New user interface and features of the SR 5000: revival of infrared CVF based spectroradiometry

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ABSTRACT

The SR 5000 Infrared spectroradiometer, developed in the mid ‘80’s, is a robust research tool for the electro-optics system development laboratory. It has been the top-of-the-line IR spectroradiometer since then, with high sensitivity and useful software packages for data analysis, but its user interface became outdated, because of the enormous advances that personal computers underwent in the 90’s. Recently, after being on the verge of disappearance, CVF based spectroradiometry has been revived.

Here we present some important new features of the system:

1. Synchronized imaging.

A CCD camera is boresighted with the line of sight of the SR 5000, to digitally record the image of the measured object and its background, in synchronization with the spectral measurement. This feature is useful in the field to avoid mishaps, and sometimes for later analysis of the results.

2. Windows Operating System.

The new system control, storage and analysis software package has been developed to take advantage of modern PC’s, generally accepted user interface modalities, and a powerful database for file management.

Keywords: UV, Visible, Infrared spectroradiometry, spectral signatures

1. HISTORICAL INTRODUCTION

For more than 25 years, IR spectroradiometry has been an important field of IR Remote Sensing, and has been consistently served by a number of commercial Circular Variable Filter (CVF) and interferometer based spectroradiometers. Spectroradiometers in the 80’s were to multi-band radiometers what hyperspectral imagers today are to multi-band imagers: they represented a transition from low spectral resolution (a few spectral bands) to medium-high spectral resolution (0.1 to 2-3% of the wavelength), in single pixel quantitative measurements of self-emitted radiation. The Manual of Remote Sensing[1], published in second edition in 1983, Volume 1, page 324, classifies spectroradiometers into four types: Filter-Wheel, Prism, Grating and Fourier Transform, each one with its own advantages and disadvantages, both in performance and in practical applicability for specific applications. The definition of an IR spectroradiometer is an instrument that measures the absolute amount of radiation emitted by an object as function of wavelength in units of spectral radiance (Watts/cm^2/sr/μ). Traditionally, this is done by comparing the measured spectrum of the object with the known spectral radiance emitted by an ideal blackbody, approximated by a “real life black” radiator. (A “real life black” radiator is defined here as an object that simulates an ideal blackbody as closely as possible). The accuracy of the measurement is strongly affected by the accuracy with which the “real life black” radiator simulates the ideal blackbody. Figures of merit and system performance models for spectroradiometers, as related to the type of optics and detectors used, were known and published in the 70’s; see for example Chapter 20 of The Infrared Handbook[2] by W.L. Wolfe and G.J. Zissis, published in 1978 by the Office of Naval Research, Dept. of the Navy, Washington DC, and in Reference 1, pages 331 and 332.

The most popular applications of IR spectroradiometers during the 80’s and 90’s can be classified in grand lines as follows: i) Spectral signatures, used for object identification, based on the information present in the object spectral emissivity and apparent temperature, ii) Sky radiance[3] and long path (from 1 to 44 Km.) spectral atmospheric transmittance[4], used for the interpretation of the IR signals received by IR sensors in the open field, and iii) characterization of artificial sources[5], used for development and production control of specialized sources such as Forward Looking IR (FLIR) test equipment, Electro-optical countermeasures (ECM), etc.

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In the early 80's, before the adoption of PC's by the industrial community, CI Systems entered the field of IR Spectroradiometry by developing its first product, the SR 1000 spectroradiometer, precursor of the SR 5000 (Figure 1). The signal processing electronics consisted of an analog electronic control unit for spectrum display on an oscilloscope, and of a pioneering digital unit (SR 2000) based on a then new Motorola microprocessor, whose function was to provide basic spectral calculations, such as spectral averaging and subtraction, needed for data analysis, and an output for recording the spectra, such as then popular analog plotters.

Figure 1: Bob Buckwald, co-founder of CI Systems with Dario Cabib, operating the SR 1000 and 2000 system in the year 1982.

The SR 1000-2000 combination represented a significant progress of IR Spectroradiometry at the time, because it was the first IR spectroradiometer turn-key system, a highly sensitive and convenient measuring system for lab and field use, but the most important of CI's contributions in this field concerned the optical performance of the instrument. In fact, the Newtonian collecting optics, combined with a refocusing ellipsoidal mirror in front of the detector (Figure 2), was a very economical layout, resulting in small signal losses, and in a more uniform response across the 6 milliradian field of view (FOV), than other contemporary instrumentation.

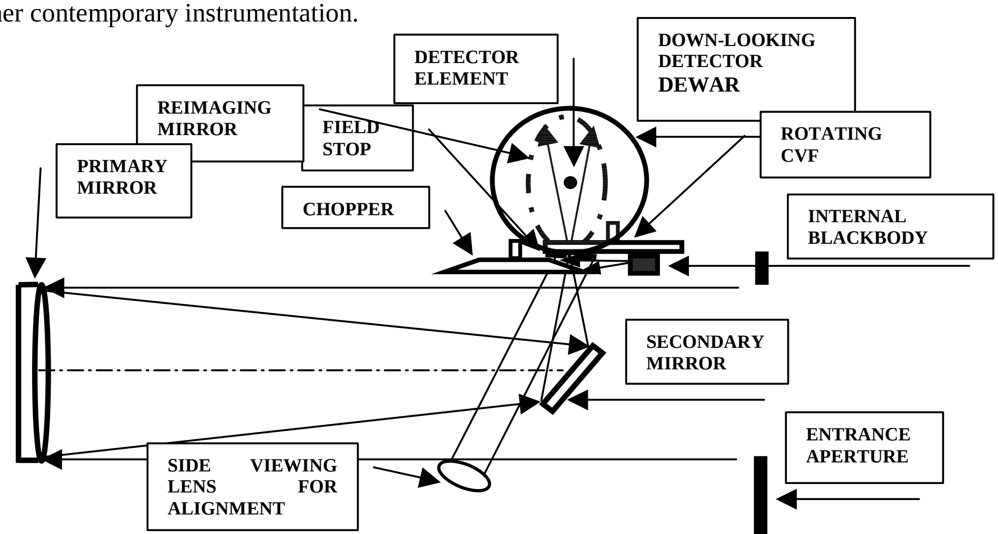


Figure 2: Optical layout of both the early SR 1000 model, and the later 5000 IR spectroradiometers.

The SR 5000 (introduced in 1985) represented a significant advance with respect to the SR 1000, by virtue of the fact that the PC (under the DOS operating system) was adopted as an integral part of the spectroradiometer: it replaced both the analog control unit and the SR 2000 processing unit, thereby reducing the instrument footprint, and in addition, it allowed data display, storage and more advanced processing. The DOS based software (called simply "SR5000") was very robust, fast, and easy to use: it provided, among other capabilities, the means to set the measurement parameters, record the results, operate arithmetically on the spectra, compare them with blackbody curves, and export them to a standard text format for use by other programs.

The CVF based IR spectroradiometers remained in use in this configuration through the '90's, until two changes took place during that period of time: i) Windows became by far the most widely used and affordable PC operating system, supplanting DOS and beating other competing ones, and ii) suddenly, in the year 1999, Optical Coatings Laboratory Inc. (OCLI), of Santa Rosa, California, decided to stop manufacturing the CVF. Until then, OCLI was the only commercial manufacturer of such optical element, so central for the operation of this type of spectroradiometer. As a result, the CVF based spectroradiometry became doomed to almost immediate death. CI and other companies continued to manufacture such instruments for a period of time, by using up the CVF stock they had purchased previously, but this could only be a short-term solution.

In the following sections we will describe the most important aspects of the CVF based IR spectroradiometer and the new Windows OS.

2. RENEWED INTRODUCTION OF THE CVF BASED IR SPECTRORADIOMETER

At this point, in the year 2000, CI decided that it would make an effort to look for alternative sources of CVF's, and that if the effort turned out to be successful, then the company would embark in the development of a new Windows based software package for the SR 5000: in fact, few people by now knew the use and were willing to learn to use DOS based programs. As a result of this effort, after a period of time, a new source of CVF's was found, and CI started the development of its new Windows based software package, again called "SR 5000".

This was a perfect occasion for CI to add and improve certain features, which were long time missing, but whose development became worthwhile only after the viability of the revived product was proven.

3. THE MOST IMPORTANT ASPECTS OF THE SR 5000 IR SPECTRORADIOMETER

CVF and detectors

As seen in Figure 2, since the optics is reflective only, the instrument can receive and transfer to the detector any radiation in the whole spectral region of 0.2 to 20 microns and beyond. However, in order for this wide range to be fully exploited, the CVF and the detector combination must be appropriate for the selected spectral range. First, a CVF can be manufactured as a section of a circle, or segment, usually ¼ circle, or ½ circle, or a full disc, covering a spectral range whose maximum wavelength is not larger than twice the smallest wavelength (see Figure 3). This wavelength range limitation is due to interference of higher orders. In fact, the CVF is a narrow band interference filter whose thickness varies linearly along the circumference of the segment, so that the wavelength of transmission also varies linearly with the position on this circumference. The spectrum is measured by rotating the CVF disc in the path of the collected IR beam from the object.

Figure 4 shows the typical wavelength of maximum transmittance, and peak transmittance of a CVF at different angles of rotation of two 180^o segments glued together.

Secondly, the best detectors for IR, the photon detectors, such as Si for up to 1 μ, 77 K cooled InSb for up to 5 μ, and HgCdTe for up to 14.5 μ etc., have also each its own limited wavelength range of sensitivity, so that they have to be combined with an appropriate companion CVF segment. Figure 5 shows the various available combinations of CVF segments and best detectors, as they relate to the various IR atmospheric windows.

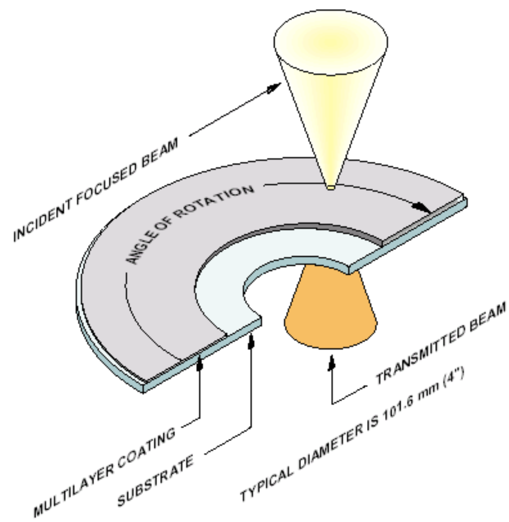


Figure 3: A typical CVF ½ disc segment, showing its active area and the cone of angle of the measured radiation (from OCLI's technical material).

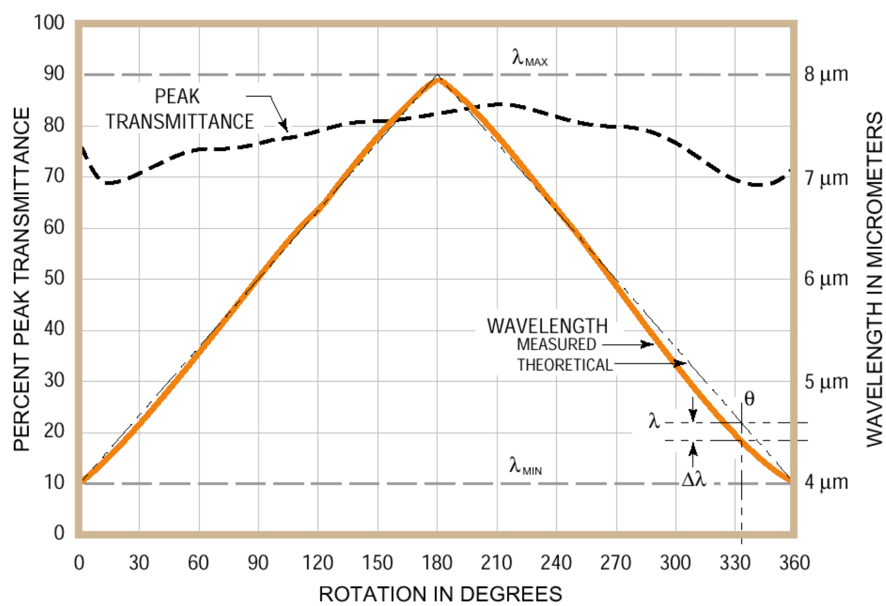


Figure 4: Typical wavelength of maximum transmittance and peak transmittance of a CVF at different angles of rotation of two 180^o segments glued together (from OCLI's technical material).

In both cases of the CVF and of the photon detectors, the wavelength coverage of the single segments and the single elements respectively, can be increased for convenience. In the case of CVF, two or more segments of ¼ or ½ circles can be glued together, to form larger segments of circle (½ or ¾) or a full circle. In the case of detectors, so called "sandwich" detectors exist, for example InSb/HgCdTe or Si/PbS combinations, which are sensitive to the combined wavelength ranges of each single detector element. For example, the CVF range of 2.3 to 14.5 of Figure 5 is obtained by gluing together three CVF segments of 110^o each, one between 2.3 and 4.1 µ, one between 4 to 6.5 µ, and one between

6 and 14.5 μ. These correspond to the well known IR atmospheric windows, and when combined with a 77 K cooled InSb/HgCdTe sandwich detector, provide the best possible sensitivity in this wavelength range.

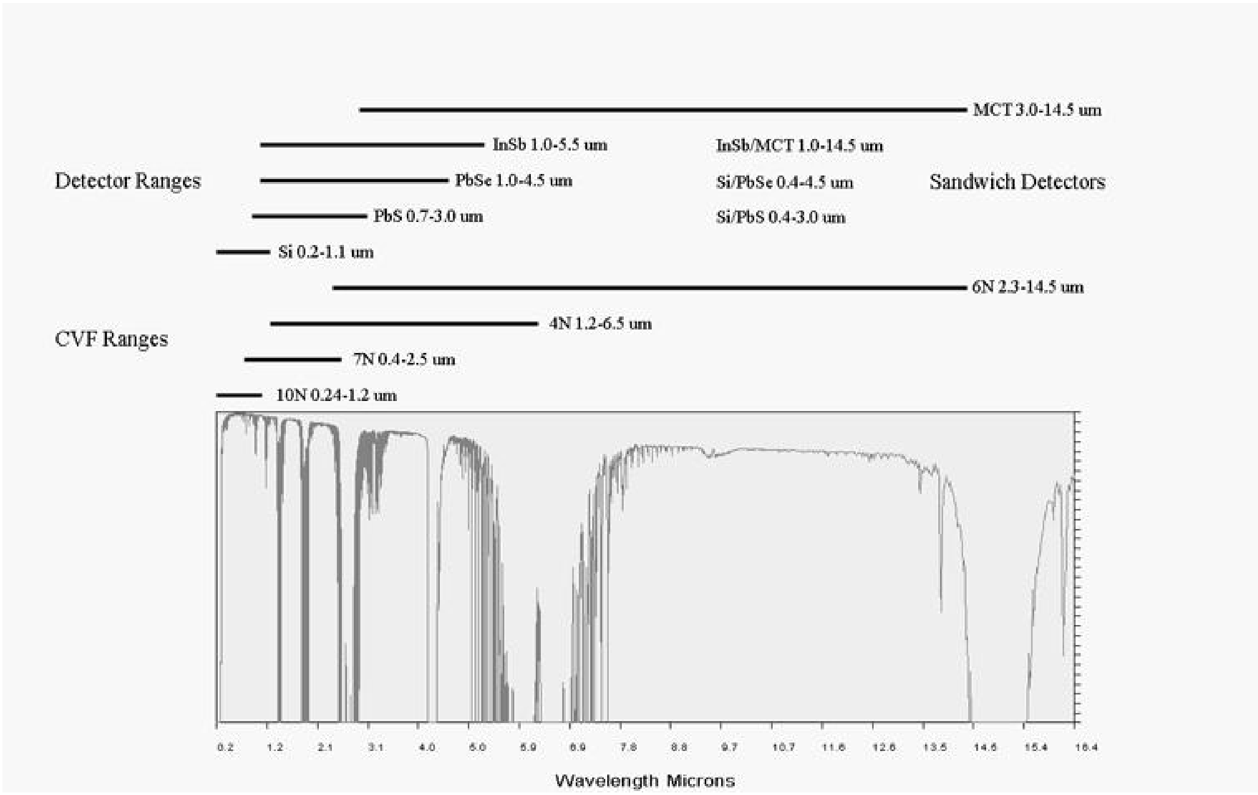


Figure 5: Atmospheric windows, and detector and CVF ranges for best spectral coverage of IR spectroradiometric measurements.

Figure 6 shows the geometric configuration and a typical response curve of a sandwich InSb/HgCdTe detector.

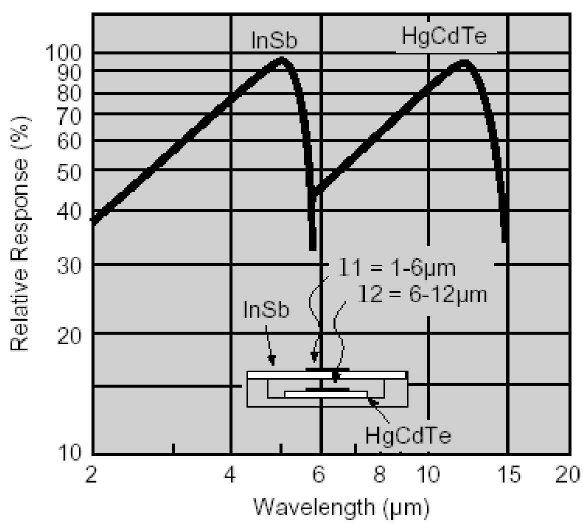


Figure 6: Typical response curve of a sandwich InSb/HgCdTe detector for maximum performance in the 2 to 15 μ region.

Fields of view (FOV's)

The SR 5000 can be configured with a wide variety of FOV's: eight small FOV values by software control between 0.3 and 6 milliradians, and two additional large values (5.7^o and 14^o degrees, by modular hardware changes, that can be done in the field by the user). In the standard SR 5000W configuration, the eight small values are twice as large as in the previous case, i.e. between 0.6 and 12 milliradians, and the two additional large values are 5.7^o and 28^o degrees.

Focusing distance

The SR 5000 can focus on an object from ∞, down to a minimum distance of 3 meters, by manually sliding the primary mirror towards the secondary mirror for farther objects, and away from it for closer ones. The alignment and focus adjustments are done by looking through a parallax-free side viewing port, which also serves as a background image recording facility, for a digital camera (see below for the description of this novel feature).

Internal blackbody and calibration in units of radiance (Watts/cm^2/sr/μ)

All objects in the environment emit appreciable IR radiation, including the internal walls and other elements of the instrument, to which the detector is exposed, so in order for an IR spectroradiometer to distinguish between the radiation from the object to be measured and this spurious one from the environment, it is most efficient to mechanically chop the former, and to AC couple and synchronously detect the detector signal so obtained. This method has been known for a long time and proven by a large amount of experience.

The existence of mechanical chopping provides an opportunity for calibration of the system in absolute units of Watts/cm^2/sr/μ. This is done by designing the system so that when the chopper blocks the radiation from the measured object, the detector is exposed to a built-in blackbody at known temperature, a so-called "internal blackbody". In this case, since the instrument output $S(\lambda)$ is proportional to the difference between the spectral radiance of the object $W(\lambda)$ and that of the internal blackbody $P(\lambda,T_{int})$ at each wavelength (see Equation 1), by knowing the constant of proportionality $K(\lambda)$ and the internal blackbody radiance as function of wavelength λ, one can easily obtain $W(\lambda)$ as function of λ. In fact, $K(\lambda)$ can be obtained by performing a similar measurement, in which the object to be measured is a blackbody at known temperature T with radiance $P(\lambda,T)$, so that in the mathematical relationship (Equation 2) between the signal versus wavelength $S_C(\lambda)$, $K(\lambda)$ and the Planck functions of the two blackbodies (the known measured one and the internal one), $K(\lambda)$ is the only unknown, and can be calculated.

$$S(\lambda) = K(\lambda)\left[W(\lambda) - P(\lambda, T_{\text{int}})\right] \tag{1}$$

and

$$K(\lambda) = \frac{S_C(\lambda)}{P(\lambda, T) - P(\lambda, T_{\text{int}})} \tag{2}$$

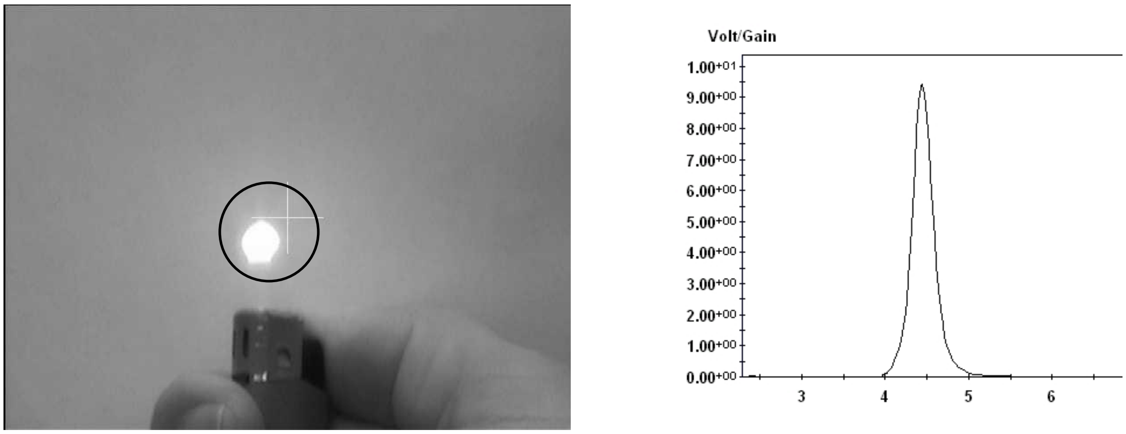
where $S_C(\lambda)$ is the instrument signal when measuring the calibration blackbody. In summary, $K(\lambda)$ is measured in Equation (2) and used in Equation (1) to find $W(\lambda)$.

The internal blackbody temperature is left to fluctuate with room temperature, and is accurately monitored continuously during any measurement. The advantage of this method is that small deviations of its emissivity from the ideal value of unity can be shown to have in this case a small effect on the accuracy of the overall measurement. Other designs, in which the internal blackbody temperature is controlled to a fixed value higher than room temperature, can be shown to introduce larger uncertainties in the final measurement result.

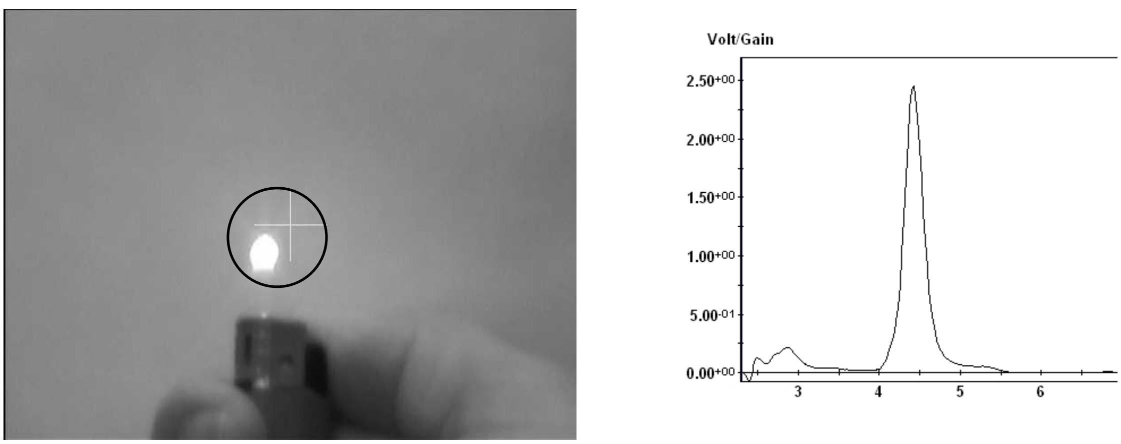
Synchronized imaging

In dynamic spectroradiometric applications where the object changes during the measurement, for example by changing its aspect angle, its size, or its temperature, it is sometimes useful to record the object's image, as it is seen by an observer situated close to the measuring instrument. This is because now the scanning wavelength is not the only parameter affecting the time dependent signal of the SR 5000, and the simultaneous spatial information may greatly help to achieve a more accurate interpretation of the momentary spectrum. A digital camera, positioned and co-aligned with the SR 5000 FOV, is operated by a trigger signal produced by the CVF at the start of each wavelength scan. In this way, a digital image of the object is recorded in synchronization with each spectrum, together with the corresponding scan number, so that the spatial information can be used in algorithms for the interpretation of the spectra.

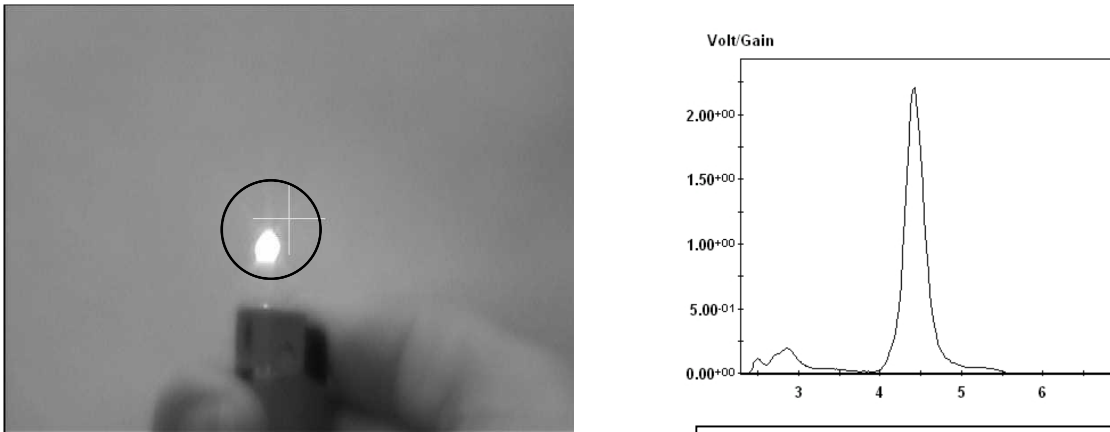
Figure 7 shows a sequence of three images and the corresponding infrared spectra of a cigarette lighter flame: as it is lit (a), in the steady state (b), and in the turning off stage (c). It is easily seen that: i) the spectrum is made of a strong peak at 4.3 μ, the well known CO_2 emission line, ii) the intensity of the 4.3 μ peak is first quite high (due to the initial burst of gas) and then it fluctuates, as it is expected.



(a)



(b)



(c)

Wavelength scale is in μ

Figure 7: Three instants during the burning of a cigarette lighter, and their corresponding spectra, showing the intensity variations of the strong CO_2 emission line at 4.3 μ.

It is seen in Figure 7 that from (a) to (b) there is a large intensity change (a decrease of about a factor of 4), while between (b) and (c) there is a small change, a decrease of about 10%. The black circle enclosing the flame and the cross hair indicate the field of view of the SR 5000, which is larger than the flame. It is easily seen from the images of Figure 7, that the size of the flame is decreasing during the measurement. A pixel count of the burning area can partially explain the intensity changes of the spectrum.

4. THE SR 5000 WINDOWS BASED USER INTERFACE

The newly developed Windows based user interface of the SR 5000 is composed of two separate programs: The “SR 5000” and the “SR 5000 Data Manager” or “SRDM”. The former controls the set up parameters of the instrument to be used in a measurement, acquires and stores the data, and is equipped with a suite of mathematical functions to operate on the spectra: besides calibration in units of Watts/cm^2/sr/μ, the SR 5000 program can calculate spectral averaging, spectral contrast, effective temperature, and other useful quantities. The latter is a tool for automatic storage of spectra and corresponding images (in synchronized imaging) according to experiments and operators, for retrieval, archiving and annotations. Another important function of the SRDM is to export any measured spectrum to a standard text file (.csv: comma separated values) for use with other Windows programs, such as Matlab, Notepad and Excel.

Figure 8 shows the parameter set-up screen, and Figure 9 shows the measurement screen. Figure 10 shows the SRDM screen.

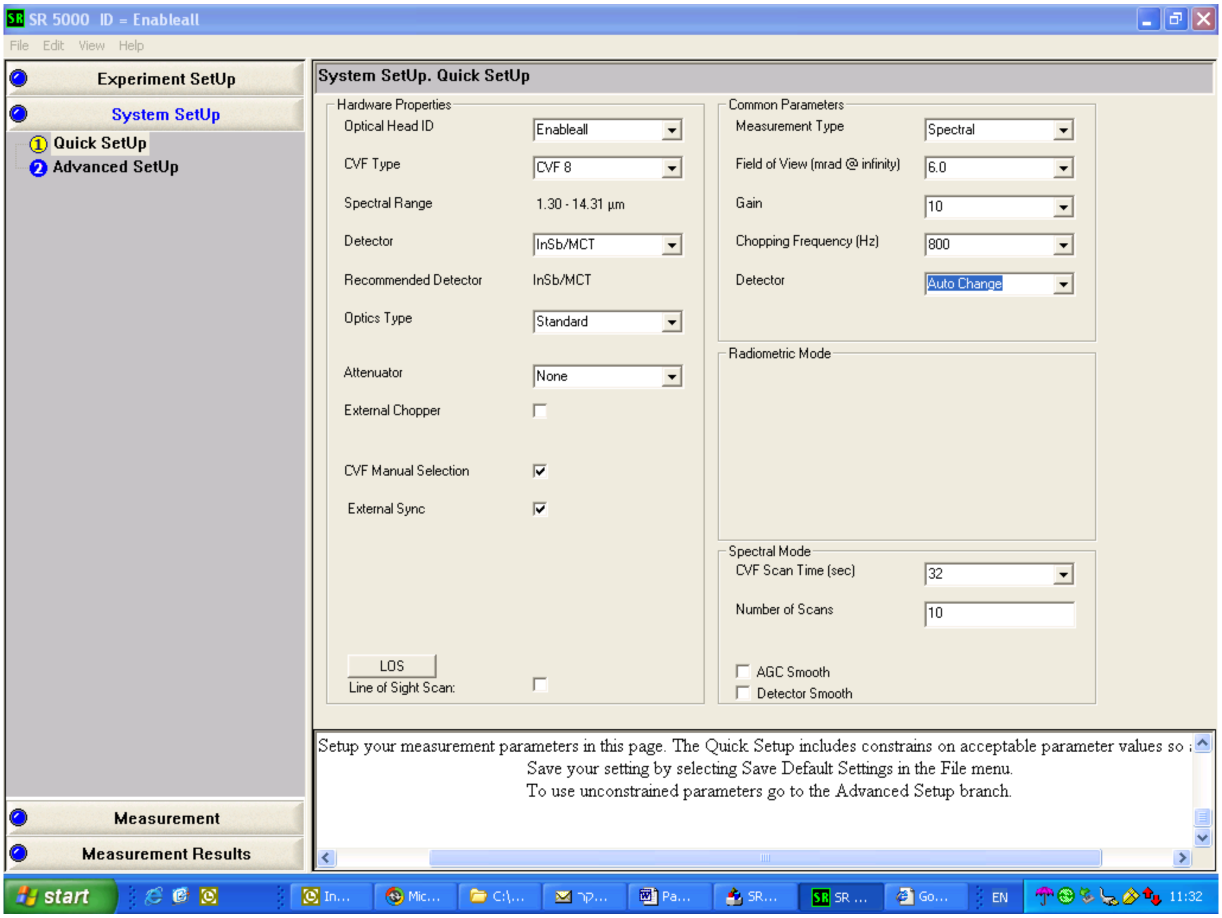


Figure 8: Measurement parameter set-up screen.

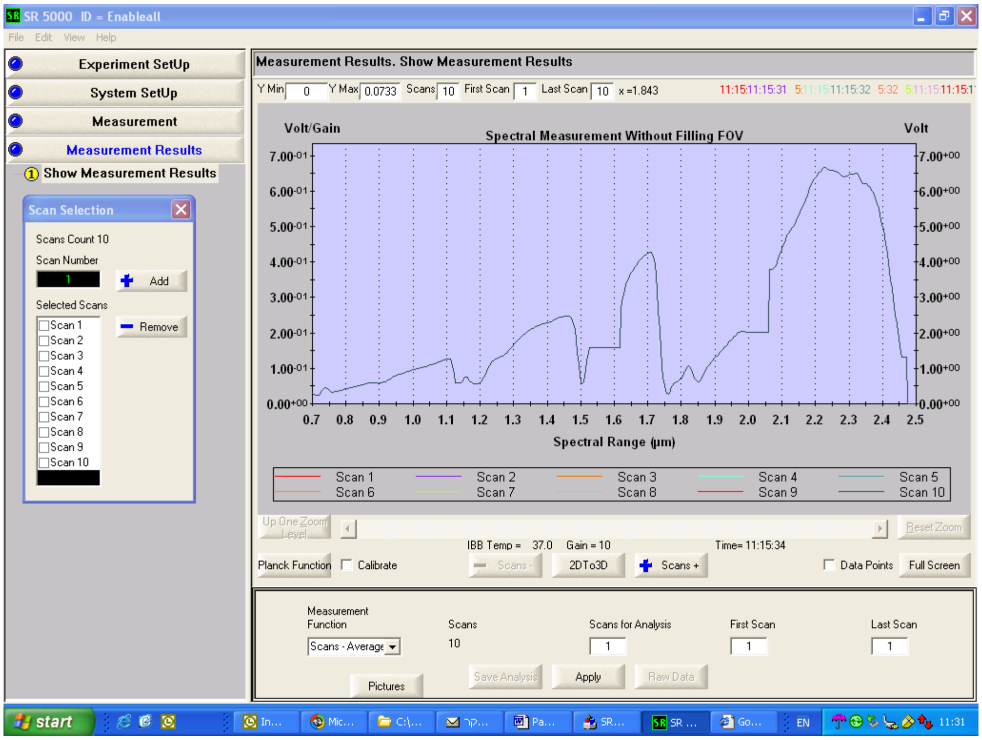


Figure 9: Measurement screen showing the graphs, the scales, superposition of spectra, and other parameters.

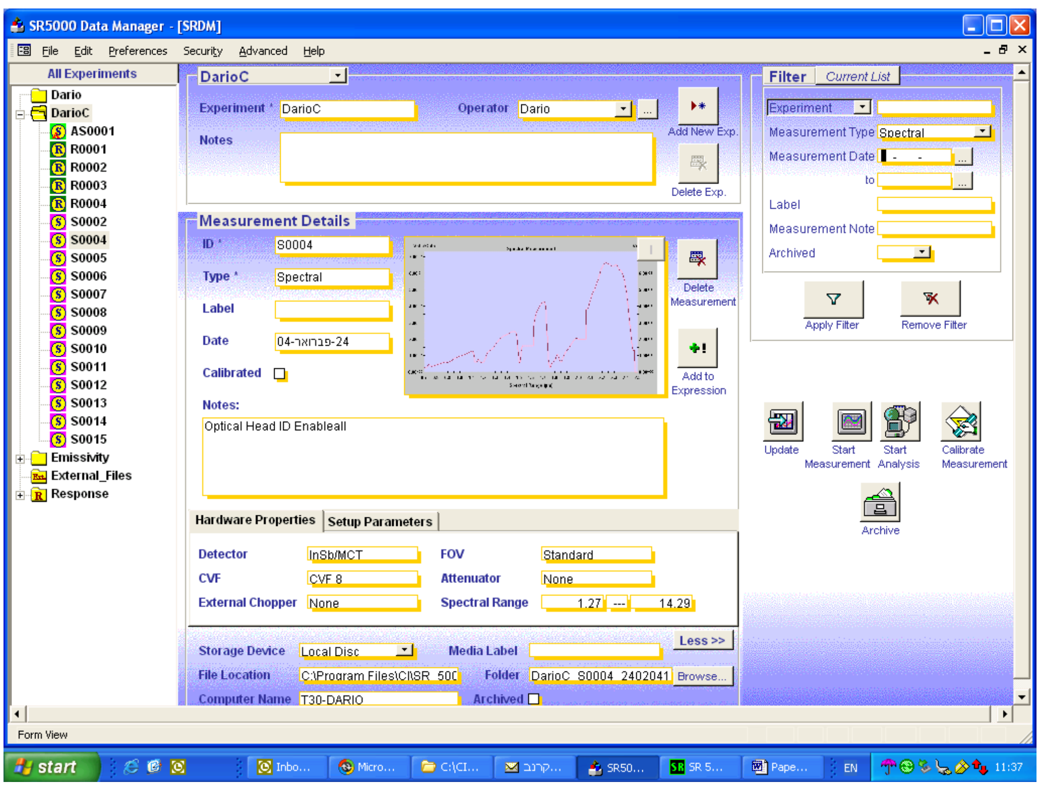


Figure 10: The SRDM stores spectra, images, and annotations, it archives, and imports/exports measurement files.

CONCLUSION

IR spectroradiometry, as it was known in the '80's, almost vanished from use at the end of the '90's, because the only CVF manufacturer in the world stopped production of these components at that time. CI Systems revived this field by: i) taking advantage of the existence of new CVF manufacturers, ii) replacing the old instrument DOS software with a Windows package, and iii) adding new useful features, such as recording images of the object and its background in synchronization with the spectral data acquisition.

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