Remote sensing solutions for when spectrometers no longer are affordable

Hedser van Brug and Huib Visser

TNO, Stieltjesweg1, Delft, the Netherlands

ABSTRACT

This paper describes one of the issues that are facing the remote sensing community in the not so far future; scientists ask for certain requirement that can not be fulfilled either due to cost issues or technological issues. The paper starts with giving a short and quick historical overview of the development of spectrometer based remote sensing systems. Next, the likely end of the spectrometers will be explained, followed by a possible alternative.

Keywords: Remote sensing, Spectrometers, Imaging

1. INTRODUCTION

Remote sensing of the Earths atmosphere started with a single pixel detector, a scanning mirror and a band filter. The scanning mirror provides the Swath coverage while the band filter yields selectivity for the gas being monitored. Sampling in the flight direction was obtained with time.

Years later linear array detectors became available and the era of the spectrometers began. These systems still required a scanning mirror to obtain some Swath coverage. The pixels of the linear array detectors were used to record a spectrum.

With the introduction of the 2D detector arrays the scanning mirror was no longer needed and a narrow strip on Earth was imaged onto the entrance slit of the spectrometer, which is then dispersed onto the detector where one dimension is used for the spatial direction while the other is used for the spectral direction. The remaining spatial dimension is covered by flying over the Earth, i.e. it is covered with time.

One of the issues in spectrometer based remote sensing instruments is the fact that the spatial resolution in the flight direction is directly linked to the integration time. The typical speed at which the satellites moves over the Earth is 7km/s which means that for a 0.5s integration time the sampling distance already is 3.5km.

Another major issue with spectrometers is that scientists ask for ever improving spectral resolution. A spectral resolution of 0.1nm is nowadays a relaxed requirement, often far smaller spectral resolution numbers are asked for.

The final issue to be pointed out is the increase in signal to noise ratio (SNR) that is aimed for. For a good SNR the intensity that is available for the measured signal should be high enough. This intensity level is dropping due to narrower bandwidths and shorter integration times due to higher spatial sampling. The higher SNR is required to get more precise measurements but the spectral and spatial requirements make it virtually impossible to arrive at high SNR levels.

The result is that the instrument will increase in size due to the fact that smaller f-numbers for the optics are required. These larger instrument will be heavier and more costly and most likely the cost will become unacceptably high in the near future.

Owing to the fact that spectrometers have been used in the past decades gives us insight in what is actually needed in the measurements. This knowledge allowed us to think about other ways of measuring the concentration of trace gasses in the atmosphere.

Further author information: (Send correspondence to Hedser van Brug)
E-mail: eddy.vanbrug@tno.nl, Telephone: +31-888668055

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For all remote sensing measurements the presence of clouds has to be monitored, for which a simple cloud sensor module will be presented. For the actual trace gas measurement an interferometer based method will be presented. Some trace gas measurements are hindered by the presence of aerosols in the atmosphere. For the measurement of the aerosol effect a third type of module, that measures the degree of linear polarisation, will be presented.

Since the explanations will be too long in case the modules would be described in full detail, only the principles of the three modules will be presented.

2. EXAMPLE: MEASURING CO_2

As an example of a task for which a standard spectrometer is not well suited the measurement of the concentration of CO_2 in the Earths atmosphere is discussed. The difficulty in measuring the concentration of CO_2 is twofold. First of all, the spectral density of absorption lines is very high leading to the requirement of a very high spectral resolution in order to resolve those narrow features, and second, in order to arrive at an accurate concentration number the measured intensities will have to be corrected for aerosol effects and the presence or absence of clouds. Besides that, the spectral features of CO_2 are always polluted by e.g. features due to CH_4 and H_2O, for which has to be corrected as well. This means that several spectral bands have to be measured some of which need a very high spectral resolution.

If the requirements for spatial resolution are increasing as well as the spectral resolution, the system will become too large, due to decreasing f-number, and thereby unaffordable.

3. PROPOSED ALTERNATIVE

The alternative we like to propose is to use an imager, an actual 2D camera, that records two or more images simultaneously. From these recorded images, e.g. the gas concentration, the presence of clouds, or degree of linear polarisation can be calculated. Behind the telescope, but before the imager, a splitting element should be present that splits the incoming beam, into either spectrally different beams, or in polarisation selected beams.

The most important point to me made is that the integration time can now be increased by using a TDI scheme (time delayed integration). Either by using a TDI detector, or by adding the appropriate pixels in software. The pixel size on Earth can now be as small as wanted while still having high enough signal levels. In principle the number of pixels added is only limited by the number of pixels on the detector in flight direction.

In the following subsections first the cloud sensor and next the trace gas sensor will be described, both in which the beams are filtered in terms of spectral content. The third and last example of a camera based sensor is a polarisation sensor in which the split images will differ in state of polarisation, i.e. each of the recorded images contains a different part of the incoming beam.

3.1 Cloud sensor

The cloud sensor we propose consists of a telescope which has a field of view both in the swath and flight direction, and an imager. The imager requires a long free working distance that is preferably tele-centric. The systems measures scattered light from the Earth and its atmosphere near the O_2A band. The idea is to measure the intensity adjacent to the absorption peak and in the absorption peak. The ratio between these two numbers gives information on the absorption strength and thereby of the effective path length. In case of clouds the effective path length will decrease strongly resulting in reduced absorption. This sensor will thus give both information on the presence of clouds as well as the cloud height.

In the tele-centric image space first a broad band-filter is placed, see Fig.1 (top) that limits the transmitted wavelength band to a width of 40nm (FWHM) about the central wavelength of 765nm. This 40nm bandwidth beam enters a beam splitter where on the splitting interface a narrow band-filter is placed, see Fig.1 (bottom), having a 20nm (FWHM). The transmitted beam of this splitter will contain the wavelengths that are transmitted by the narrow band-filter, while the reflected beam will contain the wavelengths inside the broad band-filter but outside the pass band of the narrow band-filter, i.e. the adjacent wavelengths of the O_2A band. The 20nm narrow band-filter is thus used to create the two simultaneous images of the Earth scene being measured where per pixel the intensity difference between the images yields information on the presence and if present, on the height of the clouds. Using this band-filter arrangement the intensity of corresponding pixels in the two images will be about equal for very high clouds and the ratio will be about unity. For cloudless pixels, or very low clouds, the ratio between the corresponding pixels in the two images will be higher.

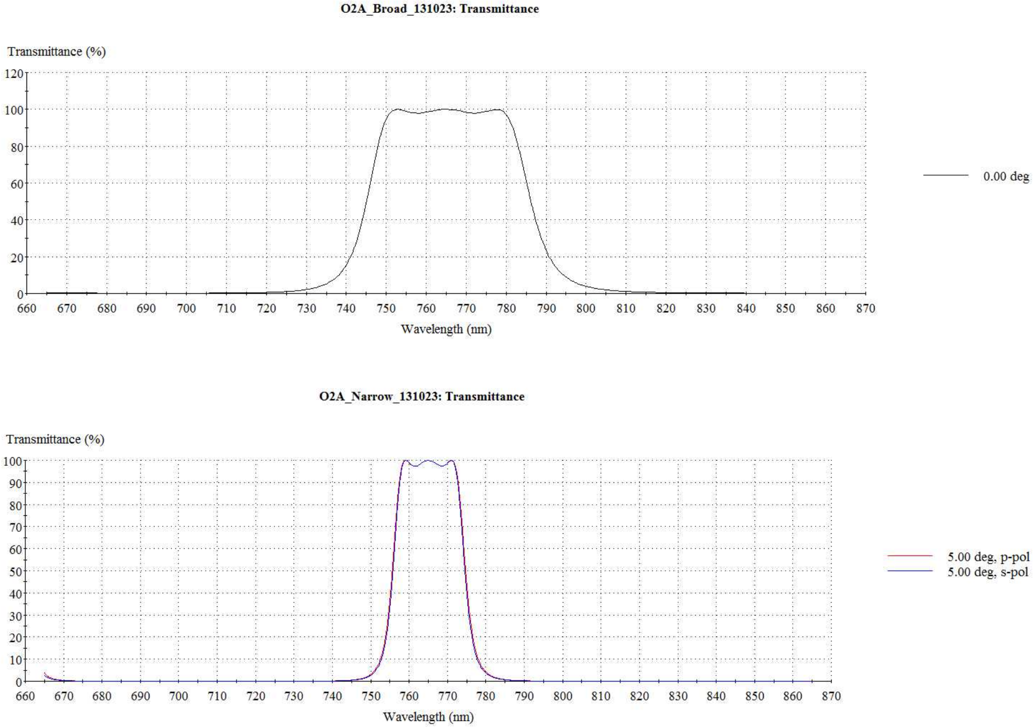

Figure 1. Transmission of the broad (top) and narrow (bottom) band filter as a function of wavelength.

The discussed approach to measure the presence of clouds can also be used to measure the concentration of H_2O in the atmosphere near the 1.4μm wavelength.

3.2 Trace gas sensor

The proposed trace gas sensor is referred to as HIGS (Huib's Innovative Gas Sensor). Just as for the cloud sensor, the idea is to measure two images of the same area of the Earth simultaneously, where the spectral content of those two images is different in such a way that the ratio between the images gives information on the concentration of the gas being measured. This ratio can be determined on a per pixel bases and will therefor result in a high spatial resolution concentration map.

The idea for HIGS came from looking at the absorption features of e.g. CO_2 and NO_2. These absorption features show, over a limited spectral range, a more or less periodic absorption pattern. The objective is to get the intensity in the absorption dips to one detector while the intensity of the spectral parts between the dips is guided towards the second detector. As filter an interferometer is being used where in one of the interferometer arms an optical path difference (OPD) is created that is chosen such that the spectral period of the interferometer throughput equals the periodic structure of the gas being measured.

The presented system is similar to the Fabry-Pérot sensor that have as drawback that they can not accommodate a large field of view. The best systems to compare HIGS with are the Fourier Transform Spectrometers. In an FTS the spectrum is measured by monitoring the intensity while the OPD in the interferometer is being scanned. The HIGS system employs a fixed OPD setting and will thus not measure a spectrum but only the spectral content pertaining to that selected OPD setting.

The required OPD can be determined via

$$\mathrm{OPD} = \frac{\lambda_0^2}{\Delta\lambda} \tag{1}$$

in which λ_0 is the central wavelength of the spectral band being measured, and where $\Delta\lambda$ is the spectral period of the absorption features of the gas being measured. As an example; in case of measurements on CO_2 in the wavelength range between 1567nm and 1574nm (i.e. in the SWIR 1 range), the central wavelength equals 1570.5nm and the spectral period is about 0.306nm, and thus the OPD has to be 8.06mm. For the CO_2 absorption figure, together with the in-phase and out-of phase interferometer filters, see Fig.2. From this figure it will be clear that the allowed bandwidth should be limited since the matching of the absorption features with the interferometer throughput period is only good within a limited wavelength range. To this end a bandpass filter is added to the system.

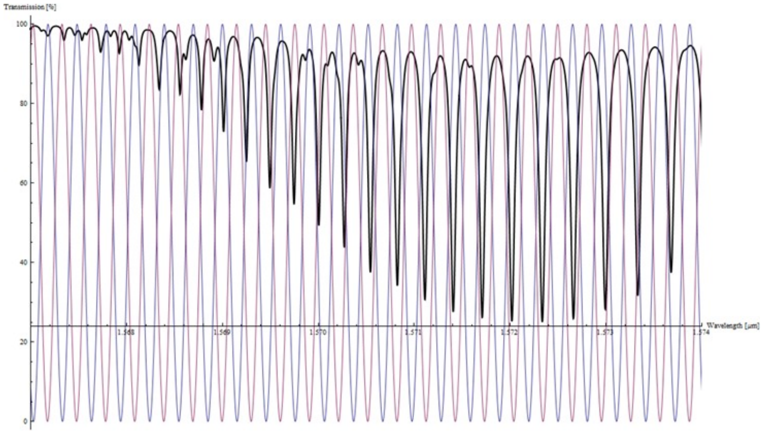

Figure 2. CO_2 transmission spectrum shown together with the two filter functions for the two interferometer outputs.

The resulting intensity obtained in the two images on the detector is given by

$$I_{a,b} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left(\frac{\mathrm{OPD}}{\lambda} \times 2\pi + \delta_{a,b} + \delta_0\right) \tag{2}$$

where the subscript a indicates that the pertaining image receives light from the wavelengths at which absorption occurs, while the b designated images receives light from the wavelengths between the absorption features. The quantity δ_0 in Eq.(2) is required to get the interferometer features to overlap with the absorption features being measured. The δ_a value can be zero which will lead to a $\delta_b = \pi$, meaning that the two images are out of phase. This π phase step is automatically obtained in case a Mach-Zehnder type interferometer is used. In case of a Michelson interferometer an intensity splitter is required to get two images out of the interferometer where for one image in one arm of the interferometer a π phase step is added, see Fig.3. In this figure SPL stands for splitter, IFM for interferometer, WDG for wedge and finally, DET for detector. On M_1 the additional height step can be seen to give the pertaining image a phase step of π.

Figure 4 shows the demonstrator of a HIGS system to monitor the concentration of NO_2 in the air. A telescope with a 10° field of view was used. The layout of the interferometer of this demonstrator is as shown in the sketch of Fig.3. Using this demonstrator the HIGS principle was shown to be working.

3.3 Polarisation sensor

As polarisation sensor we propose the system as shown in Fig.5. The acronym for this system is ASPIM; Aerosol Scattering Polarimetric Imager. The shown system was designed for measuring the degree of linear polarisation in approximately the same band as the CO_2 concentration was measured. The idea is that when the effect of aerosols is measured close to the wavelength at which CO_2 is being measured the correction for those aerosol effects will be easiest and most accurate.

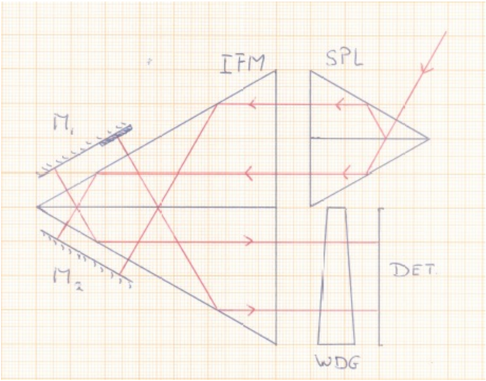

Figure 3. Sketch of the layout of Michelson based HIGS system where all powered optics has been left out.

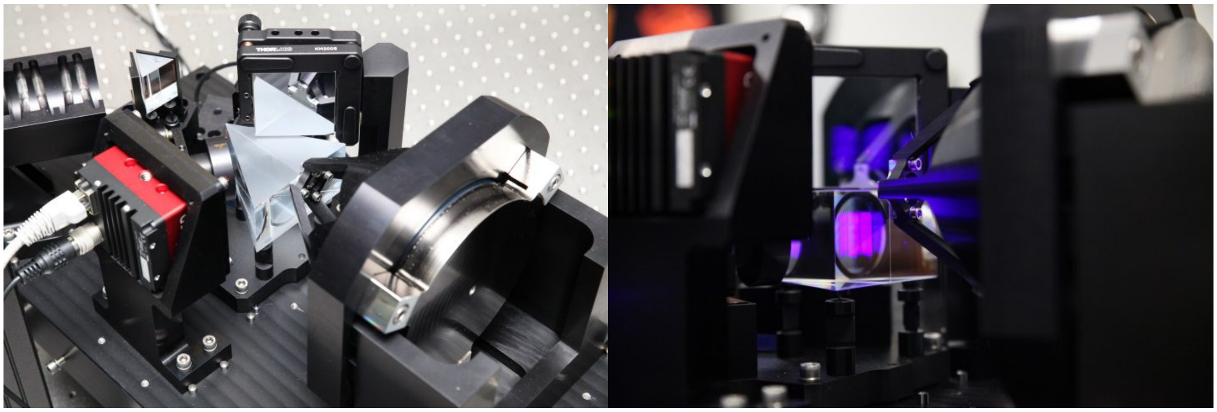

Figure 4. Impressions of the HIGS demonstrator.

The shown system has a Field of View (FoV) of circular 52° radius. In this way a 104 degrees Swath is obtained as well as a 104 degrees viewing angles in the flight direction. Suppose that an angular sampling of 2 degrees is asked for, then 52 independent viewing directions are obtained. Each ground pixel can be co-added for about 5 seconds yielding a good Signal to Noise Ratio (SNR).

The measured signal is guided through a band filter with a bandwidth of typically 30nm, where the central wavelength is selected such that no strong absorption features are present in the used bandwidth. The imager of the system was designed to yield a large tele centric image space where the polarisation optics could be inserted.

The polarisation optics consists of all flat optics, i.e. without any optical power. The first element encountered is a power splitter that splits the incoming beam into two equal intensity output beams. In one of the output beams a polarisation splitter is place with its splitting surface equally aligned with the power splitter surface, thus yielding two images, one with the polarisation in the horizontal direction, the other with the polarisation in the vertical direction. The other output of the power splitter is first guided through a intensity corrector, equalising the throughput of the s- and p-component, and next guided through a polarisation splitter that is rotated 45° about the propagation direction. Via this path two other images are obtained, one with its polarisation vector under 45° and the other under -45°.

Using this polarisation optics layout four linear polarised beams are measured simultaneously from which the intensity ratio between the images gives information about the Angle of Linear Polarisation and the Degree of Linear Polarisation.

A system in which the shown polarisation module is complemented with other modules that each measure in a different wavelength range, is a very powerful tool for measuring aerosol characteristics. The shown module uses four independent detectors, which yields the maximum number of pixels per image. If ground resolution is

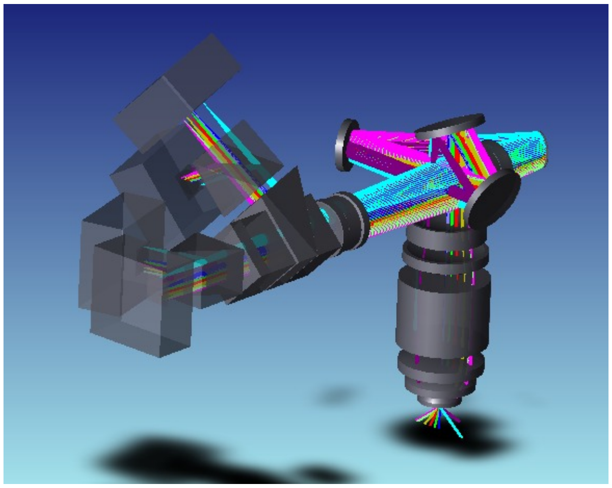

Figure 5. Artist impression of the ASPIM system.

less of importance than module cost, the number of used detectors per module can be reduced by changing the optical layout.

During the design of this module care was taken that the throughput of each component was to a high degree equal for the s- and p-polarised part of the light, and that no large differences in phase for the s- and p-polarised part occur.

4. CONCLUSIONS

This paper points out that system requirements will be given for which the standard approach no longer works. In case a spectrometer is used, the design will become large, heavy and costly, and all to a high degree.

An alternative is presented. By using the knowledge obtained by many years of measuring with spectrometers, focus now on those feature in the spectra that are actually containing the information that is looked for and measure those parts using an imager where the image is split in a number of independent images where the number of images depends on the quantity being measured.

For an instrument build up with modules as presented in here, a low resolution spectrometer might still be useful to gain insight in the continuum just outside of the absorption features.