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CALIBRATION OF THE VEN μ S SUPER-SPECTRAL CAMERA

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ABSTRACT

A high-resolution super-spectral camera is being developed by Elbit Systems in Israel for the joint CNES-Israel Space Agency satellite, VEN μ S (Vegetation and Environment monitoring on a new Micro-Satellite). This camera will have 12 narrow spectral bands in the Visible/NIR region and will give images with 5.3 m resolution from an altitude of 720 km, with an orbit which allows a two-day revisit interval for a number of selected sites distributed over some two-thirds of the earth's surface. The swath width will be 27 km at this altitude. To ensure the high radiometric and geometric accuracy needed to fully exploit such multiple data sampling, careful attention is given in the design to maximize characteristics such as signal-to-noise ratio (SNR), spectral band accuracy, stray light rejection, inter-band pixel-to-pixel registration, etc. For the same reasons, accurate calibration of all the principle characteristics is essential, and this presents some major challenges. The methods planned to achieve the required level of calibration are presented following a brief description of the system design. A fuller description of the system design is given in [2], [3] and [4].

1. BACKGROUND

VEN μ S is a small remote-sensing satellite being developed jointly by CNES (Centre National d'Etudes Spatial), the French Space research organization, and ISA (the Israel Space Agency). It is intended to help prepare for the GMES program, by investigating the application of high spatial and spectral resolution data with high revisit rates in monitoring vegetation, environmental factors and natural resources.

The satellite will carry a camera with super-spectral resolution: 12 narrow spectral bands which will image, virtually simultaneously, swaths of ground of up to 27 km wide at a limited number of selected sites throughout the globe. The orbit is chosen so that a revisit time of two days is possible for most of the earth's surface and the specific sites are chosen to be within this coverage. The observation angles and local time will be constant to allow comparison of multi-temporal images. The basic spatial resolution of the imager from a nominal altitude of 720 km is 5.3m.

It should be noted that 11 different spectral bands, will provide much more spectral detail than the 3 or 4 bands on most multi-spectral systems (such as SPOT, Ikonos etc.). True, they do not give the spectral resolution that hyper-spectral systems can offer. However, by taking

advantage of the higher sensitivity possible with this "Super-Spectral" system (high throughput and TDI detectors, which cannot be used with hyperspectral imagers), spatial resolution high enough to monitor crops on a field-by field basis is achieved. Only with much larger telescopes could such spatial resolution be obtained with a hyper-spectral imager.

The camera concept is based on an earlier project, the "David MSRS" [1] which was begun at El-Op and was partly funded by the EC but was not completed.

The satellite bus is being developed by IAI (Israel Aerospace Industries). CNES selected Elbit Systems Electro-Optics El-Op Ltd, of Israel to build the camera, referred to as the VEN μ S Super-Spectral Camera (VSSC).

2. REQUIREMENTS

The spectral bands were chosen to provide a maximum of information on the subjects of interest (vegetation, water resources, atmospheric correction, etc.). (See Table 1). The narrowest bands, 8, 9 and 10, are especially useful for determining the state of vegetation through the location of the chlorophyll "red edge". Bands 5 and 6 are identical, but are located at opposite extremes of the scan-direction field of view, thus enabling stereo imaging to derive a digital elevation map (DEM) and to evaluate image quality.

Table 1. Spectral Band Characteristics

Band	Centre [nm]	Width [nm]	Main objective
1	420	40	Atmos. correction
2	443	40	Aerosols, clouds
3	490	40	Atmos. correction
4	555	40	Land
5	620	40	Land
6	620	40	DEM, image quality
7	667	30	Land
8	702	24	Land
9	742	16	Land
10	782	16	Land
11	865	40	Land
12	910	20	Water vapor

For each band, the signal-to-noise ratio (SNR) needed to provide useful information at a given radiance level (L_{min}) was specified (See Table 2.) In general, spatial resolution can be relaxed to meet the SNR requirement of Table 2

by taking advantage of the higher SNR which can be obtained by binning of adjacent pixels in post-processing on the ground, by a factor equivalent to the square root of the number of pixels in a bin. The full resolution images are still available as well. Another requirement is that up to radiance levels of L_{max} response should be linear.

Excessive stray light could be a serious impediment to accurate radiometry. The allowable amount of stray light is specified in relation to the allowable noise when a part of the solid angle surrounding and outside the field of view is illuminated by at a level denoted by L_{cloud} and the other part at L_{min} . The allowable ratios of stray light to signal in the table are based on this criterion and refer to a distance of 5 pixels from the edge of a bright image.

Table 2. GSD and SNR requirements

Band	L_{min}	L_{max}	L_{cloud}	Required GSD	SNR at L_{min}	Stray light ratio
	[W/ μ /m ² /sr]			[metres]		
B1	40	140	220	21.2	100	0.0045
B2	50	140	220	21.2	100	0.0057
B3	30	160	220	21.2	100	0.0034
B4	30	195	220	10.6	100	0.0034
B5	20	220	220	10.6	100	0.0023
B6	20	220	220	10.6	100	0.0023
B7	20	234	234	10.6	90	0.0021
B8	15	218	218	10.6	110	0.0017
B9	20	204	204	10.6	110	0.0025
B10	30	197	197	10.6	110	0.0038
B11	30	173	173	10.6	100	0.0043
B12	30	127	127	21.2	100	0.0059

In order to derive spectral information on a particular area, accurate registration of the images from different spectral bands is essential. Since the bands are imaged by different detector arrays at different times, the spatial relations between the pixels must be known.

3. CAMERA CONCEPT

3.1 Focal Plane

The concept is based on a TDI (Time Delay Integration) detector unit which was developed specially for El-Op for space applications. The units have three identical bands, each with 5200 pixels and 32 stages of TDI. Four such units are combined in the focal plane to achieve a total of 12 bands which are scanned in sequence in the push-broom mode.

Fig. 1 shows the physical layout of the focal plane. Two of the detectors receive the image directly from the objective whilst in the other two, the image is reflected by a folding mirror. This enables the distance between the outermost bands in the focal plane to be minimized.

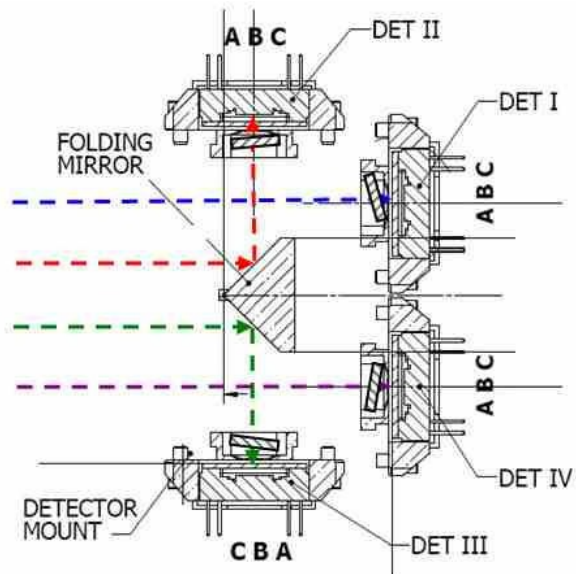


Fig. 1 Focal Plane Cross-Section

Narrow band interference filters are coated on the detector windows, one filter in front of each array, to define the spectral band for that array. To achieve the low out-of-band transmittance, a second “blocking” interference filter common to all three bands in each detector, is coated on the outer surface of the window. Since reflection back to the optics from the interference filter outside its transmission band is a primary cause of stray light in the system, absorption filters, common to the three bands of each detector, are also mounted in front of the window, to reduce some of the reflection. These filters are inclined at an angle to deflect reflection from the filter itself. In addition, an opaque mask has been added to the outside of the window with slots just wide enough to admit the light to each array of the detector and thus reduce the reflecting area. This should also reduce the stray light scattered from the optical surfaces into the detector.

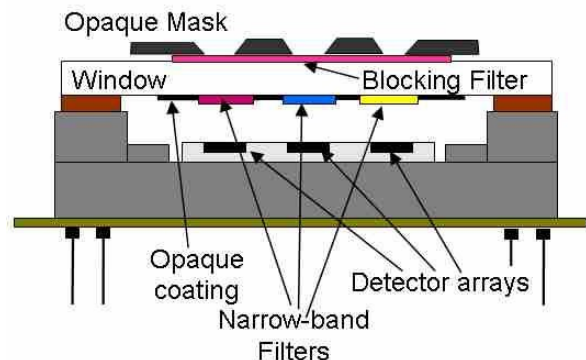


Fig. 2. Schematic view of Detector array

3.2 Optics

A catadioptric objective, of the Ritchey-Chretien type with auxiliary field-correcting lenses, images the field on the focal plane. The characteristics are:

Aperture	250 mm
Focal length	1750 mm
F/#	7.0
Central obscuration	0.5 (diameter ratio)
Field of view –	
Cross scan direction	2.2°
Scan direction	1.5°
Swath width	27.8km (from 720km)
. GSD	5.35 m (from 720km)

The objective is designed for very low distortion in order to facilitate the registration of images from different spectral bands. This is also important, to minimize the degradation of MTF which can result from distortion when TDI is used.

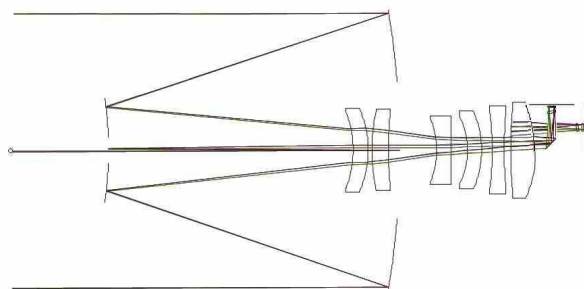


Fig. 3 Schematic Optical Layout

The main features of the camera can be seen in Fig. 4

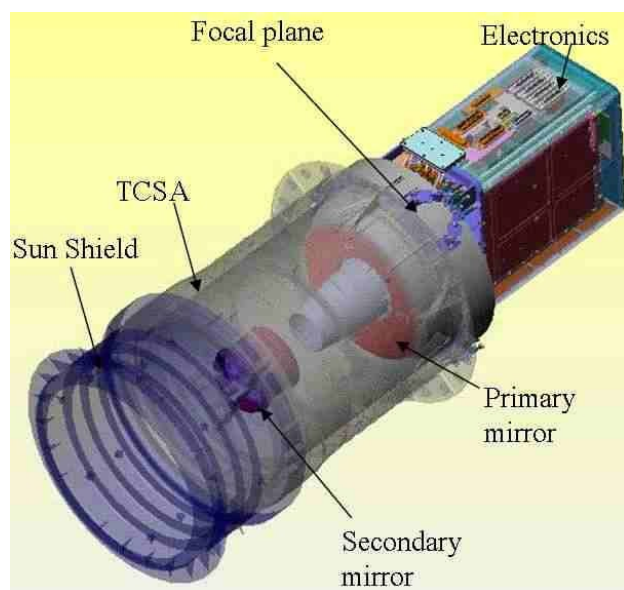


Fig. 4 Perspective view of the VSSC

3.3 Active and Passive Thermal Control

The temperature of the objective is kept within narrow limits ($20^{\circ}\pm 5^{\circ}$) to obviate the need for a refocusing mechanism. Strategically placed heating elements and thermistors are used in the control system while all externally exposed areas except the optical aperture are covered with radiation reflecting multi-layer insulation. The TCSA shown in Fig. 4 is a thermal shield around the objective structure on which some of the heaters are mounted, rather than directly on the structure itself. The control allows the camera to be pointed for a time at the moon for calibration purposes without deviating from the specified temperature range. Likewise, the temperature of the detector is kept low, within the range of $0^{\circ} - 10^{\circ}$, by conduction of heat to a low temperature radiator, to keep the dark current low. Dark current tends to increase with exposure to radiation in space and this helps to minimize the effect.

Electrical, electronic and mechanical aspects of the design are described in [3] and [4].

4. CALIBRATION AND TESTING

The main characteristics which need to be calibrated prior to launch are:

- 1) Spectral response
- 2) Signal-to-noise ratio
- 3) Stray light
- 4) Spatial registration
- 5) MTF

Some of the parameters need to be calibrated under thermal/vacuum conditions so that the system is operating under the correct environmental conditions. For these tests, a vacuum chamber equipped with thermal interfaces to simulate space conditions (TVC) will be used. This chamber has a built-in 5.5m collimator, in the focal plane of which different sources such as a monochromator or a broad-band QTH lamp, with various targets, can be mounted. An identical collimator in the clean room, independent of the vacuum chamber, can also be used for tests where vacuum conditions are not required. Some tests will be made with the camera in the vacuum chamber looking out through a window towards the light source outside, in particular, an integrating sphere with controlled radiance. Mounted alongside the unit under test will be a specially designed, calibrated detector. This detector will also be used to map the radiance over the face of the source so that when the detector is moved aside to allow the camera to be tested, its readings can be related to the average radiance seen by the camera.

4.1 Spectral Response

The parameters to be tested are the overall spectral sensitivity and the response to out-of-band light.

To calibrate spectral sensitivity, a monochromator will illuminate the telescope through the collimator. Readings at 3nm intervals will be made for all the range of 400 to 900 nm. Readings for each pixel will be averaged over several hundred video lines to improve accuracy.

Like stray light, out-of-band signal could decrease the radiometric accuracy and thus must be less than the allowable noise, which is around 1% of the reference signal. Because the filter transmittance bands are narrow, the spectral range outside each band is 12 to 30 times that within the band. The allowable average transmittance outside the band must therefore be below 1000 to 3000 times less than the in-band signal. The signal from the monochromator is too weak to measure this parameter. To test this, therefore, for each band, a pair of filters which together transmit all the range outside the band will be used with a broad-band source. The sum of the signals received through them will be compared to the signal in the band without these filters.

4.2 SNR testing

For this test, the large integrating sphere outside the TVC will be the source. The radiance in each band will be measured by the reference detector, and adjusted to match, as far as possible, the reference level L_{min} . The SNR will be computed from the average signal and the standard deviation over An image window of 100 x 100 pixels.

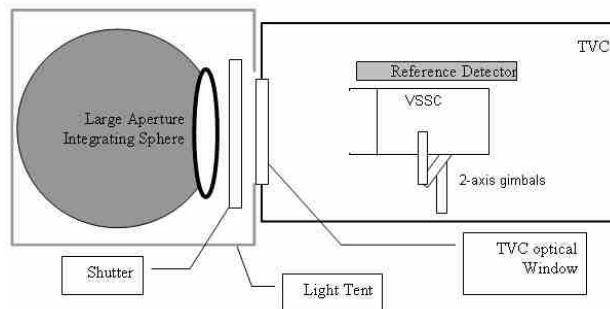


Fig. 5. Test setup for SNR measurement

4.3 Stray Light Characterization

Stray light can reach the detectors in a number of ways, including scattering from roughness and particulate contamination of the mirror and lens surfaces, scattering from baffles, reflection from the detector window interference filters back to the lenses and thence ghost reflections from the less-than-ideal anti-reflection coatings on these lenses, etc. There are also reflections inside the detector units from the detector surface back to the narrow-band filters. In this case, the filter transmittance decreases at the edges of the band whilst the reflectance is increasing. (Fig. 6)

The product of reflectance and transmittance of the filter and of the detector reflectivity gives an effective reflectance which causes a significant ghost image spread out in a geometric pattern over a small area of the detector.

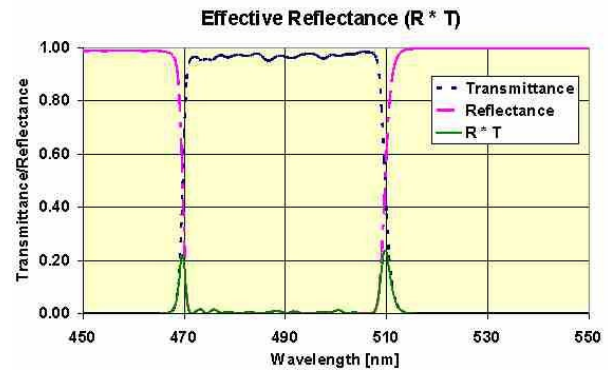


Fig.6 Source of stray light within the detector

An analysis of all the stray light sources carried out by Lambda Research Inc. found that, although the total stray light ratios would meet the specifications in some bands, in others, the requirements would not be met.

The design was later modified by the addition of the mask on the detector window, which reduces the reflecting area of the interference filter and will improve the situation somewhat, but there is still a problem with the expected level of stray light.

A partial solution takes advantage of the fact that the greater part of the stray light will come from areas which are included in the image. If the contribution of stray light from these areas to other pixels as a function of the recorded radiance is calibrated, the total amount of stray light in each pixel can be computed from the image data and subtracted as a correction to the final image. For this reason it is important to characterize quantitatively these contributions.

The contribution of scattered light from outside the image area cannot be used to make such a correction as the radiance is not known, but it is desirable to measure it in order to estimate its likely magnitude and thus to know how successful the correction technique might be.

Characterization of stray light contributions will be carried out in two stages – “Close-in” and “Out of field.” The close-in region includes not only the area covered by the scanning process but up to about 5° radius around it. Because the expected total ratios are very small (a few tenths of 1%), and the contribution of each elemental area is but a fraction of this, it is very difficult to achieve high sensitivity. A spot of light will be imaged by the collimator and as long as this spot does not fall on a given detector, the radiance can be made large or the integration time increased to achieve high sensitivity. However when the spot image falls on a detector, the radiance must not exceed the saturation level of the detector because

blooming may result in giving a false reading at the 5 pixel distance from the edge. However, in this region, most of the contribution comes from a small area of the image, and thus the individual values will be larger, so the limitation can be accepted. If the bright area generates a signal approaching saturation, it should be possible to show that the stray light ratio is less than 1:2000.

The setup is shown in Fig. 7. The region will be sampled at small angular intervals by rotating the camera on the gimbals, to get a map of the contributions from each sub-area in each band.

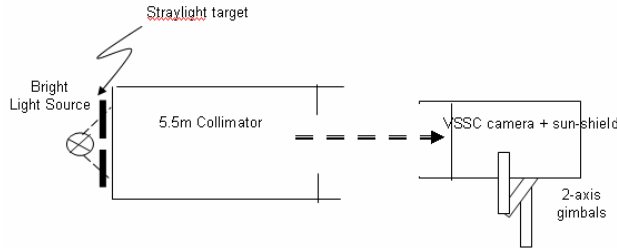


Fig. 7. Close-in stray light characterization setup

Various sizes of targets can be placed in front of the light source. For regions further away from the field, a target of about 0.25° diameter may be used, but for regions within the field of view, it may be necessary to use a smaller target size to get more detailed characterization. The stray light contribution from such a target will be less, necessitating a larger dynamic range to accurately measure the effect.

The setup for measuring the contribution from beyond about 5° (“Out of field”) is somewhat different (Fig. 8). In this case, the whole field will be illuminated at once. A large board painted white, with a hole in the middle, will be lit by a ring of lamps. A radiometer will be used to measure the radiance on this board, or else the camera itself will be used to provide a reference measurement of the reflected radiance. Beyond the hole will be a light trap target at which the camera will be pointed. The hole must be made large enough so that the board does not reflect any light into the camera field of view. Because of the limited distance from the camera to the board (about 4 m), only from about 5° from the optical axis is the full contribution measured. However, together with the data from the Close-in measurement, the characterization should be complete.

The camera will first be aligned to ensure that it faces the light trap and no illuminated areas are within the cone seen by the objective within the field of view. Then the signal recorded in various points in the field of view first without and then with the illumination on the board will be recorded. The difference between these values is the amount of stray light from the “out-of-field region for the given radiance.

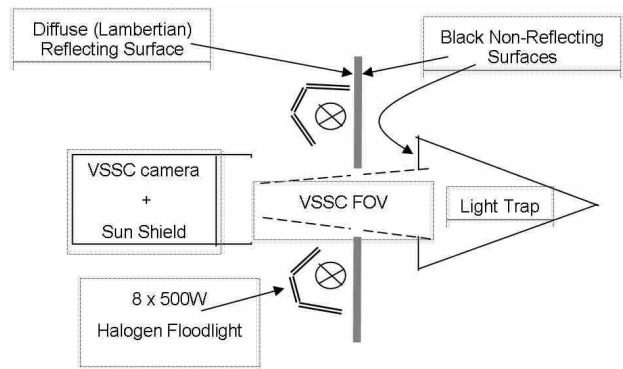


Fig. 8 Out-of-field stray light measurement setup

Because of the low sensitivity of the detectors and lower source intensity at short wavelengths, the ratios which can be measured in Bands 1 and 2 are limited to 1:200 or less. For other bands, the ratios are much better, in the region 1 to several thousand.

4.4 Geometrical Calibration

These tests are designed to characterize the following geometrical relations:

- LOS/LOD Alignment versus reference prism
- Pixel Registration
- EFL
- Band Parallelism
- FOV Angles
- Off-Axis Angle per Band

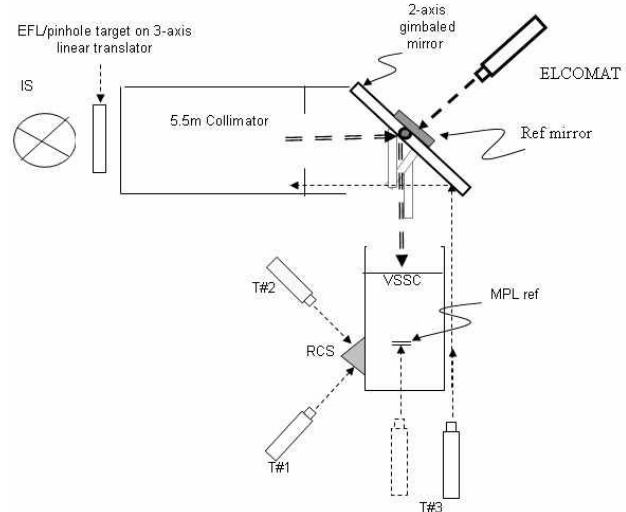


Fig. 9 Geometric Calibration Setup

The tests are based on using a collimator and a gimballed mirror to direct the exit beam of the collimator to the VSSC. The angular position of the mirror will be measured with a very accurate electronic autocollimator (ELCOMAT3000).

A target consisting of 5 triangular pinhole apertures is mounted in front of the lamp in the focal plane of the collimator. The target is shown in Fig. 10 below. Each aperture will project an image on a single pixel. Because of the shape of the pinhole, the location of the target image on the detector can be determined to an accuracy of 0.2 of a pixel width.

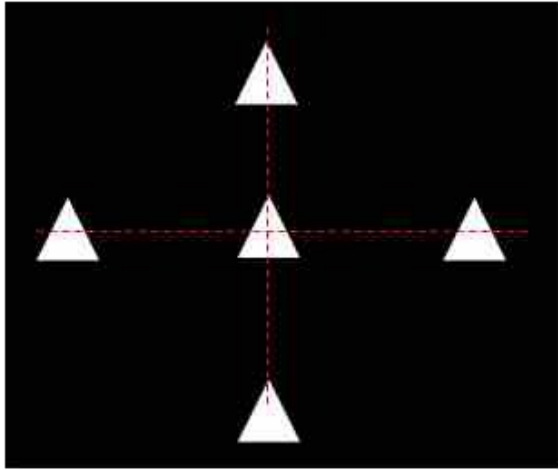


Fig. 10 Target for Geometric Calibration

The RCS is a reference mirror-cube assembly mounted on the camera to allow alignment of the telescope with the satellite bus. LOS/LOD alignment versus the RCS is

accomplished by aligning the camera with a projected pinhole, with one theodolite providing an axes reference of the camera LOS, while an additional two theodolites are used to measure the orientation of the RCS with respect to the LOS reference by auto-collimation versus the RCS reflective faces, and co-collimation versus the LOS reference theodolite. .

Accurate pixel registration is accomplished by pointing the projected pinhole at various pixels in the camera FOV, while precisely measuring the angles over which the 2-axis gimballed mirror traveled relative to a reference position. Because the electronic autocollimator does not have sufficient angular range to cover the whole field of view in one span, the camera will have to be moved several times to complete coverage of the pixel registration map. Overlap between the readings for the different positions will enable a complete picture of pixel registration to be obtained. The facility will allow pixel registration measurement with an accuracy of better than 1/3 pixel (equivalent to 0.5 arcsec). Additional geometrical characteristics, such as Band-to-Band Parallelism, FOV angles, and Band Off-Axis angles may be obtained with high accuracy by processing the pixel registration data.

Other calibration setups will be used to measure MTF, crosstalk, etc.

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