomem spectrometer used for ScanSpec is equipped with two IR-detectors, an InSb- and an MCT-detector, which gives a total spectral range from 0.7 to 18 μm. The optical layout of the spectrometer makes it possible to use both detectors simultaneously. The spectrometer has a built-in cold blackbody source used to optically subtract the internal radiation of the optics. Both of the detectors and the blackbody source are cooled with liquid nitrogen. A spectral resolution of 1, 2, 4, 8 or 16 cm^{-1} can be chosen. The spectrometer is fast, it can acquire 65 spectra/s at the resolution 16 cm^{-1} and 31 spectra/s at 4 cm^{-1} which are the most commonly used resolutions for ScanSpec. The MR254 is equipped with a narrow-angle telescope with a field of view of 0.20°, which has been characterized at FOA[9]. A CCD camera is connected to the spectrometer to make it possible to see the measured object in the visual region as a reference. For further technical information on the MR254 spectrometer, contact ABB Bomem.

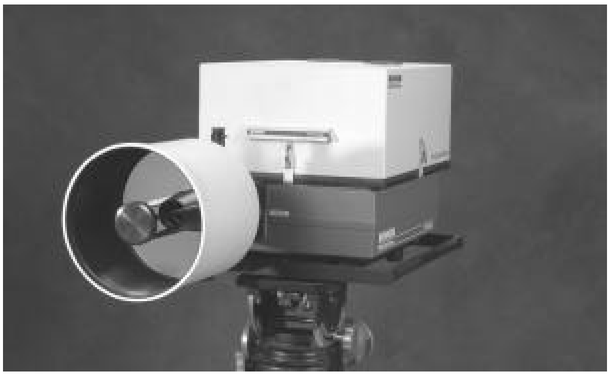


Figure 1 The MR254 spectrometer with the narrow-angle telescope mounted to it. In this picture it is standing on a tripod and is not mounted to the rest of the ScanSpec hardware. Published with permission from ABB Bomem.

2.2. Overall system design

The purpose of building ScanSpec is to add the possibility of imaging to the Bomem spectrometer by scanning a mirror in front of the telescope of the spectrometer and thus acquiring the spatial dimensions of the spectral image. The basic idea is to use the high speed of the Bomem spectrometer to sample spectra in different spatial directions by rotating a mirror to move the instantaneous field of view. By scanning a *static* scene while the spectrometer is acquiring spectra, a spectral image can be produced. We gave up the possibility of studying rapidly changing radiation, and instead decided to study how the variations change with position. Although ScanSpec is a piece of equipment used together with the ABB Bomem spectrometer the Bomem spectrometer is not in any way altered, so it can be used without the ScanSpec part to study rapidly changing IR radiation.

How ScanSpec acquires spectral images is fundamentally simple, but in practice many things have to be considered to build a successful system. The ScanSpec system, shown in Figure 2, consists of the Bomem spectrometer with a narrow-angle telescope, a mirror, a mirror-turning system, a support construction, and a PC to control the acquisition and do the signal processing.

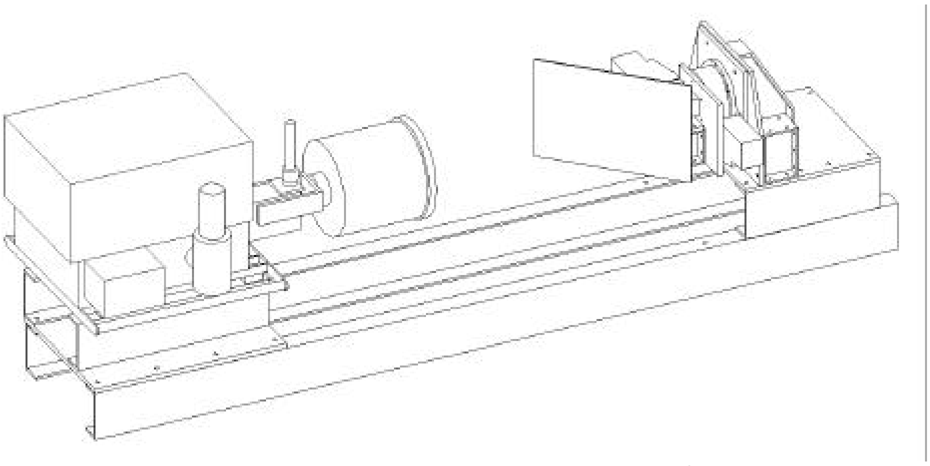


Figure 2. The ScanSpec: The MR254 spectrometer with its narrow-angle telescope (to the left), the mirror and the mirror-turning system (to the right), and the support construction.

The information flow in the complete system is shown in Figure 3. The user interacts with the PC, and uses a joystick to control the mirror in order to select the scene of interest. The PC communicates with the spectrometer using Acquire, ABB Bomem's program. It also communicates with the motion controller (MM) via the serial port, the parallel port and a data acquisition board. The motion controller runs a program that controls the two rotary tables RV120PP and RV160PP. There are two emergency power switches used to prevent the mirror-turning system from rotating outside of the physical boundaries, in case of software bugs or user errors.

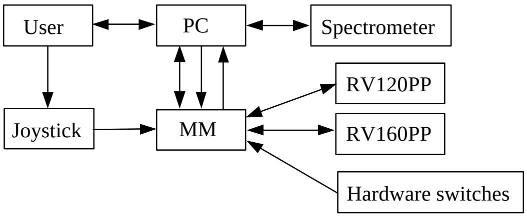


Figure 3. The information flow between the parts of the ScanSpec system

The rest of this section will cover design issues that were considered during the construction of ScanSpec. In a previously published report describing the design of ScanSpec[9] these issues are treated in greater detail.

2.3. The mirror

Many parameters must be considered when choosing a mirror for a scanning apparatus like ScanSpec.

Reflectance is important in two ways. A high reflectance is needed to minimize the signal attenuation, and also (often more importantly) to reduce the thermal emission of the mirror. Gold-coated mirrors generally have the best reflectance for IR radiation, but aluminum works well too and is better in the visible range. The reflectance in the visible range is an issue here since we want to be able to use the CCD camera connected to the MR254 spectrometer.

Flatness is of course important, but state-of-the-art mirror flatness is not needed for the ScanSpec application since the mirror only collects radiation for one pixel of the spectral image at a time. One advantage with higher flatness is that the images from the CCD camera will be sharper. A problem when choosing a mirror is that different manufacturers define flatness differently, and some of these definitions are rather vague.

Weight and bending rigidity must be discussed together. The bending rigidity of the mirror is an issue, since high angular accelerations are needed to quickly scan the mirror. The weight needs to be kept down, to enable the mirror-turning system to turn the mirror quickly. There are mirrors where weight is reduced without reducing bending rigidity much. This is done by not making the mirrors solid. However, this type of mirror is very expensive and is therefore not used for ScanSpec.

Several mirrors where considered for ScanSpec. The chosen mirror is a 6-mm float glass mirror coated with aluminum from Edmund Scientific, USA. It is inexpensive (around 200 USD) compared to the considered alternatives since it is an off-the-shelf product. Other advantages are that the delivery time was short and the mirror is thin enough to be cut by an ordinary glasscutter. The flatness of the mirror is just enough for the ScanSpec application, but it is not good enough to produce sharp images from the CCD camera. The input telescope of the MR254, which has a limited performance in the visual range, also decreases the sharpness of the CCD-images. However, the images from the CCD camera are good enough to align the ScanSpec images with visual cues. The disadvantage with the not so sharp CCD images is not a big issue compared to the great advantages in price and weight compared to a thicker and flatter mirror. The low weight of the mirror puts much less demand on the mirror-turning system and the support construction. Tests showed that the bending rigidity of the mirror was enough to handle the angular accelerations on it without significantly distorting the mirror.

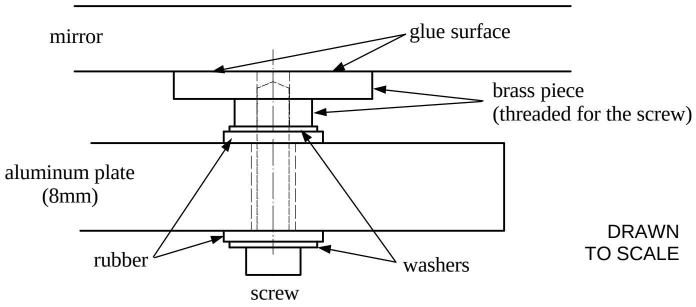


Figure 4. The mirror-mounting.

How to mount the mirror is the next issue to deal with. The solution for the ScanSpec mirror is shown in Figure 4. The mirror is mounted on an aluminum plate via three brass pieces glued to the surface of the backside of the mirror. When designing the mirror mounting the following points were considered:

No unnecessary bending. The approach for the ScanSpec mirror was to fasten it in three points to ensure that no bending of the mirror is introduced due to the mounting. In real life the fastening area cannot be a point, but it can be made small and the rubber pieces in the construction in Figure 4 minimize the moments acting on the mirror through the mounting points.

How to fasten the mirror. There are two approaches on how to fasten the mirror to the rest of the system. Either it is done by clips around the edges or by using adhesives. Adhesives were used for the ScanSpec mirror since this made it possible to fasten the backside of the mirror anywhere, not only around the edges. Two adhesives were tested, a two-component epoxy adhesive and a cyanoacrylate. Also, two surface pairs were tested, a glass/brass and a glass/steel surface. The glass/brass surface glued with the epoxy adhesive (Araldit 2012) had the best strength and was used to fasten the ScanSpec mirror.

Fastening points. Where should the three fastening points be located on the backside of the mirror to minimize the bending of the mirror due to the angular accelerations? This problem has not been treated in detail, but could be solved with finite element analysis. The solution for the 1D case (bending of a beam) was considered as a hint. The calculations showed that the bending was much less when the fastening points were located away from the mirror edge than on the edge. Another advantage with not fastening the mirror at the edges is that the weight of the aluminum plate behind the mirror is reduced, which considerably reduces the moments of inertia around the mirror turning axes.

Thermal expansion is not a difficult problem here, but it must be considered.

The mirror is the heart of the hardware system, and after it has been chosen, the mirror-turning system should be designed.

2.4. The mirror-turning system

This section contains as a brief discussion about how the mirror-turning system was built and why the solution is based on Newport’s rotary tables. The most important issues when designing the mirror-turning system are the following.

The **angular speed** of the turning system components should be chosen so that the angular speed of the moving optical axis is at least 20°/s. This is overkill in the ScanSpec application, but it is motivated by the possibility of using the turning system to track flying targets.

An **angular acceleration** of 100°/s is adequate for ScanSpec.

Angular precision. The field of view of one pixel in the spectral image is 0.10°. We want the angular error to be less then 20% of a pixel, and therefore we want the angular mechanical error to be less then 0.02°/2 = 0.01°. We divide by two since the optical angle is twice the mechanical angle for one of the rotation axes (consider the RV120PP rotary table in Figure 5).

The **torque** must be high enough to turn the mirror so quickly that the turn-around time is short compared to the effective data collection time.

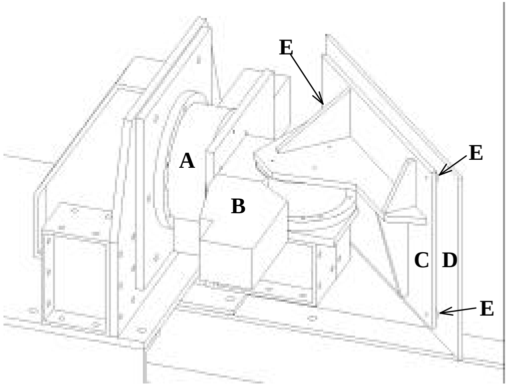
The **range** of the mirror-turning system should preferably be large enough to cover a large part of the sky, so that the equipment could also be used to track flying objects.

Control. It must be possible to control the mirror-turning system easily from a PC.

Delivery time and cost are practical issues that always have to be considered.

The first approach was to find a complete system to buy that would only leave the mirror mounting for us to do, but finally separate parts were bought. There was no complete off-the-shelf system on the market that fulfilled our requirements, and the cost of a custom-built system was not within the budget of the ScanSpec project. Products from the following companies were considered: Sagebrush, Daedal, Newport, Aerotech, Ball Aerospace & Technologies Corp., and Anorad.

The chosen system is based on two rotary tables from Newport (RV120PP and RV160PP) and a motion controller (MM4005). The rotary tables fulfil our requirements specified above. They are put together as depicted in the CAD drawing in Figure 5. A CAD system capable of modeling solids was used to design the details of the construction. By using drawings from Newport the whole construction could be finished before the rotary tables were delivered. Another advantage of using a CAD system is that the functions to compute mass and moments of inertia were very useful.



A RV160PP rotary table

B RV120PP rotary table

C Aluminum plate behind mirror

D Mirror

E Fastening points

Figure 5. The mirror-turning system.

2.5. Software system

Most of the code in the software system is written in Matlab, which is extensively used at FOA. C and C++ are used for communication with hardware, and in one case, to speed up a computation that was slow when using Matlab. A few parts of the Matlab code rely on the Matlab Signal Processing and the Matlab Image Processing toolboxes. The tasks for the ScanSpec software system are to acquire the raw data, compute the spectral image from that data, and to present the spectral image to the user. The software system follows that partitioning both in chronological order and in modularity of the software. The modules are briefly described below.

2.5.1. Module 1 - Acquiring data

This module first lets the user set the parameters for the data acquisition. This is done by choosing a scan-program – often one of the standard scan programs described in Table 1 – and the angles of the lower left corner of the spectral image to be sampled. The scan program parameters are stored in text files and can easily be modified. After the parameters are set, this module writes a motion program (in Newport's motion control language) that is sent to the motion controller for the rotary tables. The actual data acquisition is done using the Acquire software that comes with the MR254 spectrometer. The positions of the rotary tables are sampled at constant time intervals and stored on the motion controller. When the acquisition has finished, those positions are sent to the PC.

Table 1 Parameters of the 11 standard scan programs. Included in the table are also the effective scan time (from first to last pixel) and results from the MRTD measurements, see Section 4.1.3. The spectral integration intervals for the MRTD were 700–1200 cm^{-1} for the MCT detector and 2000–2200 cm^{-1} for the InSb detector

Scan program	Characteristics	Number of pixels	Spectral resolution (cm^{-1})	spatial oversampling (times)	averaging (scan/spec)	Acquisition time (mm:ss)	MRTD MCT (ºC)	MRTD InSb (ºC)
1	Normal	8 x 8	16	4	½	00:08	0.9	0.2
2	Normal	16 x 16	16	4	½	00:24	0.9	0.2
3	Normal	32 x 32	16	1	2	01:18	0.9	0.2
4	Fast	8 x 8	16	1	½	00:03	1.6	0.4
5	Fast	16 x 16	16	1	½	00:09	1.6	0.4
6	Fast	32 x 32	16	1	½	00:27	1.6	0.4
7	Low noise	8 x 8	16	2	16	01:20	0.3	0.1
8	Low noise	16 x 16	16	2	16	04:43	0.3	0.1
9	Low noise	32 x 32	16	1	16	08:58	0.4	0.2
10	High resolution, low noise	8 x 8	4	2	16	02:50	0.2	0.1
11	High resolution	16 x 16	4	4	½	00:43	0.9	0.3

2.5.2. Module 2 - Computing the spectral image

This module computes a spectral image from the spectra acquired and the sampled positions of the rotary tables. Only the start of the acquisition can be synchronized with an external event. The individual spectra are not synchronized with anything, but they are given a time stamp. The first part of this module estimates the positions of the rotary tables at each instant a spectrum is acquired. This is done using the time stamps of the spectra and by interpolation of the table positions sampled during the scanning.

When the positions of the rotary tables are known for each acquired radiance spectrum, the problem is to resample the data to a rectangular grid. This is done by linear interpolation of the radiance for each wavelength. More advanced interpolation would be too slow due to the large amount of data. It is possible to sample the scene with a higher spatial frequency than the Nyquist frequency to reduce noise. Low pass filtering is then needed. A special file format (called SIM) has been developed to store the spectral image with the scan parameters and comments by the user.

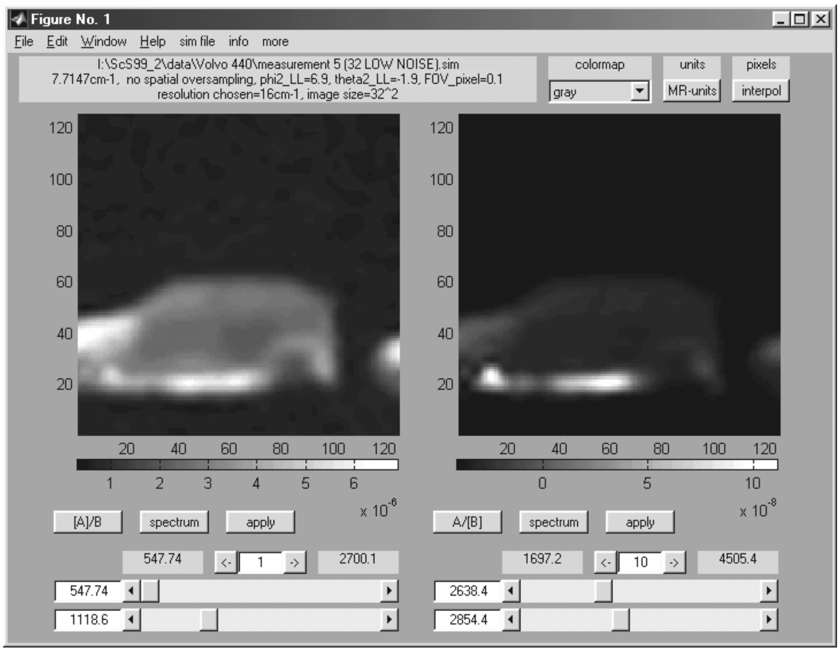
2.5.3. Module 3 - Looking at the spectral image

This module takes a file in the SIM file format and presents the data to the user as a graphical user interface developed in Matlab. An example of this user interface is shown in Figure 6 depicting the radiation from a Volvo 440 integrated in two different spectral intervals. The intervals are selected by dragging slide-bars or by typing the limits into the text-boxes. More advanced data exploration is done by manipulating the spectral images as arrays in Matlab, but this user interface serves as a convenient way to explore the data immediately after the data acquisition.

3. OPERATION

3.1. Radiometric calibration

The purpose of the ScanSpec measurements is to obtain radiometrically correct radiance hyperspectral images. Therefore a radiometric calibration must be performed and the two-point calibration routine of the MR254 system provided by ABB Bomem is used for this. Two large area blackbody sources of about 0.3 x 0.3 meters are used. One is commercially available from HGH (model name RCN300) and is used for temperatures above the ambient temperature. The other is constructed at FOA. It is used for temperatures below the ambient and consists of a flat container, which is supplied with water from a refrigerated bath/circulator from Neslab (model name RTE-211). The radiation surface is flat and painted with Krylon spray paint number 1602. Both blackbodies are traceably calibrated to national standards in Sweden, which are traceable to international standards. The temperatures of the blackbody sources are chosen to match the radiance levels in the scene.



I:\ScS99_2\data\Volvo 440\measurement 5 (32 LOW NOISE).sim
7.7147cm-1, no spatial oversampling, phi2_LL=6.9, theta2_LL=-1.9, FOV_pixel=0.1
resolution chosen=16cm-1, image size=32^2

colormap: gray
units: MR-units
pixels: interpol

Figure 6. An example of the graphical user interface (GUI) used to present the data from ScanSpec.

However, the temperature of the cold source should be kept above the current dew point to avoid condensation on the surface. The warm blackbody is kept at a temperature somewhat higher than the highest temperature in the scene coming from thermal emissions. By using this method, low-temperature radiances from the scene are accurately calibrated, but reflected high-temperature radiances like sunlight does not get as well calibrated. The blackbody sources are placed in front of the large scanning mirror of the ScanSpec to include all optics in the calibration. This ensures that all transmission losses and self-emissions are compensated for. The scanning mirror is used to view the blackbody sources. The cold source is placed horizontally under the mirror and the warm source is placed vertically in the opposite direction of the scene of interest.

The required calibration interval has been studied by measuring the radiance of a blackbody at different time intervals and comparing the results. The statistical material is not large, but a time interval of 8 hours seems to give a maximum difference of about 1.5 % for in-lab measurements. A time interval of 24 hours gave a difference of about 8 %. With reference to these results, a calibration interval of 8 hours probably is sufficient for laboratory measurements. For outdoor measurements, calibrations have to be repeated more frequently due to changes in ambient temperature. This seems to be the case even though the MR254 interferometer is temperature-stabilized. The reason is probably that the front optics including telescope and scanning mirror is not temperature stabilized. During the maritime measurements described in Section 5.1, the calibration interval varied between 3 and 7 hours, which gave a maximum difference of 4 % between two consecutive calibrations. It is not possible to draw a clear conclusion from this but it seems that the calibration interval should be at most about four hours for outdoor measurements. If the ambient temperature changes fast due to weather changes, the interval has to be shorter.

3.2. Field trials

A few field trials have been performed with the ScanSpec system. The complete system is placed in two vans or in a military truck. If vans are used, the interferometer and optical system are placed in one van and the operator and computer in another van, see Figure 7. If a truck is used, everything is placed in it. The ScanSpec collects radiation sideways though the right-side door, which is directed towards the scene of interest. This arrangement provides good weather protection for the system and shortens the set-up time.

Figure 7. The ScanSpec system with optics is placed in the left van and the operator with computer in the right van.

4. SYSTEM EVALUATION

4.1. Noise and sensitivity

Different parameters may be used to characterize the noise and sensitivity of a sensor system. For a spectrally measuring system like ScanSpec these measures have to be spectrally resolved. In this section, results from three types of noise measurements are presented together with the corresponding sensitivity figures.

4.1.1. Noise Equivalent Spectral Radiance – NESR

The Noise Equivalent Spectral Radiance is defined as the spectral radiance that will give a signal-to-noise ratio (SNR) equal to one. The NESR is different for the two detectors and it also has some variation with wavenumber. It can be determined in different ways: either spectrally resolved, or as a representative value for a certain spectral interval. In the ABB Bomem manual[4] the latter is used, which is reasonable since the variation with wavenumber is not very strong. To obtain figures that can be compared to the instrument specifications the same method was used here.

The MR254 works with complex spectra in order to retain the phase information. At radiometric calibration, the imaginary part of the spectrum is supposed to be zero. In reality this is not always true due to noise. The noise level is the same in the real and the imaginary parts, and a convenient way is to determine the noise level in the imaginary part since its base line is zero.

ABB Bomem specifies that an approximate RMS value of the signal is determined by dividing the peak-to-peak value within a certain spectral region by six. Our measurements were made at 50 ºC and the reference measurements for the two-point calibration were made at 35 ºC and 65 ºC. A blackbody radiator that filled the field-of-view was used both for measurement of NESR and for calibration. The measurements were made for different spectral resolutions and for different number of scans per spectrum. In the MR254, the average of one spectrum in each scan-direction of the interferometer is defined as one scan. Half a scan refers to a scan in only one of the directions. The results for the two detectors are shown in Figure 8. It closely follows the theoretical relationship between noise, spectral resolution and acquisition time.

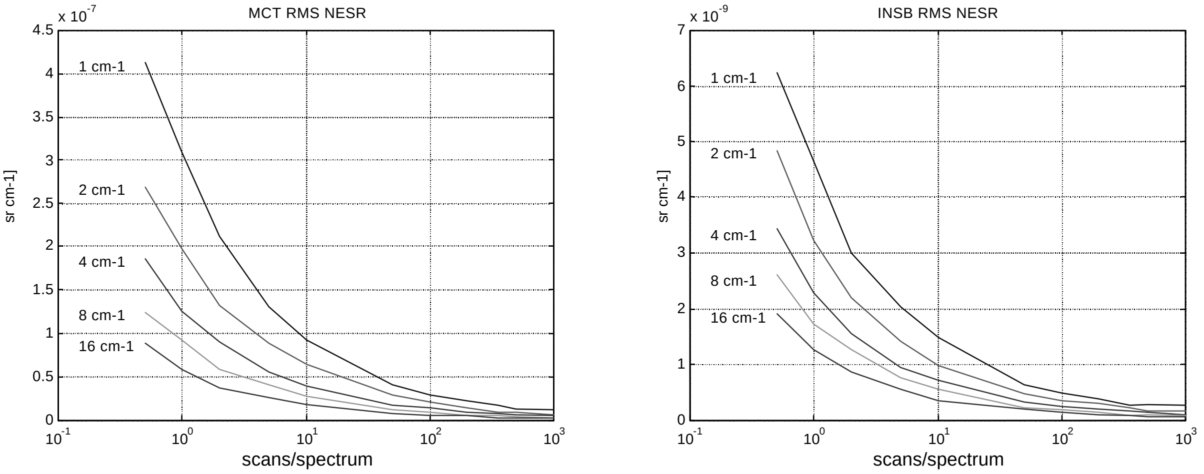


Figure 8. NESR as a function of spectral resolution and number of scans per spectrum, for the two detectors. For the MCT detector the NESR is determined in the spectral interval 800–1000 cm^{-1} and for the InSb detector it is determined in the spectral interval 2000–2200 cm^{-1}. The temperature of the blackbody radiator was 50 ºC.

4.1.2. Noise Equivalent Differential Temperature – NEDT

The NEDT is defined as the smallest measurable temperature change produced by an extended source[7]. It could be calculated from the NESR but in this work a different method was used. A spectrally resolved NEDT is more appropriate since the NEDT varies more with wavenumber than the NESR does. Ten radiance spectra were collected for two different temperatures: 20 ºC and 30 ºC. Reference measurements at the same temperatures were made previously for the two-point calibration. The NEDT for the two detectors was calculated as

$$NEDT(l) = \frac{\sqrt{\frac{1}{2}\left(s_{high}^{2}(l) + s_{low}^{2}(l)\right)}}{\bar{x}_{high}(l) - \bar{x}_{low}(l)} \cdot \left(T_{high} - T_{low}\right) \quad , \tag{1}$$

where $s_{high}(\ )$ and $s_{low}(\ )$ are the calculated ensemble standard deviations of the measured radiance for the two temperatures, $\bar{x}_{high}(l)$ and $\bar{x}_{low}(l)$ are the mean values of the measured radiance, and T_{high} and T_{low} are the two temperatures of the blackbody radiator. The results for ½, 2 and 16 scans per spectrum at a resolution of 16 cm^{-1} are shown in Figure 9. Especially the InSb detector shows a large variation with wavenumber.

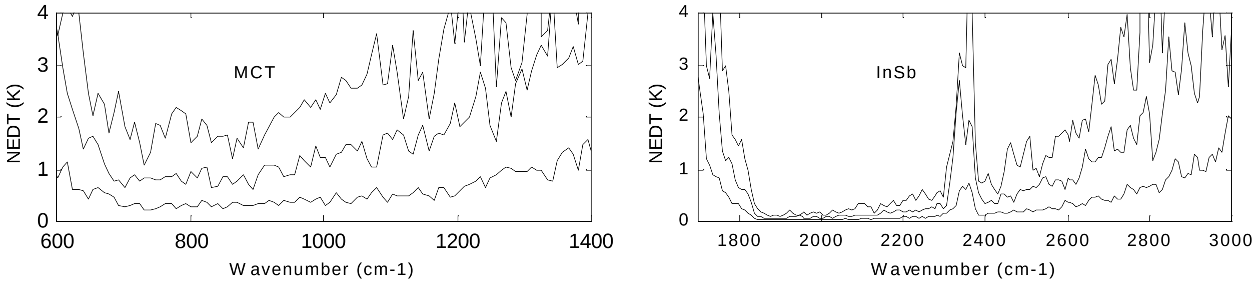


Figure 9. NEDT( ) for the two detectors measured at blackbody temperatures of 20 ºC and 30 ºC for the spectral resolution of 16 cm^{-1}. In each diagram the three curves show the NEDT( ) for ½, 2 and 16 scans per spectrum (from top to bottom).

4.1.3. Minimum Resolvable Temperature Difference – MRTD

Another measure that quantifies the sensitivity of an imager is the Minimum Resolvable Temperature Difference (MRTD), which also describes one aspect of the angular resolution of the sensor. Such measurements were performed with a Collimator Test System, CTS-1, from CI Systems. A four-bar target was used and the temperature difference between the target and the background was varied with a temperature step of 0.1ºC. Unfortunately there was only one four-bar target available with a spatial frequency that was useful. The angular frequency of the four-bar target used was 0.12 cycles per mrad and the cut-off frequency of ScanSpec was 0.28 cycles per mrad. The MRTD is defined as the minimum temperature difference between the bars and the background that permits a 70 % probability of visual recognition of the correct orientation of the bars[8]. Figure 10 shows some examples from these measurements for the integration intervals 700–1200 cm^{-1} for the MCT detector and 2000–2200 cm^{-1} for the InSb detector. The background temperature was 22 ºC for all MRTD measurements. Results of the MRTD measurements for all scan programs of ScanSpec are included in Table 1 in Section 2.5.1.

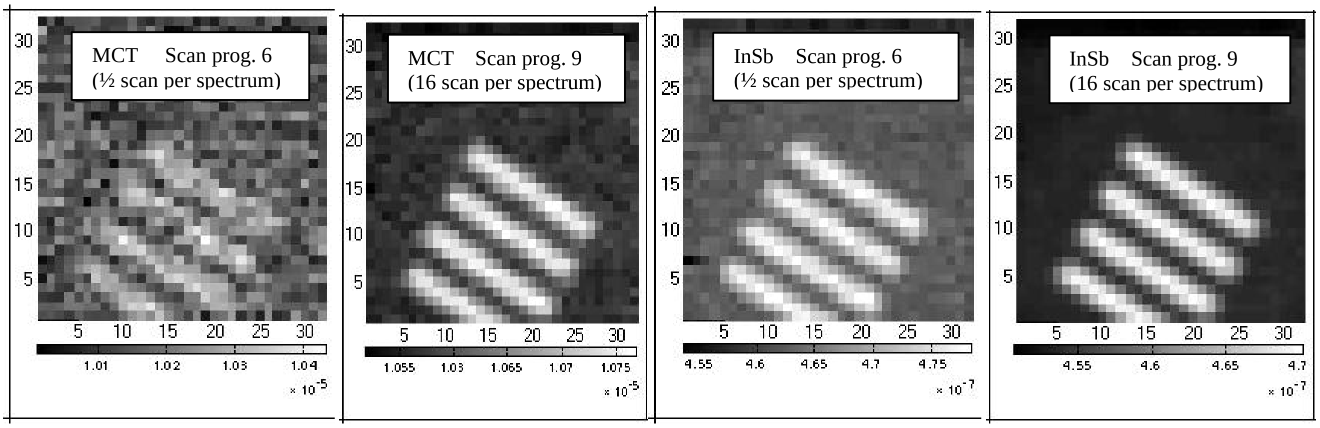


Figure 10. Examples of images from the MRTD measurements. The background temperature was 22 ºC and the temperature difference between target and background was 1 ºC. The spectral integration intervals was 700–1200 cm^{-1} for the MCT detector and 2000–2200 cm^{-1} for the InSb detector

5. MEASUREMENTS

5.1. Maritime background

As a part of field experiments[5] carried out jointly by the Defence Research Establishment (FOA) in Sweden and Netherlands Organization for Applied Scientific Research (TNO), hyperspectral measurements of maritime background were performed with ScanSpec. The purpose of including ScanSpec in the experiments was to evaluate the system in the field and to contribute to the background characterization that was one of the objectives of the field trial. The combination of spectral and spatial measurements is a valuable tool for the study of sea surface and sky phenomena. The purpose was also to measure the radiance of rocks and islands.

The experiments were performed in the Swedish archipelago about 60 km south of Stockholm. A military truck hosted the ScanSpec, the computer, and the operator. The truck was placed on a rock together with the other sensors for the experiments. The aperture height of the ScanSpec was about 11 m above sea level and the direction of measurement was close to north. Measurements with ScanSpec were made for about 48 hours with a few hours' break in the middle of the night. A few different background scenes were registered: 1 sea surface, horizon, sky; 2 distant island; 3 nearby rock. For the horizon measurement, three ScanSpec images at different elevations were collected. Combined they created an image of 3 º x 9 º. As much data as possible was collected during the time available. The selected scan program no. 9 (see Section 2.5.1) needed a scanning time of about 10 minutes. With an extra 10 minutes to store data and restart the data collection, the total time for one measurement was 20–25 minutes.

Examples of the collected data are shown in Figure 11 and Figure 12. Figure 11 shows a combined image made from three ScanSpec images collected after each other for a slightly overcast sky. The time necessary for scanning and storing of data gave a total acquisition time for the three images of about one hour. The left image (integrated 7.7–12.5 µm) shows the continuously decreasing sky radiance for increasing elevation. The right image (integrated 3.3–5.5 µm) shows the sunlit clouds with a high radiance. Figure 11 also shows radiance spectra and spectra of apparent temperature for increasing elevation. For 8–13 µm it is evident how the apparent temperature drops for increasing elevation. At 3.5 µm in the spectra the scattered sunlight can be seen.

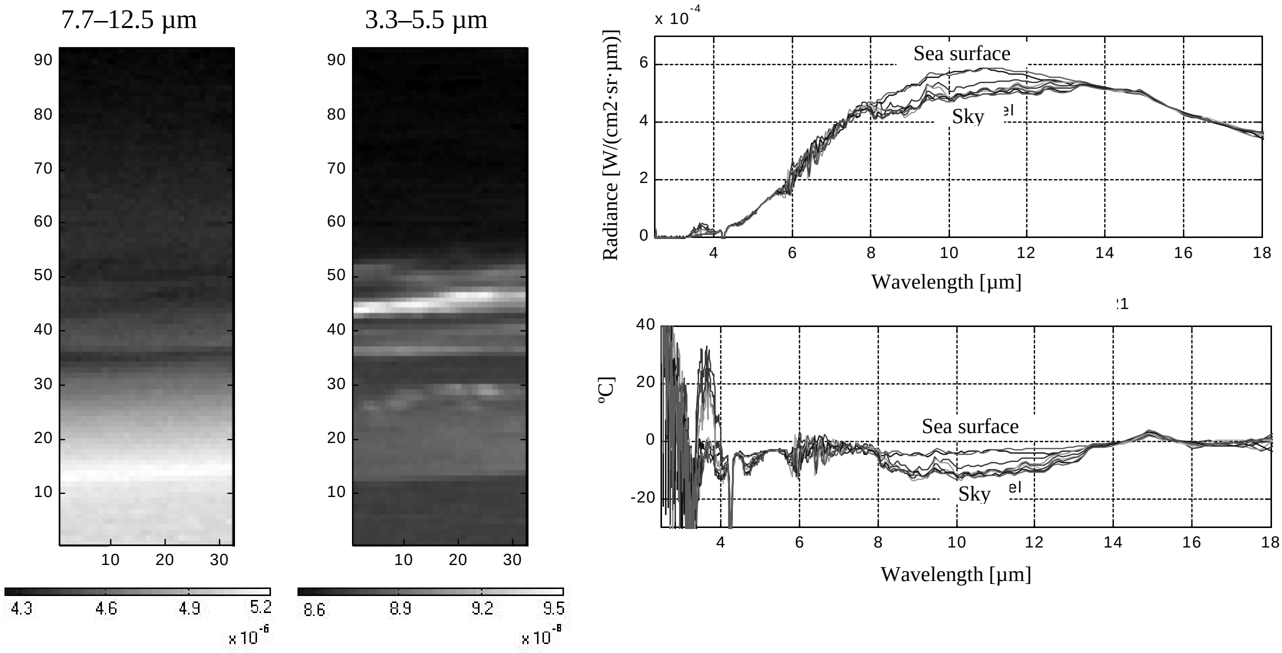


Figure 11. Hyperspectral images and spectra from a maritime scene with sea surface and a partly cloudy sky. The images are created from three combined ScanSpec images collected with scan program 9. Radiance spectra and spectra of apparent temperature are shown to the right. The top spectrum in each diagram is from the sea surface and the bottom spectrum from the sky. The others are from equidistant elevations in between.

Figure 12 demonstrates an effect present in the 9–14 µm region. In the short-wave (9–11 µm) part of the band, the sea surface shows the same radiance level as the boundary layer of the atmosphere. At the horizon the radiance level is close to that of a black body at air temperature. For the long-wave (11–14 µm) part of the band the radiance level of the sea surface is lower than that of the horizon. This indicates that the colder sky is reflected in the sea surface.

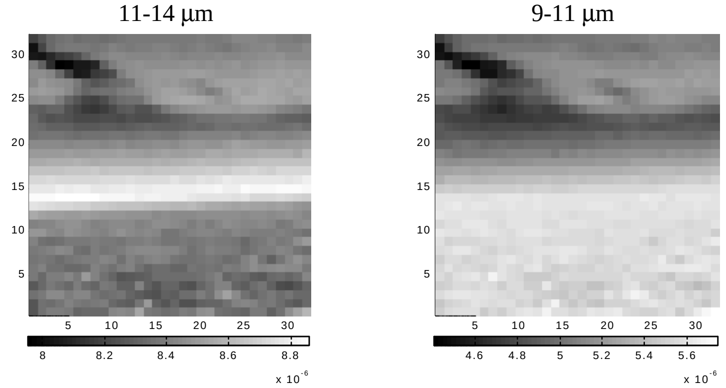


Figure 12. Hyperspectral images of the sea surface and the sky integrated over two spectral regions. The field-of-view is 3.2° x 3.2°.

5.2. Detection of ammonia

For the detection of gas phase chemical warfare agents and toxic industrial chemicals (TIC), passive FTIR spectrometry is one of the promising techniques. The method relies on the fact that a cold gas will absorb background radiation and a warm gas will emit radiation above the background level. These effects are localized to the absorption bands of the gas. FOA has activities in this area, and as a first test ScanSpec was used at a field trial where ammonia and methanol were released under controlled conditions. Measurements made by other instruments at this field trial have been reported[2] previously. The ScanSpec was set up at a distance of 800 m from the release point for the gas. A few releases were made with ammonia and approximately 2 kg was released over a 5-minute period each time. Two different scan programs were used for ScanSpec: program 3 and program 10, see Section 2.5.1. The data was collected as radiance spectra in the same way as for the background measurements in Section 5.1. For analysis the radiance spectra were transformed to apparent temperature spectra *T( )* . If the temperature difference between the gas and the background T_B is small (<20 K at 300 K) and the product of the absorption coefficient (*( )*), gas concentration (*c*), and path length through the gas (*d*) is smaller than 0.1 (• *c* • *d* < 0.1), a linear relationship can be assumed[2]:

$$T(n) = \left(c \cdot d \cdot \Delta T\right) \cdot e + T_B \quad . \tag{2}$$

A least squares fit of the temperature spectrum *T( )* to the absorption coefficient spectrum *( )* was employed to determine *c·d· T* and T_B. The calculations were performed individually for all pixels in the image. The absorption spectrum was obtained from Hitran-PC[6]. The spectral region between 900 and 1000 cm^{-1} where the two strong absorption lines of ammonia are located was used, see Figure 13. To validate the results, the correlation between the measured temperature spectrum and the fitted spectrum was calculated. A threshold of 0.5 was set to indicate valid results. Figure 14 shows the resulting images. Detection towards the sky gave a positive *c·d· T* product, and detection towards the sun-heated sandbank gave a negative *c·d· T* product. The amount of ammonia probably did not vary so much with the height over the ground, and the results emphasize the influence of the *T* on the detection limits.

The primary purpose of the experiment and analysis was to show the benefits of an imaging spectrometer for the detection of chemical agents. No attention has been paid to the handling of atmospheric water vapor absorption and to interference between different chemical agents, which could improve the detection performance.

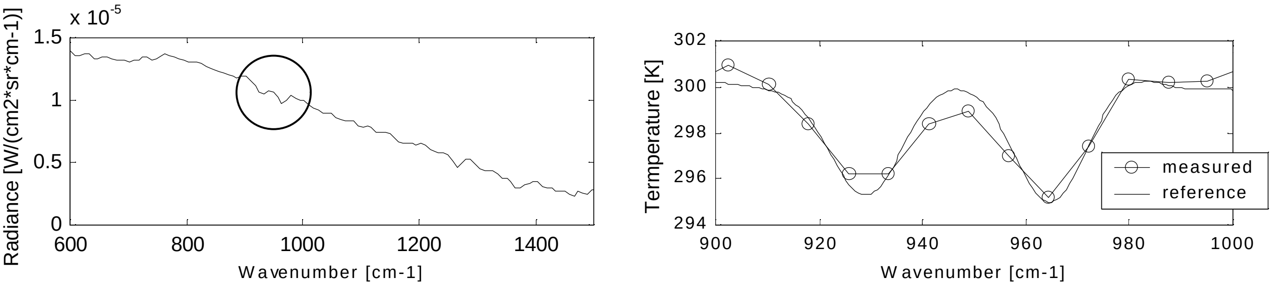


Figure 13. The left diagram shows the radiance spectrum for a measurement condition where cold ammonia was seen towards a warmer background. The absorption lines at 950 cm^{-1} are circled. The right diagram shows the apparent temperature calculated from the measured radiance as well as a fitted reference spectrum (magnitude and offset). The spectra correspond to pixel (29,23) of Figure 14.

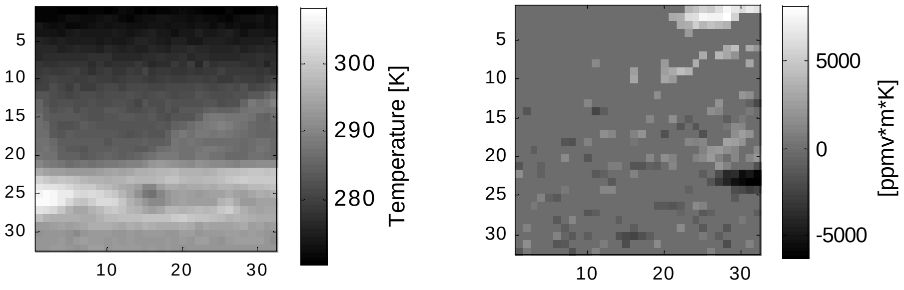


Figure 14. The left image shows the determined background temperature and the right image the c·d· T of the scene. Level 0 (gray) indicates areas where no ammonia was detected (correlation < 0.5).

6. MEASUREMENT UNCERTAINTY

All measurement results reported have an uncertainty, and a proper reporting of measurement results should be accompanied by an uncertainty analysis. However, the purpose of this paper is not to report on exact values upon which decisions are to be made. Therefore, only a few comments on the uncertainty will be made here.

The method used for determining NESR must be considered approximate. The reason for using it is that it is the standard method for performance tests at ABB Bomem. It is easy to use, and shows changes in noise level over time for maintenance reasons but it should not be used to determine detection limits of the system. The NEDT tests are more reliable and the uncertainty due to reference temperatures etc. is less than 10 % outside the atmospheric absorption bands. The uncertainty is higher in the absorption bands and for short wavelengths (< 3 µm). MRTD measurements are always difficult to perform since they include the subjective interpretation by a human observer. The temperature step was 0.1 ºC, which also increased the uncertainty for low values of MRTD.

The radiance measurements of Section 5.1 have a radiometric uncertainty that, among other things, depend on the blackbody radiators and on the non-linearity and stability of the spectrometer. The combined relative uncertainty was estimated to 8 % for the radiance. The ammonia results also include uncertainty in the absorption reference spectrum, which was obtained from the Hitran database. No uncertainty analysis has been made for that case.

7. CONCLUSIONS

ScanSpec, a hyperspectral imager for research purposes, has been constructed based on an ABB Bomem MR254 FTIR spectrometer. The goal was that the ABB Bomem spectrometer should limit the total performance of the spectral imager. This goal has been met for the most important parameters such as acquisition time, spatial image size, spectral resolution, spatial resolution and post-processing time. The characteristics of the system are a high spectral resolution (16 cm^{-1}, 4 cm^{-1} or even higher) but a low spatial resolution: maximum 32 x 32 pixels. The acquisition time depends on the radiation levels of the scene and of the required signal-to-noise ratio in the image. For a background scene of 32 x 32 pixels where one of the low-noise programs (no. 7–9) is necessary, the acquisition time is 9 minutes. The fastest program has an acquisition time of 3 seconds, which can be used for scenes with high radiation-levels. ScanSpec has already proved to be a valuable tool for FOA and we believe that future results will illustrate important issues in hyperspectral imaging. Also, it was developed within a limited budget – only a fraction of the cost of a commercial hyperspectral system.

Several improvements could be made to the system. The most obvious is the design and implementation of new scan-patterns. For sky radiance measurements, a scan pattern consisting of a vertical column or two parallel columns of pixels would be useful. For other applications, scan patterns adapted for the wide-angle input optics of the MR254 FTIR, which has a field-of-view of about 4º, could be useful. Irregular patterns are also interesting, e.g. radiance measurements of certain objects in a scene. By just measuring in a few directions the acquisition time will decrease and time varying phenomena could be studied. New scan-patterns will only require software changes.

Other work in the future will be simultaneous measurements with ScanSpec and IR imaging systems with higher spatial resolution. By combining a high performance in different aspects a better characterization of target and background signatures will be possible.

8. REFERENCES

1. E.J. Bakker, *Hyperspectral Imaging at TNO-FEL*, TNO report FEL-98-B303, Netherlands Organization for Applied Scientific Research (TNO), 1998.
2. A. Beil, R. Daum, and T. Johnson, "Detection of chemical agents in the atmosphere by passive IR remote sensing", *Internal standardization and calibration architectures for chemical sensors,* E. Shaffer and R. A. Potyrailo, eds., SPIE 3856, pp. 44-56, 1999.
3. M. Berglund, *Utvärdering av ScanSpec – en bildalstrande FTIR-spektrometer*, FOA-R--99-01382-615--SE, Defence Research Establishment (FOA), Sweden, 1999.
4. *Bomem MR254 Spectrometer Manual*, ABB Bomem Inc., Quebec, 1995.
5. A. N. de Jong, J. Winkel, A. Hågård, and R. Persson, C. Nelsson, P. Nilsson, *Common Preliminary Report on Swedish-Netherlands 'Baltic 99' IR Experiments, May 1999,* TNO report FEL-99-I160, Netherlands Organization for Applied Scientific Research (TNO), 1999
6. *USF Hitran-PC ver. 2.50 Manual*, Ontar Corp., North Andover, 1996.
7. G. C. Holst, *Electro-Optical Imaging System Performance*, SPIE Optical Engineering Press, Bellingham, 1995.
8. J. M. Lloyd, "Fundamentals of Electro-Optical Imaging Systems Analysis" *Electro-Optical Systems Design, Analysis, and Testing (vol 4 of The Infrared & Electro-Optical Systems Handbook)*, M. C. Dudzik, ed., pp. 1-53, SPIE Optical Engineering Press, Bellingham, 1993.
9. F. Lundberg, The design of ScanSpec – a scanning imaging FTIR spectrometer, FOA-R--99-01041-615--SE, Defence Research Establishment (FOA), Sweden, 1999.