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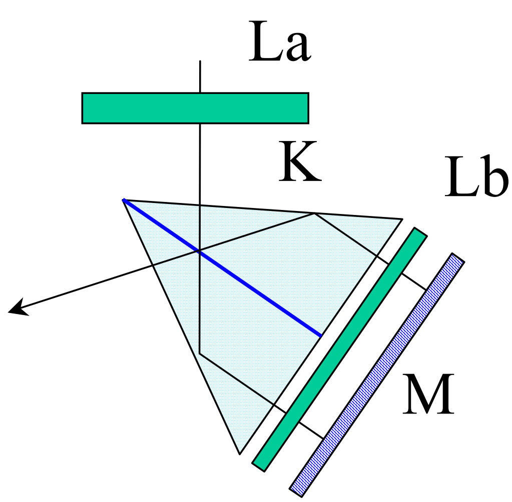
Integrated Computational Imaging Systems

Technologies for new possibilities

Ingmar Renhorn



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Report title
Integrated Computational Imaging Systems, Technologies for new possibilities

Abstract (not more than 200 words)
New imaging optical sensor technologies based on progress in nano and micro technologies are discussed. This rapid development together with the advances in computing and information processing is shown to form the basis for a new paradigm in sensor system design. This will not only make adaptive sensor systems feasible and improve performance but also influence stealth technologies. The basic principles and some realizations of such systems are given. The technical performance of such systems is now being improved. The effective employment of the systems has to be developed in parallel.

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Beräkningsintensiva avbildande sensorsystem, ny teknik för nya möjligheter

Sammanfattning (högst 200 ord)
Nya avbildande sensorteknologier, baserade på nano- och mikroteknik diskuteras i denna rapport. Den snabba utvecklingen inom detta område, tillsammans med utvecklingen inom dator- och informationsbehandlingsområdet utgör grunden för en ny sensorsystemdesign. Denna utveckling medger inte bara utveckling av adaptiva sensorsystem med förbättrade prestanda utan kommer även att påverka utvecklingen inom signaturanpassningsområdet. Grundprinciperna och några realiseringar av sådana system ges i denna rapport. Prestandaförbättringar av dessa system pågår. Effektivt utnyttjande av sådana system måste utvecklas parallellt med teknologiutvecklingen.

Nyckelord
Beräkningskrävande avbildning, hyperspektral, multispektral, adaptiv optik, MEMS, informationsbehandling

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Content

Introduction

The rapid development of broadband optical focal plane arrays with high quantum efficiency and other optical components such as MEMS now being produced allows new sensor concepts to be developed. Multi/hyperspectral sensors as well as polarimetric sensors will be used to explore target characteristics. Advanced signal processing also allows a completely new paradigm where the signal onto the detector no longer has to be an image in the conventional sense. Trade-offs between spatial, spectral and polarization sensing capabilities can therefore be realized. Efforts will increase with respect to integrated signal and image processing and on algorithm development. Broad band focal plane arrays with high sensitivity will also allow more functionality to be built into a single sensor system, thereby reducing the radar cross-section and improving on the platform signature. The optical cross-section is however often high and remedies have to be found.

The sensor development will of course make stealth technologies become of higher priority making present sensors less effective and future sensor development more demanding. The detection/recognition/identification process will depend on adaptive sensor capabilities, on board signal processing capabilities and aided decision-making. Large opportunities will result from the development of high-speed computers and digital signal processing. Passive and active technologies will be fused to provide high spatial, spectral and temporal resolutions. The presence of sensor systems both at strategic level and at various tactical levels will also require a rich flora of different types of sensor systems and capabilities. A rich flora of sensors will also be required in order to counter jamming, dazzling, decoying and obscuring the sensor systems.

Hyperspectral imaging can be used to improve on target/background discrimination and to identify spectral characteristics of specific targets. Multi/hyperspectral capability together with signal processing can substantially improve on detection and identification of targets under canopy, reduce the effect of camouflage and differentiate between different types of material such as camouflage fabrics, military paints, rubber, plastic, taggant and glass. The technical performance of such systems is now being improved. The effective employment of such systems has to be developed in parallel.

In missile threat warning applications as well as subpixel detection of ground-based targets, selections of differences of sub-bands would have substantial payoff. Multicolor IR has been shown to provide excellent clutter rejection for specific band combination in specific scenes. The desire to detect missile plumes with a minimum of background contribution has driven the designs to the MWIR spectral region. Similarly, multispectral or hyperspectral sensors in surveillance or reconnaissance applications will enhance target detectability by exploiting spectral features which have large separation from the highly correlated background for certain spectral combinations. Ideally, this should be accomplished using a spectrally adaptive sensor that has the ability to select spectral bands with respect to target/background separation[1]. Such designs will be discussed below.

The optical component development is allowing new capabilities to be implemented into the optical sensor systems. Adaptive optics can correct for optical aberrations and partly mitigate against atmospheric distortions. The development of MEMS technologies can be used for dynamic spectral adaptation and advanced optical processing at sensor level. Regions of interest can be selected, jamming countermeasured and the trade-off between different imaging parameters such as spectral band selection, polarization direction selection and combinations of these can be dynamically adapted to the situation at hand.

The advances in both imaging technologies and the application of information theory to imaging has changed what constitutes an imaging system from purely optical to integrated optical and computational. The performance of integrated systems relies on the integration of sensor design and signal processing. It is no longer optimal to just cascade electro-optical devices, coding processors and restoration algorithms as independent elements. Integrated designs including detector and detection processors are needed in order to capture target information and perform necessary post-processing and feature extraction. An emerging area of research is to consider the information content of an image. The capability of these new systems will critically depend on the balance between optical technologies, both passive and active, and electronic processing, both analog and digital. Physical properties to exploit are shape, target dynamics, spectral and polarimetric properties, spectral coherence properties and temporal intensity fluctuations. This report will focus on optical technologies that support computational imaging systems.

Primarily new passive imaging systems are discussed. The next generation of sensors will explore various combinations of three-dimensional imaging, spectral imagers, imaging polarimeters, coherence imaging and hyperspectral imaging. The architecture of these imagers might also involve adaptive and conformal optics, wavefront coding and special purpose signal processing.

Target detection, classification and recognition are an integrated part of the sensor functionality. Although information theory is useful in optimizing the total sensor system, that subject is not treated here. New sensors are discussed with these possibilities in mind and these new sensors will allow development and test of multi-dimensional coding, novel signal processing algorithms and applications to advanced information theory. Detection, classification and recognition using synthetic discriminant filters will be discussed in a separate note.

Novel designs of spectral, polarimetric and tomographic imagers are given by example. Coherent imaging is a field that is being made practical by the availability of high performance processing. The imaging Fourier transform spectrometer is a special realization of this field. Geometrical imaging, spectral imaging and polarimetry can be combined in a single instrument. The information content is however limited by the number of pixels and the dynamic range of each pixel. A trade-off between the different dimensionalities has to be found with respect to the intended application. The mutual coherence of the electromagnetic field can be utilized for discriminating between objects in the scene. The theory related to these phenomena is quite involved and will not be presented here[2]. Relevant parts of the theory can be found in the references given. Image reconstruction is discussed with respect to micro-scanning, phase diversity and optical flow. Data compression will also affect the image quality and feature extraction capability. The compression algorithm is therefore an integral part of the sensor performance. The importance of post-processing will also be touched upon.

Optical component development

Optical Micro-Electro-Mechanical-Structures (MEMS) are an enabling key technology for new classes of optical instrumentations in development. These devices will allow detailed manipulation of the optical phase front in optical systems. As will be shown below, the result of this manipulation can be exploited in many different ways. A optical MEMS consists of an array of micro mirrors each of which can modulate the phase and/or the amplitude of the phase front. A high degree of control of these modulations will add significantly to the functionality of the device. The availability of such devices is however rather limited. One device in commercial use is the Texas Instruments´ Digital Micromirror Device (DMD). Other devices are being developed for demanding applications as e.g. in lithography (Fraunhofer ISM[3]). For adaptive optics application, a membrane is deformed using control electrode structures (OKO Technology[4]). These types of devices are often used to implement Zernike polynomial corrections to the phase front.

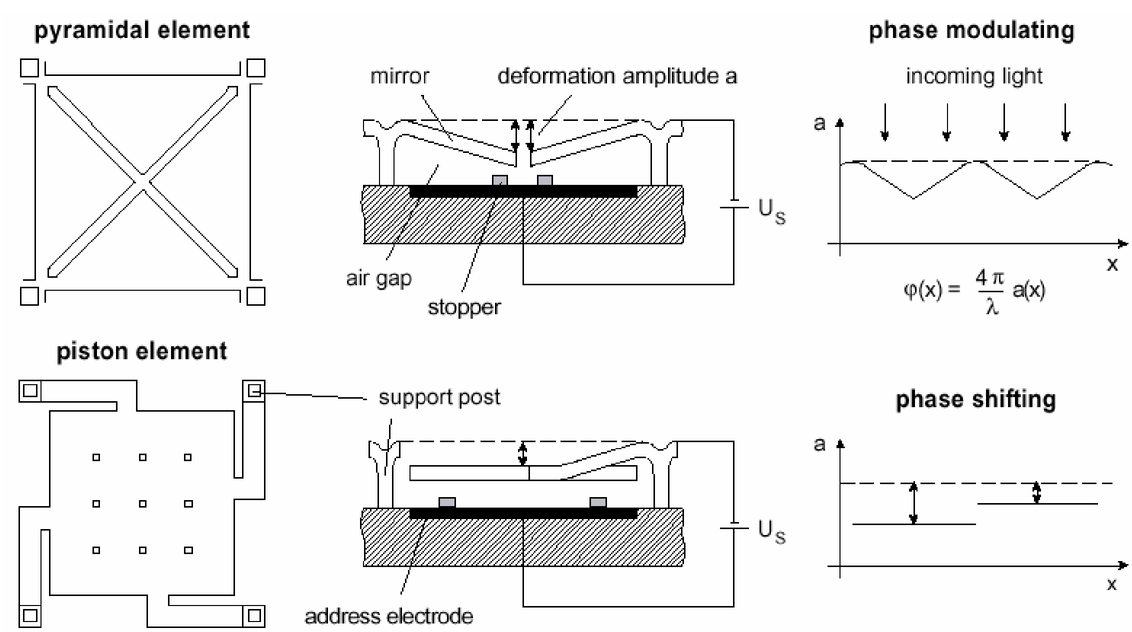

Fig. 1. MEOMS structure intended for lithography applications.

Micromachined membrane deformable mirrors are being used in adaptive optics applications. A thin membrane is suspended over an array of electrodes and deformation is achieved by applying a voltage between these electrodes and the membrane. By varying the voltage on the electrodes, a controlled deformation of the mirror can be obtained. The shape of the deformation also depends on the configuration of the actuator electrodes. Often a symmetry that can be connected to wavefront analysis, e.g. Zernike polynomials, is being preferred.

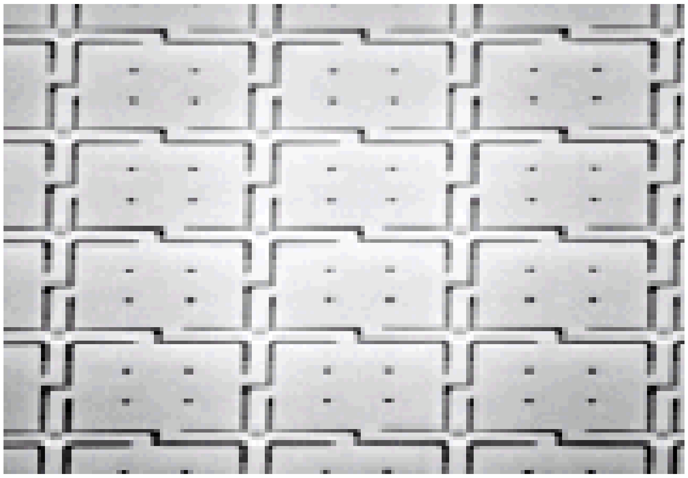

Fig. 2. Detail of a micro-mirror device.

Even so, quite general surface deformations can be obtained also approximating other types of wavefront basis functions. The low spatial frequency modes are generally producing the largest gain factor. The edge of the mirror is often fixed why the whole mirror can not be used for wavefront corrections. A trade-off therefore has to be found between the fraction of the mirror being used and the degrees of freedom needed to obtain a certain correction. This trade-off therefore depends on the aberrations of the system.

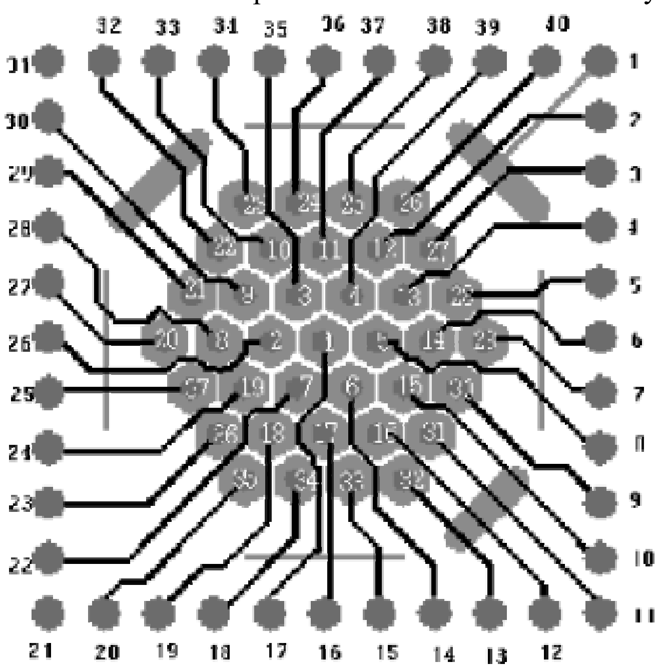

Fig. 3. Actuator layout of a deformable membrane mirror.

The response of adaptive mirrors is non-linear and adaptive control algorithms have to be developed[5]. The feed-back has to come from a wavefront sensing instrument or an imaging quality criteria as discussed below.

Phase and amplitude modulations can also be obtained using Liquid Crystal Spatial Light Modulators (LCSLM, BNS). These devices are however limited by the spectral properties of the liquid crystal.

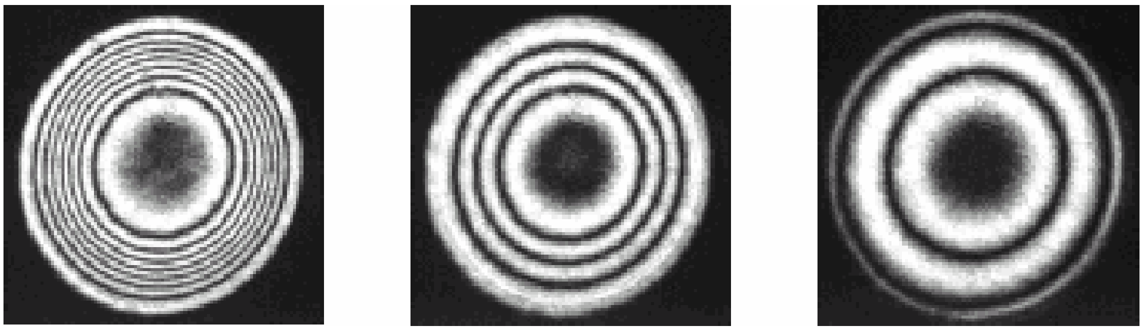

Fig. 4. Interference fringes formed by a liquid crystal tunable lens.

Microscanning

Staring focal plane arrays are fundamentally under-sampling the scene with the drawback of aliasing effect. This can be compensated by scanning the image in steps that corresponds to parts of the pixel pitch. This will increase the resolution of the instrument and decrease the effect of aliasing[6]. In many applications, the frame-rate can be increased over the video frame rate without loss of signal to noise ratio. This would allow micro-scanning without compromising the video rate requirement. This applies also to the thermal infrared spectral regions for cooled focal plane arrays. The different frames have to be interlaced to produce the final image[7].

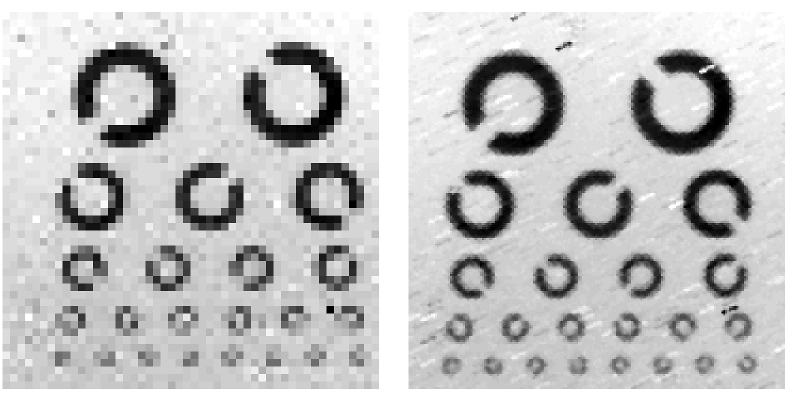

Fig. 5. Initial (under-sampled) image to the left and micro-scanned image to the right.

Micro-scanning can be achieved in many ways, e.g. using rotating wedge-wheel, micro-adjustable mirrors or lens elements and deformable gel. The rotating wheel is the simplest design but also the least attractive design from an application point of view.

Basic imaging concepts

Everybody is familiar with how a camera works. In a camera, a lens is forming an image of an object onto a sensor (photographic film or CCD). Here, generalizations will be introduced that allows for using other types of optical elements than the traditional lens and where the intensity distribution on the detector might be combinations of spatial, spectral and polarization information. Two basic designs are prevalent. The type I design shown below is equal or similar to the conventional imaging instruments and the functionality depends on modifications to the phase front at the input aperture. Examples of modifications are spectral filtering, phase front rectification (adaptive optics), chromatic focusing (zone plates) and polarimetric imaging (polarizers). The type II design uses an intermediate focal plane and re-imaging optics. Optical elements such as field stops and slits are introduced in the intermediate focal plane.

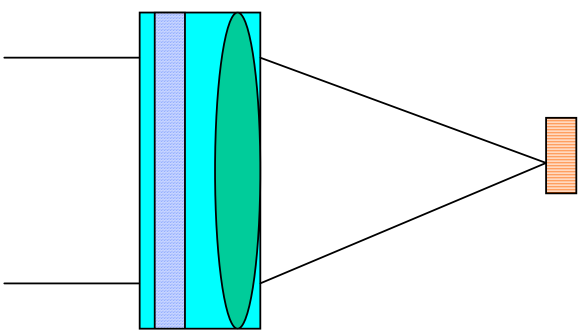

Fig. 6. Type I imaging system.

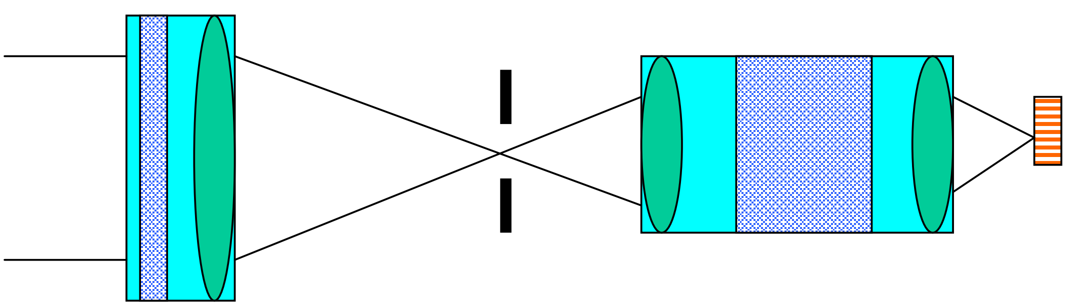

Fig. 7. Type II imaging system.

New capabilities are being developed for both types of systems. Major contributions to this progress comes from Micro-Electro-Mechanical-Structures (MEMS) technologies, Liquid Crystal Spatial Light Modulators (LCSLM) technologies, Computer Generated Holograms (CGH), new types of Focal Plane Arrays (FPA) and Digital Signal Processing (DSP) technologies. A more basic prerequisite to the progress for all the technologies mentioned is the development of nano-technologies. At present, nano-technologies are being utilized in scaling known functionalities to smaller sizes. There is also a development to come where new phenomena can be utilized due to the physics of small scales (quantum effects). That development is not discussed in this report.

Type I imaging

Conventional imaging

Conventional imaging suffers strongly from degradations due to e.g. atmospheric turbulence, platform vibrations and optical aberrations. Furthermore, turbulence is causing intensity variations or scintillations when the spectral bandwidth is small compared to spectral decorrelation phenomena. Scintillations can be of great importance in thermal infrared imagery. Improvements in conventional imagery with respect to some of these degradations are discussed below.

Deformable mirror imaging

A deformable mirror can be used for modulating the phase of the electromagnetic field. The wavefront correction has to be derived from a wavefront sensor. In astronomy a Shack-Hartmann sensor has become a standard sensor for wavefront sensing. The low order wavefront errors can also be derived by using a technique called phase diversity[8].

The mutual coherent function can be studied by introducing phase-front errors of the order of the wavelength such that the phase front emanating from different parts of the scene are mixed on the focal plane array. The interference fringes being formed can be translated into mutual coherence parameters. A source within the scene can therefore be distinguished by its spectral properties.

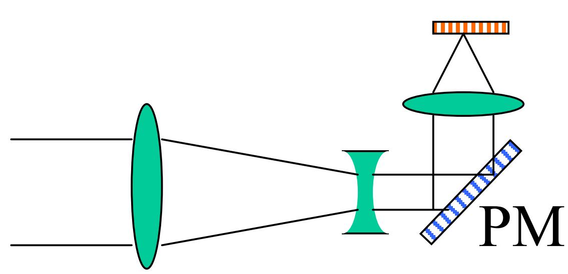

Fig. 8. Type I imaging. This is an example including a phase modulator PM.

Micro-electromechanical mirror imaging

Spectral imaging can be obtained by introducing a Fresnel zone plate or cylindrical zone plate. Dynamic chromatic focusing can be obtained by using a micro-electromechanical mirror as a phase modulator. The chromatic focus can be scanned rapidly over the spectral region of interest. Similar solutions have been designed using movable zone plates. Introducing a micro-electromechanical mirror allows the optical transfer function (OTF) to be programmable. As will be discussed later on, the phase modulator can also be used for phase diversity imaging and adaptive optics. The depth of focus can also be manipulated by generating wavefronts with extended focus properties. This can be useful when a large focal depth is aimed at.

Type II imaging

In type II imaging, an intermediate field modulation is introduced. In its most simplistic form, the field modulation is just a field stop. With active components such as the MEMS discussed above, more general modulations can be achieved such as region-of-interest (ROI) designation, dazzle suppression and polarization selection.

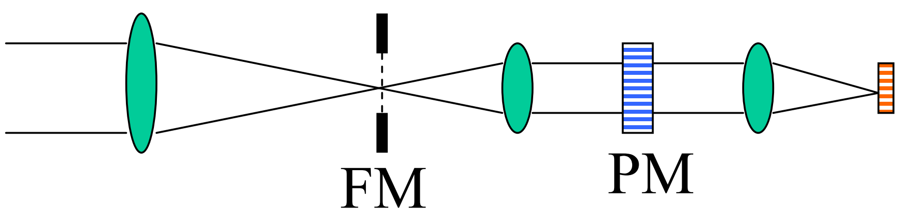

Fig. 9. Type II imaging. FM is a field modulator.

In figure 10, the FM and PM modulators is generalized and illustrated. This is just to show an example and the rich diversity in the modulation formats that can be achieved using new components. The detailed transfer function is of course selected with respect to the overall instrument functionality. A number of realizations will be illustrated and discussed later on.

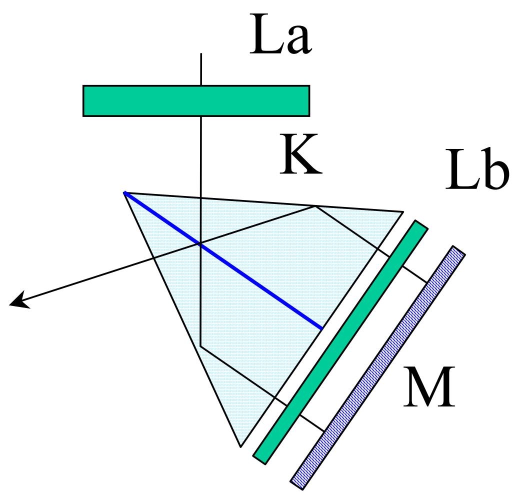

Fig. 10. FM or PM modulator. K is a Kösters prism that could be polarizing or nonpolarizing. La, if present, could be a λ/2-plate, Lb, if present, could be a λ /4-plate and M is a micromirror device that could operate as an amplitude modulator or a phase modulator.

The image or phasefront can be split into two copies with same or orthogonal polarization. Each image can be independently modulated and than recombined. The same basic design can therefore be used in a multitude of applications. The detailed functionality is determined by the modulation of the micromirror device that can be changed in real time.

The realization of these instrumentations including computational requirements will be discussed in the following sections.

Spectral and polarimetric imaging

Since sensors will often be placed on moving platforms imaging moving targets, there is a strong requirement to be able to record both spatial and spectral information simultaneously. Various trade-offs can be made depending on the detailed application. In remote sensing at large distances, the scene is regarded as being semi-static and pushbroom techniques are often employed. In these applications, a minimum of spatial information is recorded simultaneously while the detailed spectrum is highly emphasized. For tactical imaging, the dynamics of the scenario requires greater emphases on the spatial information at the expense of spectral information. Truly simultaneous spatial and spectral measurement requirements have in practice been obtained using dispersive spectrometers. Other types of sensors, e.g. spatially modulated interference patterns using variations of the Sagnac interferometer are now being developed as well as sensors employing other aspects of the partial coherence properties of the radiation.

Spectral imaging

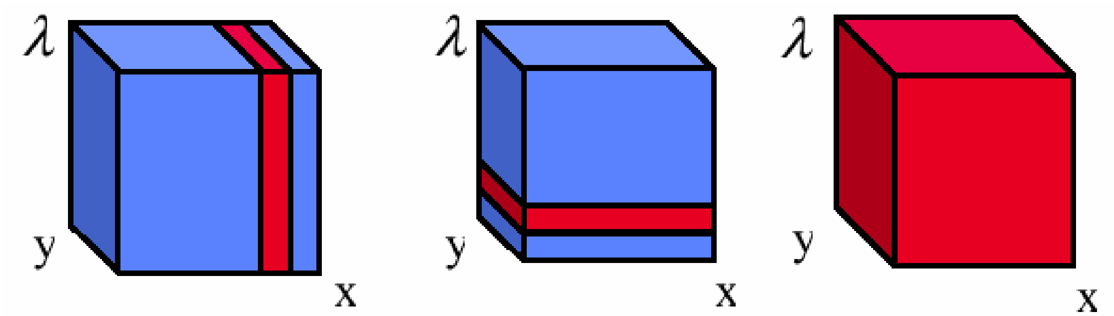

Fig. 11. The different ways of obtaining the spectral data imaging cube is illustrated. The first one illustrates a line scanner where the scene is sequentially scanned. The next one illustrates a multispectral sensor, where the spectral bands are sequentially being scanned. The third one illustrates the simultaneous registration of both spatial and spectral information.

In figure 11, the first illustration symbolizes a scanning spectrometer, the second one an imaging spectral radiometer and the third one a system recording both spatial and spectral information simultaneously. Such systems will be exemplified below. In figure 12, a hyperspectral image “data-cube” is illustrated. This type of data is now commonplace in remote sensing.

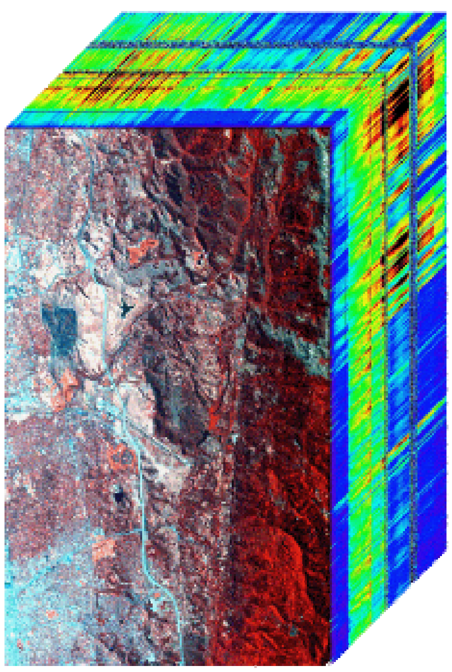

Fig. 12. Hyperspectral image where the “data-cube” has three dimensions. (AVIRIS, NASA, JPL)

The Advanced Solidstate Array Spectroradiometer (ASAS) is using a grating in an imaging spectrometer in a pushbroom configuration. This is one step forward compared to the line scanner. By using a focal plane array and record the full spectrum over a single line, dwelltime on each pixel is improved.

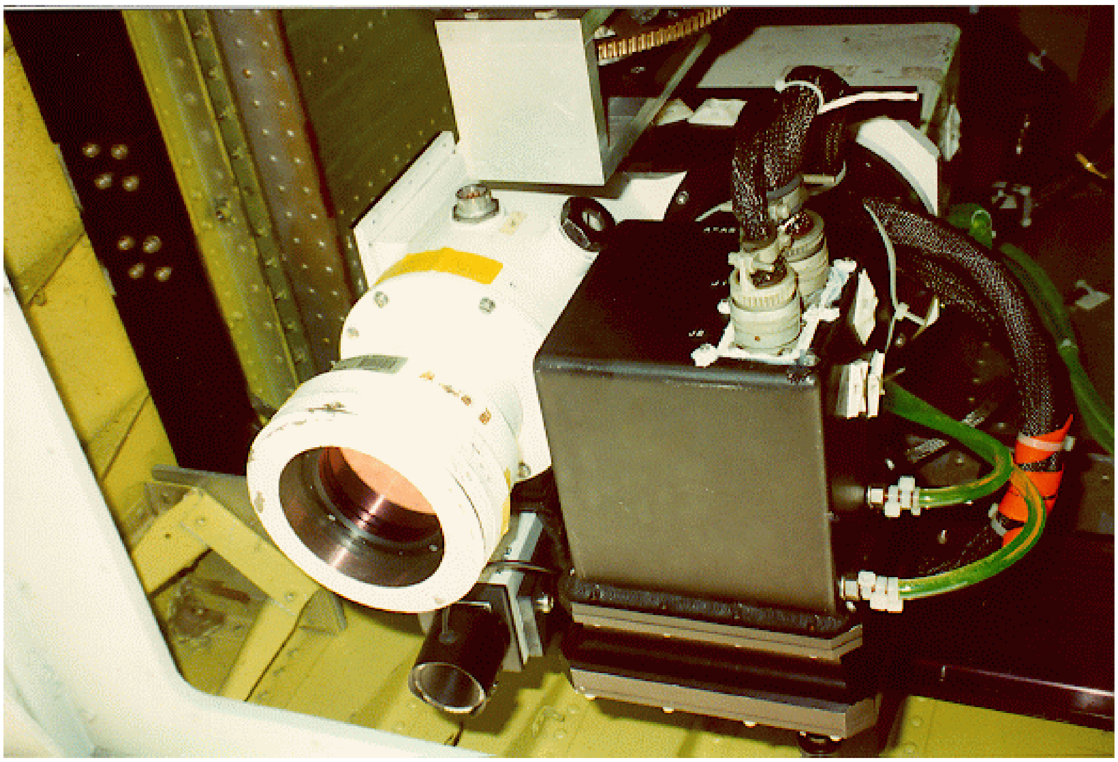

Fig. 13. The ASAS system flown in an aircraft.

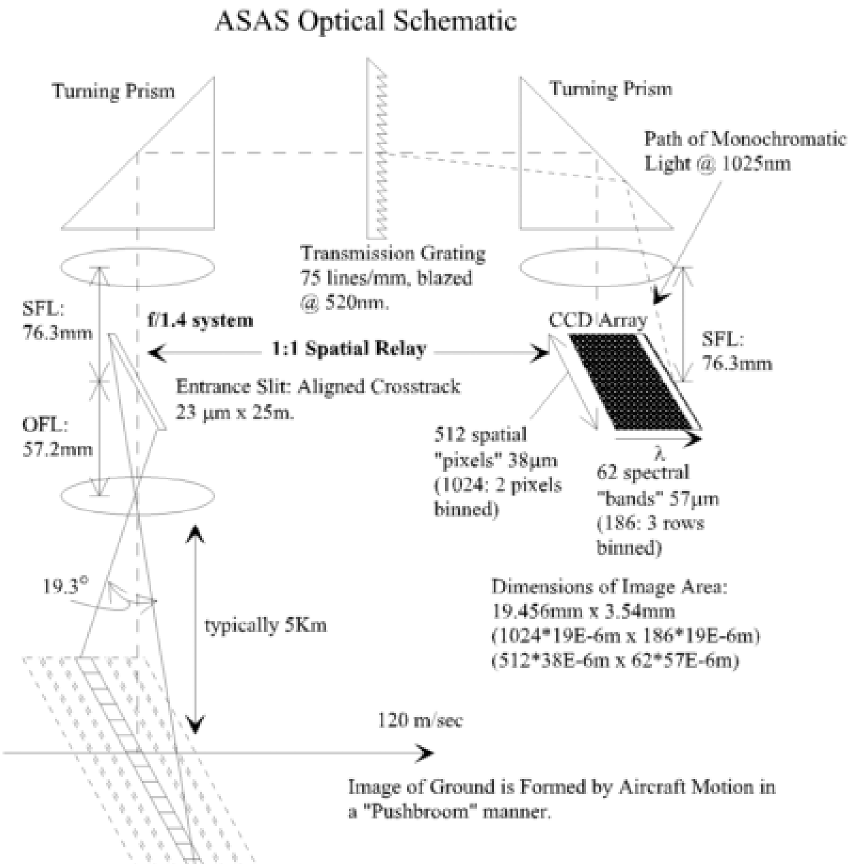

Fig. 14. Layout of the optics of the ASAS system.

Spectral imaging using filter wheel

Sensors with spinning filter wheels are being used for test purposes. They are not practical in tactical systems due to gyro-effects in rotating parts and the latency connected to such systems. Such systems are however very flexible since filter-wheels optimized for specific applications can be tested.

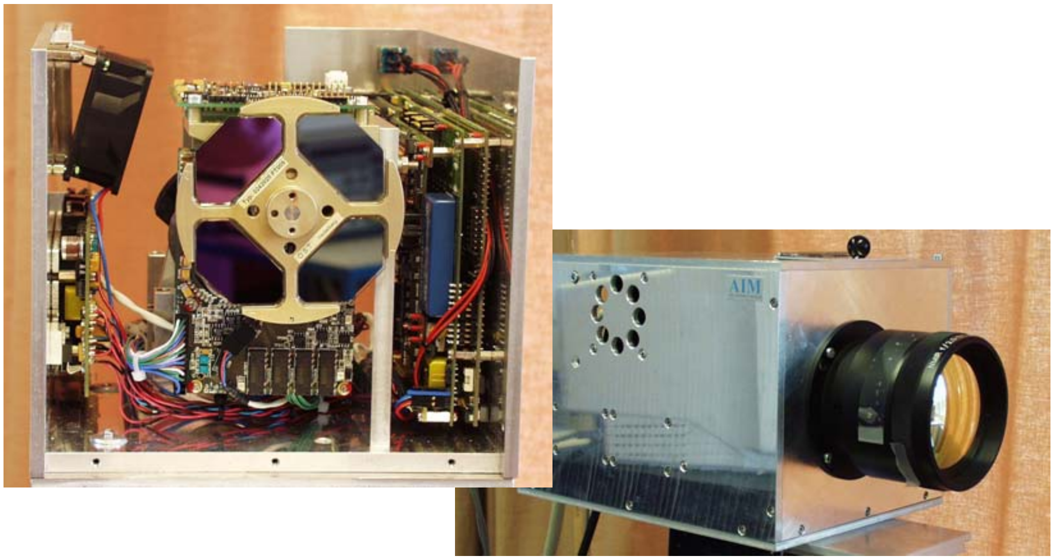

Fig. 15. Staring focal plane array with removable spinning filter wheel, sensitive in the spectral region 1.5-5.2 µm.

The detailed transmission properties of the optical filters depend on the application. In order to be able to optimize the filters, detailed know-how about target and background spectral properties are needed as well as validated modeling. For monitoring high altitude aircrafts from space using micro satellites, the altitude dependent water vapor content of the atmosphere can be used. In this way, aircrafts can be detected against a fairly homogeneous background. Such an instrument is shown in figure 16.

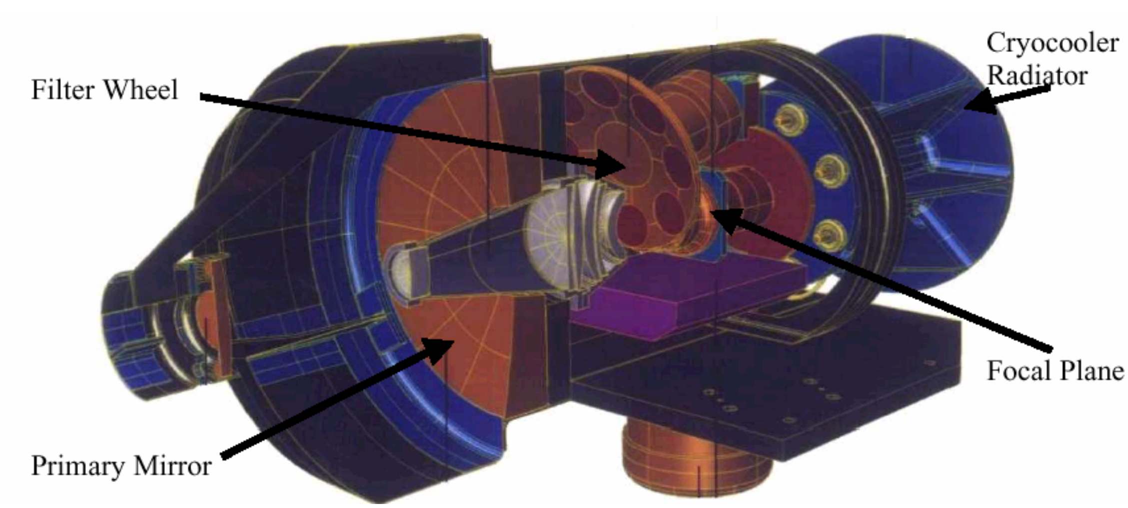

Fig. 16. Medium wave infrared imager has a 200 mm aperture F/2 Dall- Kirkham reflective telescope and a refractive relay lens system. The imager filter wheel carries filters for 4.3 to 5.15 microns and 5.4 to 6.0 µm wavelength bands as well as other wavelength bands.

The aircraft is detected by observing the changes in consecutive frames (optical flow). Small changes in the images can be observed and aircrafts detected from its motion. The aircraft direction and speed can also be extracted. An example is given in figure 17.

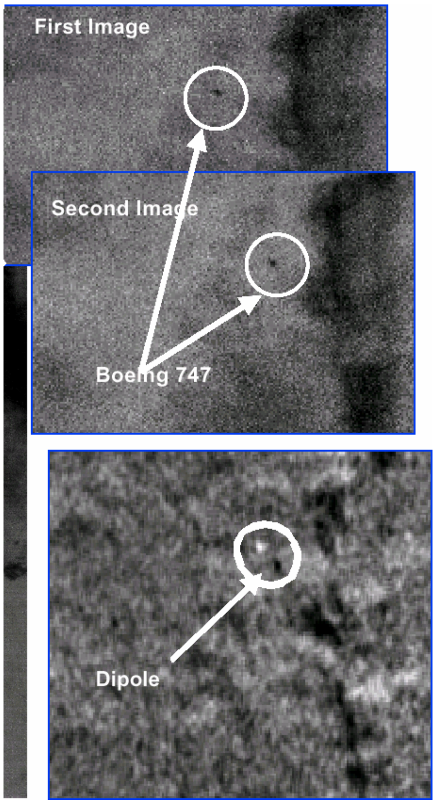

Fig. 17. Aircrafts are detected using a "frame differencing" technique, which compares two images taken over the same area at slightly different times. Dipole signal means only that the difference signal is both positive and negative.

The sensor should be optimized for the spectral regions where optimal contrast to the background can be obtained. For space applications, this can be very different from what is optimal at lower altitudes. The cold water vapor is used as a featureless background. The example shown above might not be the optimal wavelength region. The wavelength region around 20 µm is also interesting since the water vapor is highly absorbing in this region at lower altitudes and the target emission is substantial. This should result in an improved target-to-background contrast.

Tomographic imaging using rotating prism

A simplified form of tomographic imaging can be obtained by simultaneously recorded spectral and spatial information using a type II imaging with a rotating prism. Spatial and spectral information can subsequently be separated by considering multiple exposures with the prism in different orientations. The disadvantage with this method is that multiple exposures are needed in order to obtain the spatio-spectral result.

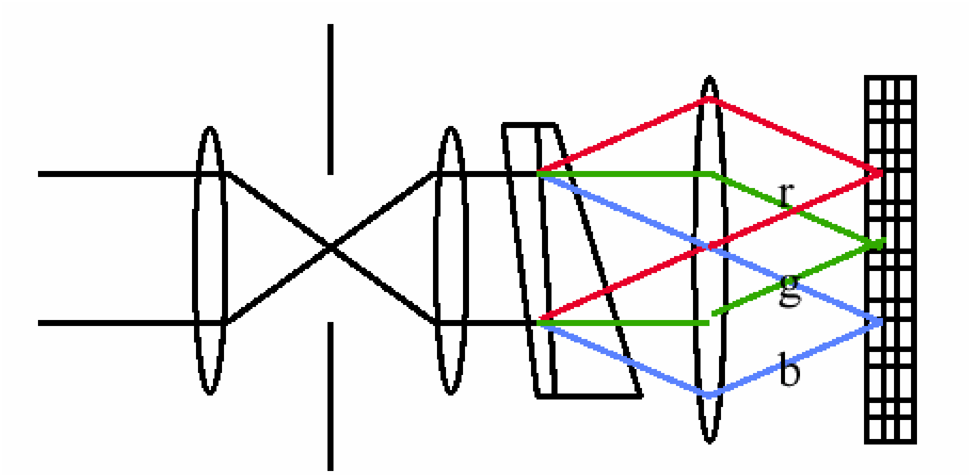

Fig. 18. Spatio-spectral diversity imaging design by Solid State Scientific Corporation using a rotating prism.

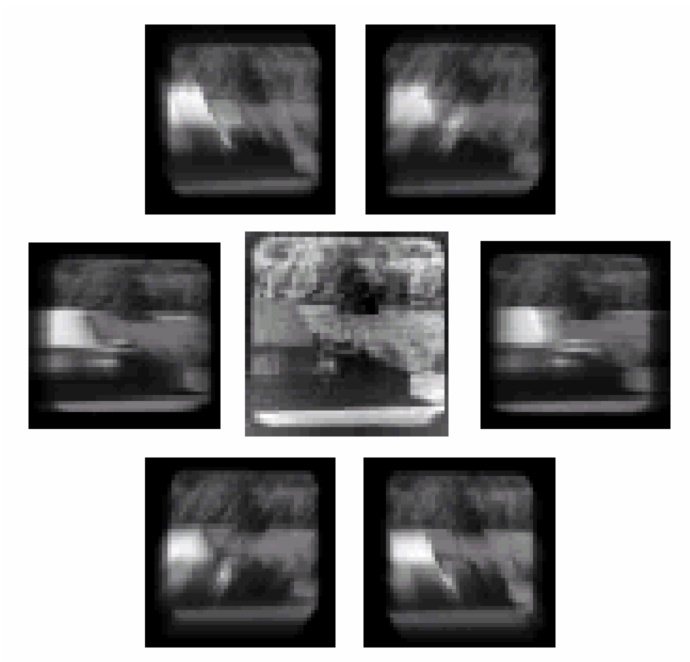

Fig. 19. Example of recording with the dispersive element in six different orientations. The image in center is a monochromatic version of the scene.

Tomographic imaging using holographic disperser

A high-speed imaging spectrometer, capable of simultaneous recording of spatial and spectral information has been developed by E. L. Dereniak et al[9]. The collected data is after image reconstruction in the form of a three-dimensional data set or an image cube. In this type of imager, a trade-off is simultaneously obtained between spatial, spectral and temporal resolution. The full spectral and spatial information is obtained within a field of view during a single integration time[10]. The dispersive element is derived from a computer-generated hologram (CGH)[11]. A larger degree of freedom in tailoring spectral passbands could be obtained if such elements could be obtained as volume holograms. At the moment, holograms with high efficiency in the first few diffraction orders can be designed. Even so, the information capacity of the focal plane array is not fully utilized.

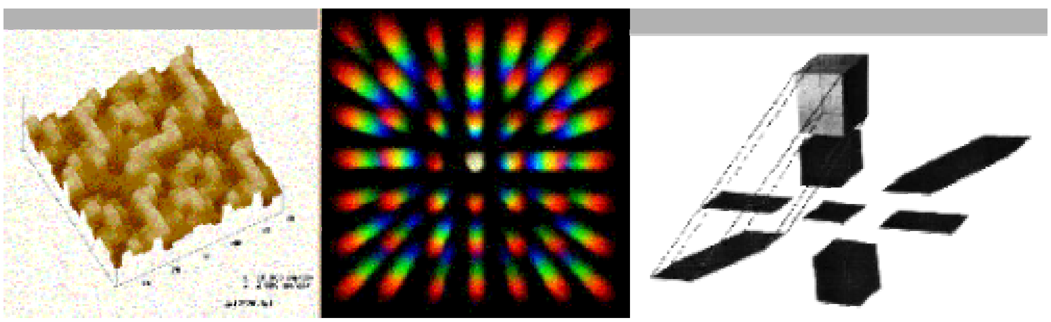

Fig. 20. Illustration of the dispersive holographic element, the corresponding spectral projection of that element and the tomographic representation of the data.

With this system, high-speed spectral imaging of a missile in flight has been demonstrated. The system is based on computed-tomography concepts and operates in the visible spectrum. Extension into the infrared spectral region is strait forward and has also been demonstrated.

Spectral imaging using diffractive focusing

Spectral discrimination can be obtained by using a very chromatic focusing element such as a Fresnel zone plate[12]. For a monochromatic wave, the element acts as a lens. The focal length will be inversely proportional to the wavelength. In an imaging application, the zone plate can be scanned thereby bringing one wavelength at a time into focus. The Fresnel lens is closely related to the Fresnel zone plate but here the design is intended to act as a refractive element but due to the 2π phase delay at each zone edge, also the Fresnel lens is highly chromatic in similarity to the zone plate. The spectral resolution of the system can be balanced by combining the Fresnel lens with refractive lens systems.

Fig. 21. Spectral imager using a scanning Fresnel zone plate.

White light Fourier-transform imager

Fourier transform spectrometers are routinely being used in field experiments. This technology is being upgraded to perform imaging multi-pixel transforms. Fourier transforms are normally based on the Michelson interferometer and are extremely computationally intense which has prevented this technology from real time realizations. A substantial problem is that the complete spectrum is recorded sequentially and temporal variations as well as dynamic scene variations will interfere with the spectral recording. It is therefore necessary to develop techniques where the complete spectrum is recorded simultaneously. This is mandated e.g. by the widespread use of spectral imaging in remote sensing using pushbroom-type scanning methods. From moving platforms, changes in viewing angles will also induce spectral noise. In order to obtain instant spectrum, a trade-off between spectral and spatial resolution has to be made.

Methods have been developed to produce white-light interference patterns. With this type of interferometer, low-coherence-length sources can be analyzed from the output pattern. Effective signal processing is needed in order to distinguish fringes when the SNR is low. One of the more successful ones is the Sagnac interferometer which is rather easy to align and quite stable. This type of interferometer is employed by the spatially modulated imaging Fourier transform spectrometer (SMIFTS)[13].

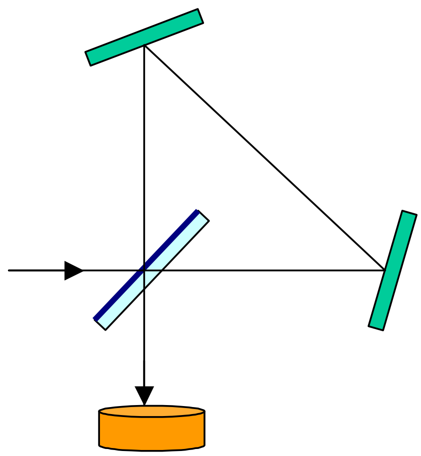

Fig. 22. Variation of the Sagnac interferometer.

In the SMIFTS sensor, a spatially modulated interference pattern is produced. This pattern is focused onto a focal plane array. The input field stop (i.e. the slit) is also imaged onto the detector using a cylindrical lens.

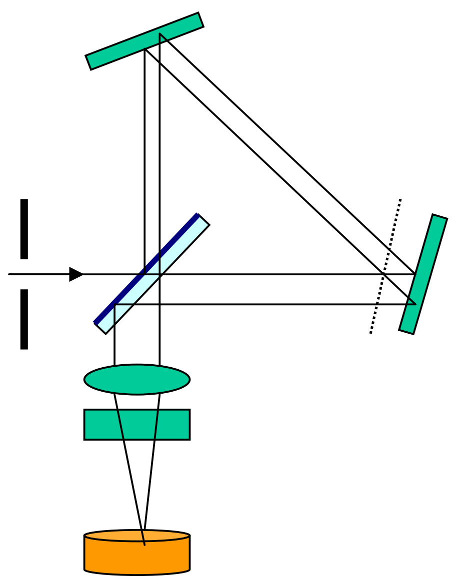

Fig. 23. Schematic of the SMIFTS sensor.

The spectral resolution can be varied using spectral pre-filtering and varying the imbalance of the Sagnac interferometer. The imbalance of the interferometer produces two laterally separated coherent images of the input slit that will interfere. The size of the slit will not affect the spectral resolution or the spectral calibration. Examples of demonstrated spectral ranges and spectral resolutions are a spectral resolution of 95 cm^{-1}, in the spectral region 1-5,2 µm and a spectral resolution of 35 cm^{-1}, in the spectral region 3-5 µm. The polarization behaviour can be rather complex and a calibration of the Stoke vector as a function of wavelength is needed as well as sensor calibration.

A further development of the SMIFTS concept is to abandon the slit and perform imaging on the detector. This is the high-efficiency hyperspectral imager (HEHSI)[14]. The images will have a stationary interference pattern superimposed and the image and changing the field of view will create the necessary variation in sampling needed for a spectral analysis.

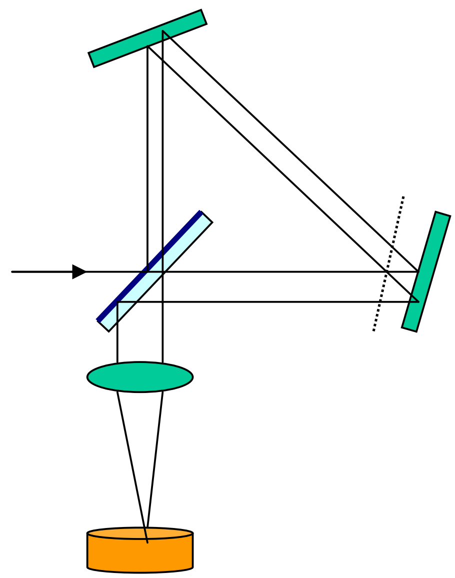

Fig. 24. The high-efficiency hyper spectral imager (HEHSI).

There are many variation on the Sagnac interferometer theme and there are still many alternatives that has not yet been explored. The phasefront can be studied by varying the off-set in the design described above making the concept applicable to stationary scenes. The phasefront within the interferometer can be varied using lenses, adaptive optics or holographic optical elements. This will allow the possibility to optimize the functionality with respect to detect very specific coherence properties within the scene.

Spectro-polarimetric imaging

It is possible to simultaneously measure both the spectral dependence and all four components of the Stokes vector using only a few passive polarization components. This type II imager is called a channeled spectropolarimeter system. In order to optimize such a system, close attention has to be paid to resolution, noise characteristics and data reduction requirements. An example of spectropolarimetric imager is the combination of polarization elements with the tomographic imager using holographic disperser described above. The radiation passes through two thick (high order) retarders and a polarizer. The polarization state will be strongly dependent on wavelength. This linear superposition of the Stokes component spectra is studied using an imaging spectrometer. With the proper choice of modulation frequencies, i.e. retarder thicknesses and materials, the Stokes component spectra can be separated in the Fourier plane. Inversion techniques have been developed that takes non-idealities as material dispersion and varying retarder thickness across the pupil into account. Figure of merits for such designs have also been developed[15].

Coherent imaging

The applications of coherent imaging have grown rapidly since the early laser technology. Especially over the last twenty years, the understanding of coherence properties and coherent imaging has improved. The major applications are utilizing fully coherent radiation from lasers with applications in e.g. testing, information processing, data processing and analysis, 3-D images and holograms. Lately, the understanding of how partial coherence can be used in target characterization has increased.

The coherence properties of the scene are determined both by the spectral properties of the target, the propagation properties of the atmosphere and the spectral and imaging properties of the sensor. If the coherence properties of a specific target are to be interrogated, care has to be taken not to conceal these properties by the choice of sensor properties. The measured spectral properties from broadband sources will be determined by the sensor transfer function. If there is a specific spectral feature that is distinguishing the target from the background, the coherence properties emanating from that feature might be possible to exploit. This feature is likely to be superimposed on a large background signal, why the dynamic range of the sensor system is of importance.

Astigmatic imaging

Astigmatic imaging will allow a wider range of properties to be sampled and processed besides the conventional image. Correlation between points can potentially supply independent data. An astigmatic coherence sensor (ACS) could be a practical solution for sampling the coherence function of the aperture[16]. The technique is related to phase diversity imaging. The basic function of the ACS is to be able to vary the focal length independently in the vertical and horizontal plane. This could be done using adaptive optics. A more restricted but practically simpler method is to introduce non-spherical lenses. The mutual coherence function will be sampled differently in the vertical and horizontal plane and by changing the orientation of the lenses, the mutual coherence can be deduced from the observed intensities in the focal plane. Since there is no need for aligning two different interferometric arms in this set-up, the sensor system is very insensitive to relative motion between the components.

Axicon imaging

The axicon is a holographic element that can produce a uniform optical intensity along the system axis within a specified region[17]. The imaging properties in partially coherent light have also been studied[18]. The specific interest here in this type of imaging systems is to be able to interrogate the partial degree of coherence in a compact system. This technique has not yet been proven but the imaging properties of the axicon shows very promising properties[19].

Adaptive optics

Hardware for adaptive optics implementation has been developed over the years for many applications. Components for phase control includes adaptive mirrors, liquid crystal phase modulators, phase-front sensors and beacon based techniques. The adaptive correction of phase distorted extended targets remains as one of the most challenging problems in adaptive optics. The major drawback is the lack of a reference wave front that represents the undistorted image. Partially this problem can be reduced by using phase diversity imaging. Already at weak turbulence, correction for the thin turbulent phase screen is difficult. For strong turbulence and long propagation paths the correction is further complicated by the small isoplanatic angle.

As an alternative, image sharpness criteria can be used for phase front correction. The real time performance of such systems is strongly dependent on image quality criterion and the amount of computation needed. The phase correction must be possible to derive in a time that is short compared to the effects causing the distortion. Criteria based on the power spectrum of the image can be rapidly obtained using optical information processing[20]. The correction might have to be focusing on specific regions of interest depending on the strength of the turbulence induced distortion.

Optical flow for turbulence corrections

Images are being degraded by space variant random, internal warping due to the effects of atmospheric turbulence[21]. The turbulence effect is particularly severe in horizontal path and slant path imaging. The warping as a function of image coordinates is determined from a time-sequence of short exposure data. Each frame is dewarped according to a shift map that represents an estimate of the warping function relative a template and the apparent internal motion is subsequently removed. There are four general types of numerical techniques being employed: correlation, gradient, spatiotemporal filtering, and Fourier phase or energy techniques. Correlation is the most common technique, but gradient implementations are often more efficient. Turbulence is observed to be intermittent, i.e. the turbulence magnitude and spectrum varies with time. Local high frequency turbulence can result in suppression of the high frequency optical transfer function. For these cases, monitoring the data quality and down-weighting or removal of intermittent high frequency perturbation might be an option. Atmospheric turbulence will also introduce a random micro-scanning effect and sub-pixel displacement estimates can be used for image quality improvements. Since the gradient algorithm relies on the assumption of constant intensity, intensity-fluctuations and noise can introduce errors and consequently degrade the restoration quality. This effect can be of increased importance in the thermal infrared spectral region. It might be possible to build in constraints to the motion vector map based on the temporal statistics of atmospheric tilt[22].

Optical flow for 3-D imaging

Two dimensional Fourier transforms are well established in image analysis. The 3-D Fourier transform is less studied with respect to 3-D imaging. A reason for limited interest is the very large computational demand that follows with this type of signal processing. There might however be possibilities to bring about ultra-high speed processing using optical correlators[23]. With this type of processing capability, real time passive 3-D imaging might be feasible.

Restoration using information theory

In an imaging system, the optical system parameters are being optimized with respect to certain criteria. The most common parameters are the optical transfer function of the lens and photodetector. Other important parameters, commonly disregarded in optical system design, are sampling effects such as aliasing and quantization noise due to the digitization process[24]. Since most systems of interest are sampled imaging systems, these effects must be considered. The sampling artifacts are inherent to all such systems and new methods of evaluating the information capacity of such systems must be developed. The image acquisition/reconstruction process is illustrated in the figure below.

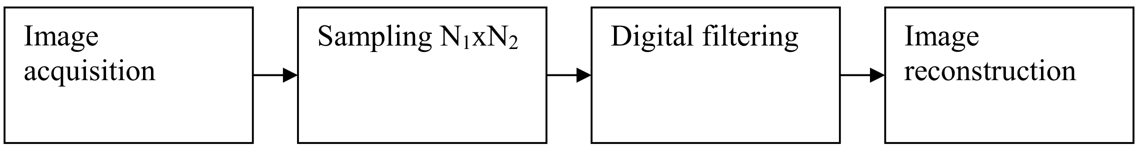

Fig. 25. Illustration of the acquisition/reconstruction process.

The image acquisition process involves atmospheric turbulence and the point spread function of the lens and photodetector aperture. This process is described by the circular convolution of the image s with the combined point spread function h,

$$g=s*h$$

where * is the convolution operator. The quantisation and sampling is given by

$$p=Q(g)\,\text{Ш} + n_e$$

where Q represents the quantization operation which converts the continuous input signal g to at quantized signal producing the quantized signal

$$g_q=g+n_q$$

where n_q models the quantization noise. Ш represents the sampling operator which samples the image at $(n_1\xi_1, n_2\xi_2)$ with constant intersampling distances (ξ_1, ξ_2) where (n_1, n_2) is the corresponding pixel number. The quantized and sampled image can now be written as

$$p=g+n_a+n_q+n_e$$

where n_a has been introduced due to aliasing artifacts[25]. The image consists of a blurred version of the original scene sampled at discrete locations and noise terms due to aliasing, quantization and electronic noise. The restoration filter should be designed to minimize the impact of these noise terms. The Wiener restoration filter (WRF) is often used for this purpose. This filter can be implemented if the optical transfer function (OTF) and the power spectral density of the radiance field from the scene (PSD) is known. In the Fourier domain, WRF is given by

$$\Psi = \frac{\Phi_s H^*}{\Phi_s |H|^2 + \Phi_a + \Phi_q + \Phi_e}$$

where Ψ is the restoration filter and Φ_a, Φ_q, Φ_e are the PSDs of the aliasing, quantization and electronic noise respectively. *H* is the OTF of the imaging system. The PSD of aliasing noise is defined by $\Phi_a = \Phi_s |H|^2 [F(Ш)-\delta(0,0)]$ where *F*(Ш) is the Fourier transform of the sampling operator.

The Shannon information capacity of the imaging system can be formulated as the mutual information between the radiance field s and the sampled image p, which can be written as

$$I_{Sh} = \int_{-\omega_c}^{\omega_c}\int_{-\omega_c}^{\omega_c} \log_2\left[1 + \frac{\Phi_s |H|^2}{\Phi_a + \Phi_q + \Phi_e}\right] d\omega_1 d\omega_2$$

where ω_c is the Nyquist frequency. It is possible to make some general estimates on the effect of the various noise terms if some assumptions about the scene and the optical system is introduced. It has been observed e.g. that the earth when imaged from space can be described by

$$\Phi_s = \frac{2\pi\sigma_s^2\mu^2}{\left[1 + 4\pi^2\mu^2\left(\omega_1^2 + \omega_2^2\right)\right]^{3/2}}$$

where μ is the mean average detail in the scene with respect to intersample distance and σ_s is the standard deviation of the radiance field. Calculations can be further simplified when the OTF can be approximated by a Gaussian as

$$H = e^{-\frac{\omega_1^2 + \omega_2^2}{\rho_c^2}}$$

where σ_c is the 1/e point of *H*.

SNR depends on detector size. Modern digital cameras are advertised with the number of pixels (megapixels) as a direct measure of resolution. The amount of information in a picture depends not only on the number of pixels and the corresponding angular resolution, but also on the signal to noise ratio. Therefore the improvement by reducing the pixel size is limited[26]. This is illustrated in the figures below where an original picture has been degraded, first by simulating a low SNR situation and then improving the SNR a factor two by increasing the detector size by a factor two. The noise for different types of detectors scales differently depending on the type of detector. A detailed noise model has to be employed when simulating image quality.

Fig. 26. Original image showing the Rocky Mountains.

As long as the modulation transfer function has sufficient bandwidth, smaller pixel size can result in better resolution. Under low light conditions, the smaller pixels collect less radiated power, which leads to noise-corrupted grainy images. As a result, fewer pixels with better signal-to-noise ratio might be preferred. The useful content of an image is often quantified by the space-bandwidth product of the image and is specified by the area of the image divided by the resolution of the optical system. As discussed above and illustrated below, the signal-to-noise ratio must also be considered. What can be observed is, that there are situations where the information capacity first increases for smaller pixels and than reaches a maximum and starts to decrease with the increased level of detector noise. Ideally, it would be advantageous to be able to change the detector size with the variation of scene radiation. This is of course not practical. One step in this direction is to be able to bin pixels directly in the detector read out in order to somewhat improve on the signal-to-noise ratio. This is of special interest in e.g. low light level applications.

The issues discussed above can most likely be generalized to other sensor parameters such as spectral and polarimetric resolution and the consequences on the total information capability when these parameters are being varied. The information capability approach can be further generalized by invoking features as the information sought for and using a Markov chain approach. Now, *a priory* information will contribute to the total information content, causing an increase in the amount of information. Until now, these issues have not been considered when designing optical systems. The theory is not yet well developed for this approach and there are a lot of research opportunities in this field. With the development of adaptive systems for automatic or aided target recognition, these issues will be still more relevant.

Fig. 27. The same angular resolution as the image above but half the SNR compared to the image below.

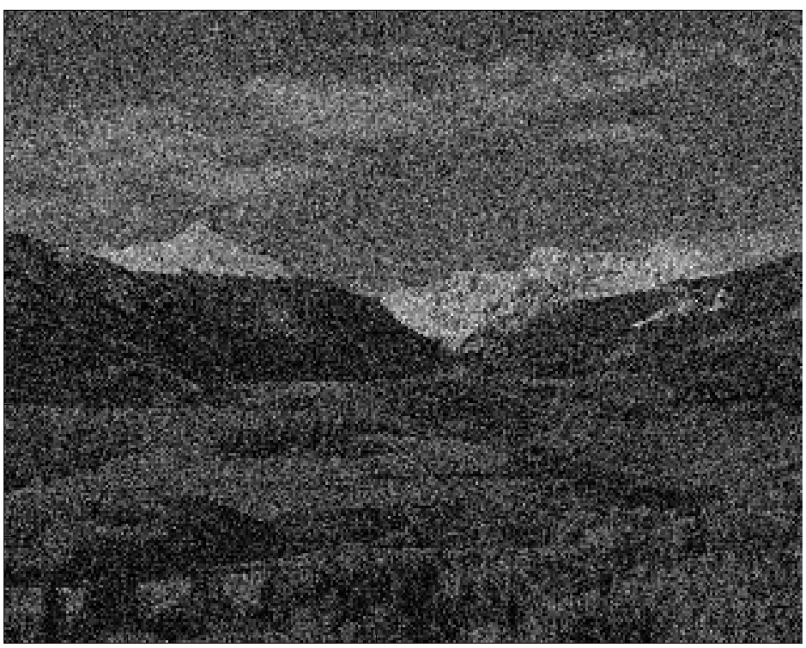

Fig. 28. Half the original angular resolution but twice the SNR compared to the figure above.

Sensor network tomography

As imaging sensors and embedded processors drop in price, smart and distributed sensors will be deployed for surveillance. Both sensors requiring illumination (CMOS) and thermal infrared sensors (un-cooled) can be used in many situations of tactical interest. By setting up a number of imaging sensors that are viewing a region of interest from different perspectives connected with wireless communication, three-dimensional surveillance can be obtained. Processing capability for tomographic volumetric modeling[27] is achieved by using a networked system. The rapid development within the IT community in the area of image compression and distribution as well as low-power personal digital assistants makes this application very affordable.

Discussion

Infrared and electrooptical imaging technologies are still rapidly developing both with respect to capability and with respect to affordability. Available technology is influenced by the progress in nano-technologies. Focal plane arrays are improving in both number of pixels and spectral diversity. The optical phase front can be manipulated in detail using MEMS techniques. More general imaging concepts can be realized by combining general optical transfer properties with advanced signal processing. This will bring about a new class of adaptive imaging instrument based on computational imaging. These capabilities will lead to improved detection and classification capabilities and will also put a question to stealth technologies.

Applications of these new capabilities will be found at all tactical and strategic levels, from the individual soldier to the space based reconnaissance sensor. Low weight and small volume requirements will also require innovative use of the new technologies varying from close range support to micro satellites. The time factor is of vital importance and improved identification capabilities will serve the defense greatly. The sensor systems are at the heart of the network systems now being anticipated and all concepts now being discussed will rely on efficient and effective sensor systems.

Even if the new technologies being developed in research laboratories look very promising, the realization of all that promise is likely to take time. It takes a major effort to bring a laboratory device into a commercial component and into a rugged system. The MEMS technologies still have many practical problems to solve such as reliability and long time before failure. Signatures have to be better understood in order to be able to optimize the multisensor systems. Signature and measurement intelligence is vital for target acquisition and identification. With all these things in place, the new technologies can be brought into useful work.

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