Development status of the telescope for the Ingenio/SEOSAT mission primary payload

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ABSTRACT

Ingenio/SEOSAT is the flagship mission for the Spanish Space Plan 2007-2011, as is currently under development by a Spanish industrial consortium in the framework of an ESA contract. Ingenio/SEOSAT is a multi-spectral high-resolution optical satellite for Earth Remote Sensing, designed to provide imagery to different Spanish civil, institutional and governmental users, and potentially to other European users in the frame of GMES and GEOSS. SEOSAT/Ingenio is a Low Earth Orbiting mission. It features a Primary Payload (PP) with one 2.5 meter resolution panchromatic channel and four 10 meter resolution visible/near infrared spectral channels. The PP swath close to 55 km ensures a frequent revisit period, and offers quick accessibility to any point on Earth in emergency situations. In this paper are described the main characteristics and development status of the instrument from an opto-mechancial point of view, as well as the estimated performance data.

Keywords: Ingenio, SEOSAT, Earth Observation, Korsch telescope

1. INTRODUCTION

Ingenio/SEOSAT is a multi-spectral high-resolution optical satellite for Earth remote sensing, designed to provide imagery to different Spanish civil, institutional and governmental users, and potentially to other European users in the frame of GMES and GEOSS. Ingenio/SEOSAT is a Low Earth Orbiting mission. It features a Primary Payload (PP) with one 2.5 meter resolution panchromatic channel and four 10 meter resolution visible/near infrared spectral channels. The PP swath close to 55 km ensures a frequent revisit period, and offers quick accessibility to any point on Earth in emergency situations.

Ingenio/SEOSAT is the flagship mission for the Spanish Space Plan 2007-2011 elaborated by CDTI in 2006, and part of the Spanish Earth Observation Satellite System. This system comprises two spacecrafts with imagery capabilities in the optical and radar ranges, Ingenio/SEOSAT and Paz/SEOSAR, respectively. Following approval by ESA Council on 13-14 June 2007 an Agreement has been signed between the CDTI and the European Space Agency (ESA) concerning the technical and managerial assistance that ESA will provide to the Implementation phase of the Ingenio /SEOSAT Space and Ground Segment activities.

This framework sets a novel scenario, as for the first time an industrial Spanish consortium is fully responsible of the design, development and in-orbit operation of a satellite of this characteristics. The consortium is led by EADS-CASA, prime contractor and responsible for the satellite. SENER is prime contractor for the primary payload, a multi-spectral high-resolution optical instrument. The PP industrial consortium is integrated as well by THALES ALENIA Space-E as responsible for the detector and electronics module, and INTA as responsible for the instrument assembly, integration and verification (AIV) activities and for optical support studies, including straylight analysis.

Ingenio/SEOSAT is designed for application in areas such as land use mapping, cartography, emergency support, water resources management, agriculture monitoring, environment, etc. The primary users, composed of several Spanish Governmental Organizations and Scientific Institutions, have defined the requirements of the mission, encompassing state-of-the-art image quality and radiometric performances. In order to fulfill these requirements, it has been defined a high performance instrument, facing several engineering challenges in both design and manufacturing terms.

Figure 1. Artist's view of the Ingenio/SEOSAT satellite

2. DRIVING REQUIREMENTS

The primary payload of the Ingenio/SEOSAT mission is required to acquire images operating in push-broom mode. In this acquisition strategy, the instrument images at an instant of time a single line of the terrain, which is sensed by linear detector arrays. Forward motion of the satellite in its orbit displaces the sensed line on the ground, producing in this way two-dimensional images.

The instrument is required to provide a panchromatic (PAN) channel and four multi-spectral (MS) channels, located respectively in the blue (B), green (G), red (R), and near-infrared (NIR) spectral regions. The three RGB channels have been included in order to obtain real color, to ease image interpretation by comparison with existing satellite and aerial imagery. The NIR band has been included due to its interest in agriculture and forestry resources studies.

Ground sampling distances of 2.5 m for PAN and 10 m for MS channels are required at nadir. The specified minimum swath width for both PAN and MS channels is 55 Km. Across-track images can be obtained with viewing roll angles up to ±35º for emergency cases accessibility.

A maximum value of 2% has been specified for the instrument distortion at the edge of the Field of View (FoV).

The image quality performance is defined in terms of the Modulation Transfer Function (MTF) value at Nyquist frequency. At PP level before post-processing, the MTF is required to be higher than 0.115 for the PAN channel, and higher than 0.3 for the MS channels. This relatively high MTF requirement is a mayor driving requirement of the instrument, and has been in fact the primary dimensioning parameter to size its entrance pupil diameter.

Concerning radiometric performances, the main dimensioning parameter has been the signal-to-noise ratio (SNR). For each channel, three top-of-atmosphere radiances have been considered, corresponding to minimum, reference and maximum values. Minimum SNR values are required at both minimum and reference radiances, taken to represent nominal signal values from dark and average targets, respectively. Maximum radiances are used to specify the useful dynamic range of the instrument, where absence of saturation and linearity requirements are to be enforced. The high dynamic range specified for the instrument, combined with the demanding values of SNR at minimum and reference conditions, have been mayor driving requirements for the design of the optical payload.

Table I. Defined minimum (L_{min}), reference (L_{ref}) and maximum (L_{max}) channel radiances. Units in W $m^{-2}sr^{-1}\mu m^{-1}$

	PAN	MS-BLUE	MS-GREEN	MS-RED	MS-NIR
$\mathbf{L_{min}}$	23	43	28	18	6
$\mathbf{L_{ref}}$	74	82	77	70	114
$\mathbf{L_{max}}$	341	347	353	325	218

3. CAMERA OVERVIEW

A 3D view of the instrument, composed of two identical cameras, is presented in figure 2. Following the light path, each camera is composed of the following elements:

- An optical telescope based on the Korsch concept, composed of three on-axis conical mirrors plus a plane folding mirror. The mirrors are made of lightweighted Zerodur and are supported by a structure made of titanium and invar for the more thermally sensitive elements.
- A thermal refocusing element included in the secondary mirror support, intended to provide in-orbit focusing capabilities.
- A focal plane assembly composed of two panchromatic plus two multispectral detectors, co-planarly located. Detectors for both channels are of CCD type. The detectors used for the panchromatic channel are based on the Time Delay and Integration (TDI) technology to increase the number of generated photo-electrons, with the corresponding increase in signal-to-noise ratio. A 4-line CCD detector has been used for the multi-spectral channel, with a line devoted to sense each of the B, G, R and NIR bands. Both PAN and MS detectors are mounted on its proper sub-assembly, which includes the filters defining the spectral bands and the corresponding proximity electronics.
- The electronics modules, including the electronic video units, the video power supply and the interface and control electronics.

Figure 2. 3D view of the Ingenio/SEOSAT primary payload

4. OPTICAL DESIGN

An optical layout of the designed Korsch-type telescope is displayed in figure 3. The system is composed of three conical on-axis mirrors plus a plane folding mirror to direct the image to the focal plane (FP), in the upper part of the drawing. This design presents a high mechanical compactness, and maintains a relative ease of both manufacturing and alignment.

The designed system is all-reflective but for filters and windows located at the focal plane, and hence is essentially free of chromatic aberrations. This is particularly convenient given the extended spectral range of the instrument, spanning from blue to near infrared. A second important advantage in our case with respect to alternative concepts, such as the Ritchey-Chretien (RC), is the capability of accommodating large focal planes. In RC designs, the field corrector is usually close to the focal plane and is roughly of the same size, which might lead to practical problems connected to the manufacturing and integration of large refractive components.

One important constraint of the Korsch concept is the relatively limited field of view that could be accommodated with diffraction-limited optical quality. In our case it is required to image a terrain line with a swath of 60 Km, which subtends an angle larger than 5º observed from the nominal satellite orbit of 670 Km. This results in a FoV considerably larger than the practical limit for these type of systems, which is conventionally taken close to 3º. In our case this has been solved by splitting the instrument field of view in two halves, each covered by an identical camera imaging 30 Km-wide terrain stripes. In the ground post-processing step, both sub-images will be routinely merged to generate images with the required swath width. Even by following this approach, the FoV of each camera slightly surpasses the 3º value, due to different restrictions in the focal plane detector accommodation. This issue has significantly constrained both the design optimization and the manufacturing and assembly tolerances, in order to ensure an excellent image quality throughout the entire field of view of the system.

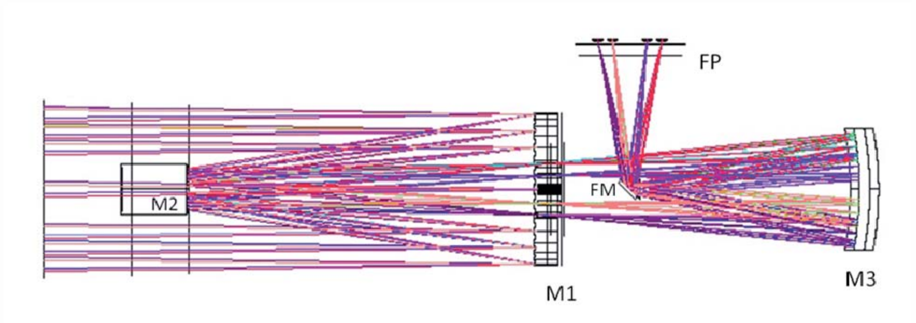

Figure 3. Telescope optical design layout. Incoming light (from the left in the drawing) is focused on the focal plane (FP) after reflections on the primary (M1), secondary (M2), tertiary (M3) and plane folding (FM) mirrors.

The aperture stop of the system has been placed on the primary mirror (M1) to maximize the entrance pupil diameter, optimizing both image quality (by reduction of diffraction effects) and signal-to-noise ratio for a given telescope diameter. Following the light path, the first element encountered is the subset formed by the primary and secondary mirrors (M1-M2), which forms an intermediate image at a plane slightly inside M1. Accessibility to this plane to place a stop adjusted to the intermediate image size is determinant both for straylight control and to reduce the total light flux on filters and detectors under direct solar viewing, an eventuality that might briefly occur before the satellite AOCS takes control. Passage of image-forming light beams onto the four detectors has been enabled by appropriate machining of four rectangular slots in M1. Also, a small on-axis circular hole has been provided for M1-M2 alignment purposes. The image provided by these two mirrors has been optimized at the centre of the field of view to ease the interferometric alignment of the subset.

The image provided by the M1-M2 subset is field corrected by M3, which reimages it on the focal plane after a reflection on the folding mirror. This last mirror has been placed very close to the exit pupil of the instrument, to minimize its size and to avoid potential vignetting risks. A Lyot stop has been placed at the exit pupil location, playing a crucial role in the elimination of direct light accessing the system through the M1 slots without previous passage through the M1-M2 optical path. In the designed system, the contribution of these direct rays has been brought virtually to zero through adequate dimensioning of this stop.

Within its many advantages, the Korsch telescope concept presents also some disadvantages, which have been carefully monitorized during the design process. One of them is the relatively large maximum angle of incidence of rays in the focal plane even at moderate fields of view. This angle is determined by the location of the exit pupil, relatively close to the focal plane, combined with the image size, which is typically large due to large focal lengths and fields of view. The presence of high angles of incidence on the focal plane causes some disturbances, such as an angle-varying spectral shift towards shorter wavelengths in the filter response, which require restricting the maximum value of this parameter. In our system, the maximum angle of incidence has been set to 20º, which enabled to maintain the filter response for all angles of incidence within the limits of the required spectral templates.

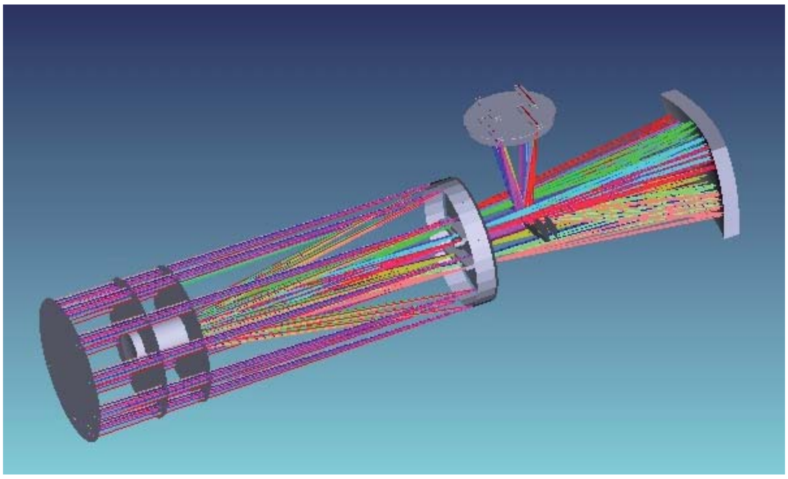

Figure 4. Telescope optical design, 3D view

After integration of the telescope and focal plane, the most critical parameter affecting performance is the axial distance between primary and secondary mirrors, with variations with respect to the nominal value degrading image quality basically by image defocus. To somewhat alleviate the high criticity of this parameter, an scanning based on the paraxial approximation was performed in order to select candidate starting points for the optimization process that fulfil a combination of different design goals and particularly are, within the criticity, relatively more tolerant in defocus to axial M1-M2 displacements. The analysis performed provided an optimum starting point on a system with a length (distance M2-M3) of around 1150 mm, a M3 magnification close to 1, and a M1-M2 intermediate image roughly at the location of M1, for a system with a focal length of 3571 mm.

5. STRUCTURAL DESIGN

A view of the opto-mechanical camera design is presented in figure 5. The camera is composed of a 3+1 mirror Korsch telescope, a focal plane integrating the detectors and a set of structural and supporting mechanical elements. All mirrors have been manufactured in Zerodur, due to its extremely high thermal stability. The two larger mirrors, M1 and M3, have been lightweighted to reduce their mass. The M1 and M3 interface mounting devices (IMD) have been manufactured in titanium with super Invar pads. The M2 is equipped with an Invar IMD. The folding mirror is equipped with a Titanium IMD. This choice of materials for the IMDs partially compensates the dimensional variation of the supporting structure under temperature changes, increasing the thermal stability of the system. Ingenio/SEOSAT mirrors and IMDs are currently being manufactured by SAGEM. Mirror units for the engineering qualification model will be delivered to SENER in the following months.

The primary mirror, M1, is attached to an optical bench, manufactured in titanium, which acts as the mechanical backbone of the system. The secondary mirror structure is supported by an hexapod manufactured in Invar, with a mechanical interface formed by three titanium spiders. The choice of material for the hexapod rods has been primarily determined by the high mechanical stability required for the M1-M2 axial distance, which has forced to use materials with high stiffness and very low coefficients of thermal expansion, coupled with a tight temperature control for this cavity.

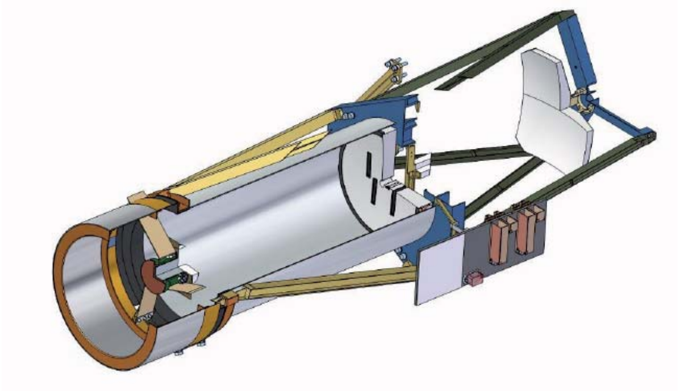

Figure 5. Telescope opto-mechanical design

M2 has been equipped with a thermal refocalisation device, providing the capability of adjusting the M1-M2 axial distance by modifying the temperature of an aluminium vessel which serves as mechanical interface of M2 to the telescope structure. The temperature of this vessel is precisely controlled, providing a total stroke of ±18 μm with an accuracy better than ± 2 μm. The inclusion of this device provides an in-flight refocusing capability to the system, which could also be used for final performance optimization at the end of the AIV phase.

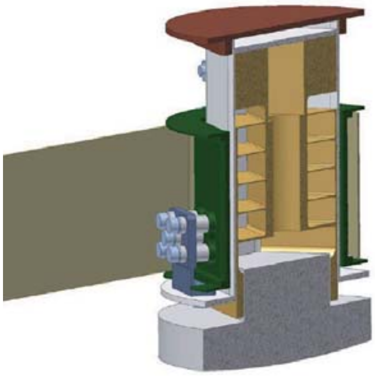

Figure 6. M2 thermal refocusing device. The aluminum vessel is depicted in light gray, surrounding the M2 IMD, displayed in gold.

The tertiary mirror, M3, is attached to the optical bench by means of a hexapod, with legs manufactured in this case in titanium, due to the lower thermal stability requirements for this mirror. Finally, the folding mirror is supported by a titanium structure attached to the optical bench.

The focal plane has been manufactured in SiC due to its low coefficient of thermal expansion, and its high stiffness and thermal conductivity. The ceramic pieces in SiC for the PP have been manufactured by BOOSTEC.

The complete PP, as presented in figure 2, is composed of two identical tilted cameras with the structure described, and its set of electronic modules. All the elements constituting the PP are located over a High Stability Support Panel (HSSP). This concept was proven to be the most convenient in terms of stiffness and integration in comparison with a decoupled structure for optics and electronics. The HSSP has been manufactured in carbon fiber reinforced polymer (CFRP), material chosen due to its good thermal stability and excellent stiffness-density ratio. A contract to manufacture this item has been awarded to BTS.

6. FOCAL PLANE DESIGN

In figure 7 are presented two views of the Ingenio/SEOSAT camera focal plane, both as an engineering drawing and in a photograph of the recently integrated focal plane for the PP engineering qualification model. The focal plane core is constituted by four CCD detectors, two for the PAN channel and two for the MS channel. The use of two detectors per channel, both for PAN and MS, is needed to match the number of pixels per image line to the required values of camera swath width and spatial sampling distance.

The two detectors corresponding to the PAN channel are displayed in the upper part of both images, with the lower detector pair corresponding to the MS channel The gap existing between both detector pairs corresponds to the image zone obscured by the folding mirror. The vertical (Z_{CA}) separation between detectors has been minimized to reduce parallax effects. A detector overlap of 200 pixels (PAN)/50 pixels (MS) has been set between detectors of the same channel to enable a seamless merging of both sub-images during post-processing.

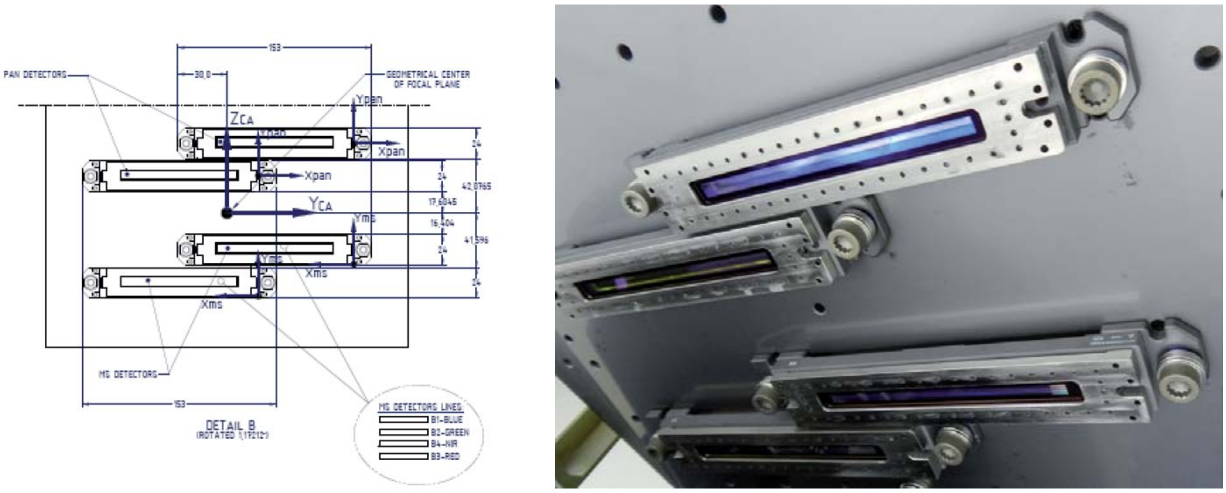

Figure 7. Left: focal plane engineering drawing; right: photograph of the assembled focal plane for the engineering qualification model

All detectors are manufactured by e2v (e2v/ATMEL). The PAN detector is a TDI mode back-illuminated CCD, with photoMOS type pixels with lateral anti-blooming structure. The image section has 6000 columns of active pixels each 13 μm square and is clocked continuously to give a time delay and integrattion (TDI) function. The transfer of charge along the CCD is made synchronous with the velocity of the scan image.

The MS detector is a quadrilinear CCD. The spacing between the centres of adjacent lines is 936 μm, allowing the necessary area for the readout registers and associated bus structures for each line. The photo-sensing element of the pixel is a photodiode. Each line of pixels has 1500 photo-elements with 52 μm pitch and the size of each photo-element is 52 μm square.

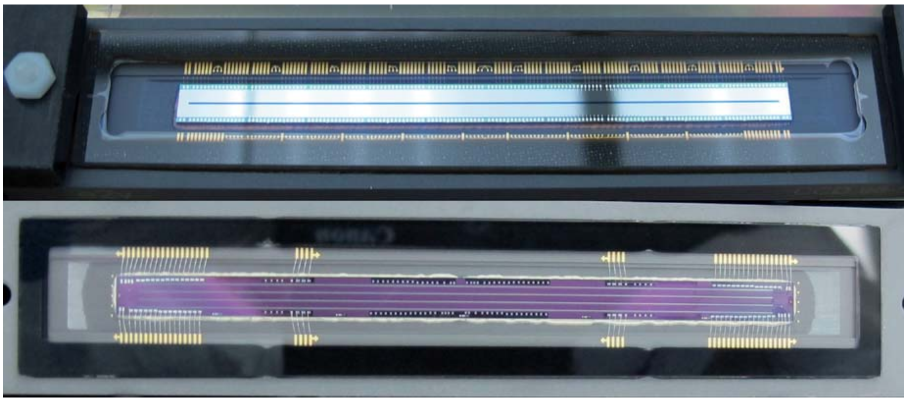

Figure 8. PAN (upper part) and MS (lower) SEOSAT/Ingenio detectors, manufactured by e2v

The spectral band of operation of each CCD line is defined by a spectral band filter located in front of the detector. Both PAN and MS filters have been manufactured in fused silica, due to its excellent radiation resistance properties. The PAN filter is implemented as broad bandpass filters, deposited on both sides of the filter window. The geometry of the MS filter is somewhat more complex, as it has to match the configuration of CCD lines in the quadrilinear MS detector, while defining a separate spectral channel for each of them. This has been solved by depositing four micro-stripe filters in the filter telescope side, defining the requested spectral bands. The detector side has been coated with a common blocker filter providing a high transmittance in the global 400-900 nm band. The inactive areas in both the PAN and MS filters have been coated with an absorber for enhanced stray-light control. Figure 9 shows a side-view diagram of the MS filter, and the resulting spectral transmittance curves for the different telescope channels. SEOSAT/Ingenio filters have been designed and manufactured by Jena Optronik, recently supplying the units for the engineering qualification model.

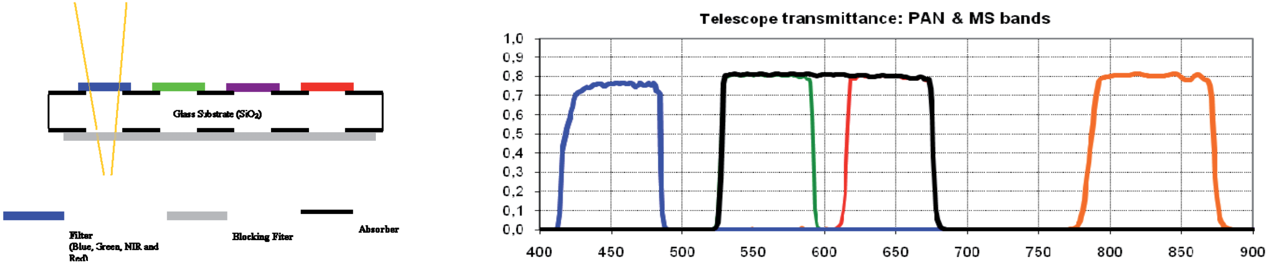

Figure 9. Left: side-view diagram of the MS filter; right:telescope spectral transmittance curves for the PAN(black) and the four multi-spectral channels. NIR channel displayed in orange.

7. PERFORMANCE DATA

The main performance parameters of the PP are listed in table II.

Table II. Performance parameters of the PP Payload, for panchromatic (PAN) and multi-spectral (MS) channels

Parameter	**Value**	
Spatial sampling distance	2.5 m (PAN) / 10 m (MS)	Nominal values at nadir, for a 670 Km altitude orbit
Swath width	> 55 Km	Minimum value, fulfilled during the complete orbit
Telescope aperture	254 mm (F#14)	Dimensioned primarily for MTF
MTF	0.115 (PAN) / > 0.3 (MS)	MTF values at Nyquist freq., before post-processing
SNR	values per channel in table III	
Distortion	< 2%	Positive (pincushion) distortion
Power consumption	270 W	due to electronics and thermal control. Peak value
Mass	130 Kg	Including both cameras, electronic boxes and HSSP

A major design driving requirement has been the MTF value, which is specified at level 0, before post-processing. To fulfill this requirement, it has been designed a system with a relatively large focal ratio for the Korsch concept (F#14), and diffraction-limited in the complete FoV. Especial care has been taken to minimize the effect of other sources of MTF degradation, such as in-orbit thermo-elasticity. The detector design, developed by e2V, has been tuned to optimize the MTF values by fine adjustment of the wafer thickness. In figure 10 are displayed the telescope spot diagrams and MTF curves for the PAN channel. Spot diagrams are referred to the PAN pixel size, 13 µm. Tangential and sagittal MTF curves are presented for different fields, reflecting the effective telescope diffraction-limited performance in the complete field of view.

The nominal spectral range of the PAN and four MS channels, together with the estimated SNR values are included in table III. Reported SNR values correspond to the center of the field of view, in Beginning of Life (BoL) conditions.

Table III. Spectral ranges and estimated SNR values at minimum and reference radiances.

	PAN	**MS-BLUE**	**MS-GREEN**	**MS-RED**	**MS-NIR**
Spectral range(nm)	528-676	416-485	528-592	615-676	800-889
SNR (L_{min})	53	121	105	79	43
SNR(L_{ref})	126	187	221	219	374

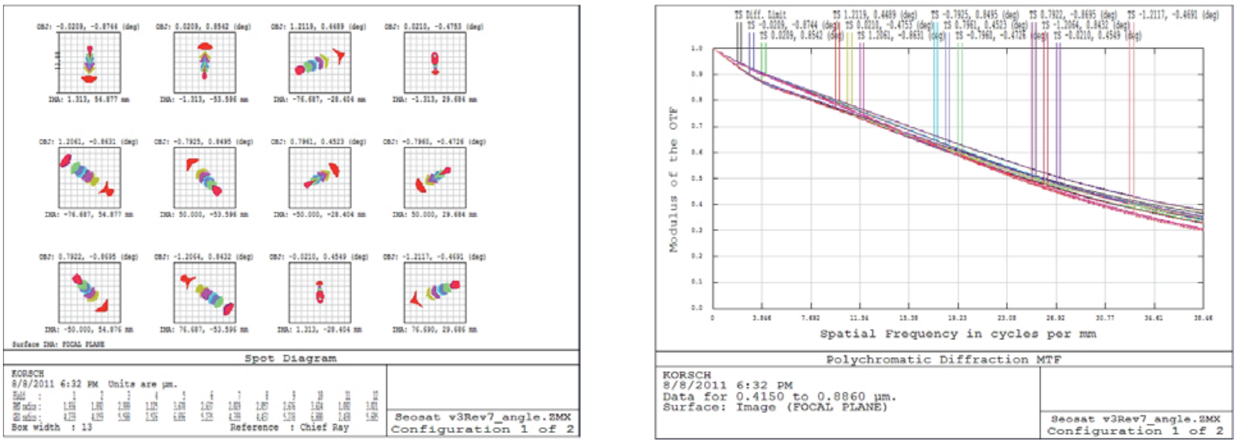

Figure 10. Left: Telescope spot diagrams; right: MTF curves for different fields

8. CONCLUSIONS

The SEOSAT/Ingenio PP Flight Model will be delivered to SC Prime in mid 2013 for a satellite launch in 2014.

The PP works on four MS channels (RGB as per the human eye wavelengths, and a near infrared NIR), implementing narrow bands. It also works on a PAN channel which matches exactly the G+R MS bands together, allowing PAN-sharpening of the MS images.

The PP provides a high resolution of 2.5m in PAN channel (mainly for cartography 1:12500 and urban development) and 10m in MS channel (mainly for agriculture and environment), allowing continuity with existing satellite products.

The driver of the overall PP design has been using certain recurrent detectors and their associated electronics, reducing development time, risk and cost. These detectors provide large pixels, and therefore a large focal plane had to be built. The large pixel allows a high SNR and MTF, but forces a larger telescope. The Korsch concept is optimal for high F#, is able to accommodate the large FP, and being all reflective, avoids chromatic effects and is resistant to radiation. It also allows a good straylight control. In addition, the on-axis concept reduces alignment complexity.

The optical design is diffraction limited up to the edge of the field of view. The entrance pupil is around 250mm, maximizing the MTF. The optical surfaces are of high quality. As a drawback, the need to pack the telescope on the reduced envelope has made the angle of incidence to vary widely along the image plane, which is overcome by an appropriate filter design.

The thermoelastic stability has been a priority of the design, obtaining a isostatic structural design for thermal decoupling with the SC platform, and minimizing the temperature gradients. There is an active thermal control guaranteeing a tight thermal control of the critical elements. The materials chosen have excellent mechanical and thermal properties. Finally, a refocusing device, thermally controlled, has been included. It allows not only for in orbit correction, but as well for on-ground compensation of contributors to the MTF which may become higher than expected. Thank to this all, the SEOSAT/Ingenio PP obtains high radiometric and image quality performances, with high dynamic range, high resistance to blindness, and controlled geometrical distortion.