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FROM SPOT 5 TO PLEIADES HR : EVOLUTION OF THE INSTRUMENTAL SPECIFICATIONS

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ABSTRACT

Image quality specifications should aimed to fulfil high resolution mission requirements of remote sensing satellites with a minimum cost. The most important trade-off to be taken into account is between Modulation Transfer Function, radiometric noise and sampling scheme. This compromise is the main driver during design optimisation and requirement definition in order to achieve good performances and to minimise the mission cost.

For the SPOT 5 satellite, a new compromise had been chosen. The supermode principle of imagery (sampling at 2.5 meter with a pixel size of 5 meter) imp roves the resolution by a factor of four compared with the SPOT 4 satellite (10 meter resolution).

This paper presents the image quality specifications of the HRG-SPOT 5 instrument. We introduce all the efforts made on the instrument to achieve good image quality and low radiometric noise, then we compare the results with the SPOT 4 instrument's performances to highlight the improvements achieved. Then, the in-orbit performance will be described. Finally, we will present the new goals of image quality specifications for the new Pleiades-HR satellite for earth observation (0.7 meter resolution) and the instrument concept.

1. SPOT5 HRG THR IMAGE QUALITY SPECIFICATIONS

SPOT5 was successfully launched on the 2nd of May, 2002 from Kourou Space Center, French Guiana. As previous SPOTs, the two identical SPOT5 telescopes, named HRG's (a french acronym for High Geometric Resolution), deliver both high resolution panchromatic images and multispectral low resolution images covering the visible and near infrared spectral domain, with a 60 km swath [1]. These images are acquired according to the classical pushbroom principle. A linear array of CCD detectors, placed in the focal plane of the telescope, acquires a scanline over an integration time Ti. The satellite's motion along its orbit, which is perpendicular to the linear array, ensures acquisition of successive lines.

Usual radiometric specifications deal with signal to noise ratio (SNR) values over a given radiance range and Modulation Transfer Function (MTF) values at Nyquist frequency.

The noise specification, NeDL, varies according to the L radiance level and means that the system is able to discriminate between two extended uniform radiance areas with close radiances L and L+NeDL.

Furthermore, high resolution remote sensing systems, should be able to identify a tiny signal modulation, for instance some faded texture, in the instrumental noise. A main parameter for this appears to be the Point Spread Function (PSF), which is the real extended image of a point object. Taking the Fourier Transform of the PSF yields the MTF, which tells how a sine signal with spatial frequencies (fx, fy) is weakened by the instrument.

Up to SPOT 5, it was considered that the MTF should take high values at Nyquist frequencies. For instance, MTF specification could rise up to 0.5 for multispectral bands and 0.3 for panchromatic band. Such specifications do not fit with Shannon sampling condition : MTF should be negligible outside from the frequency domain retrieved by the sampling scheme, which is called the reciprocal cell. High MTF values at Nyquist frequency mean aliasing artefacts corrupting high frequency patterns and contours and causing difficulties for resampling and fine processing such as automatic correlation. Above all, such a system is not optimized since the instrument catches high frequency components that are lost during sampling : with the same telescope, resolution could be improved provided that the sampling scheme be adapted to the MTF.

As shown in [2,3], this problem arises with classical pusbroom sampling when the MTF cut-off frequency is equal to the elementary detector size inverse, which unfortunately happens to be the sampling frequency. In order to decouple cut-off frequency and sampling frequency, the solution adopted by SPOT 5 consists in using a two lines detector, each line being shifted by 0.5 pixel along the CCD direction and (n+0.5) pixel along the velocity direction. Each CCD line thus produces classical 5 m images, with a 2.5 m offset along both row and column directions. Interleaving the two images yields a quincunx sampling, well suited to SPOT 5 panchromatic MTF since MTF maximum value at Nyquist frequency is now 0.15, to be compared to 0.35 with the classical pushbroom sampling [fig1a and 1b]. This mode of acquisition is called the THR mode.

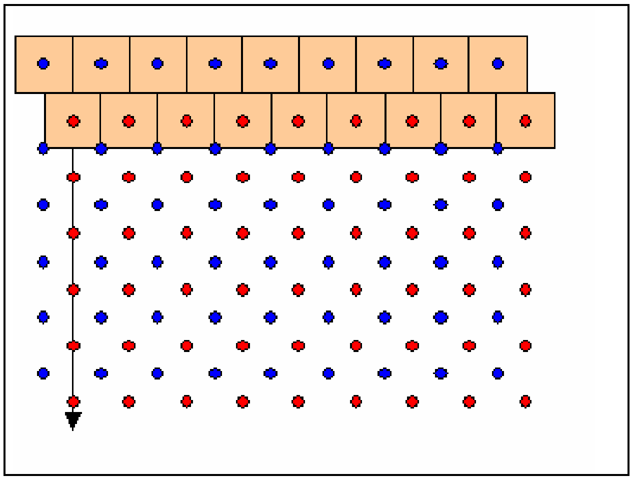


Fig 1.a SPOT 5 THR grid

The quincunx grid is generated by two shifted CCD linear arrays, separated along the row axis by 0.5 pixels and along the columns axis by 3.5 pixels.

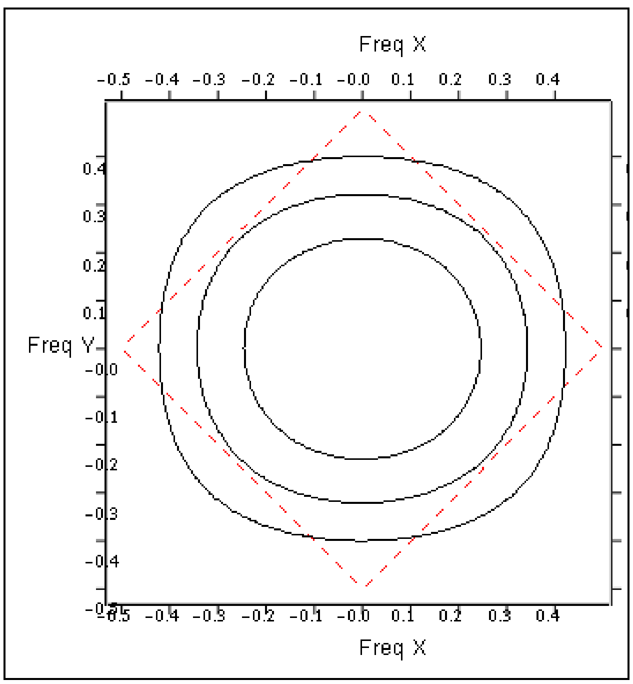


Fig 1.b MTF and reciprocal cell for SPOT 5 THR mode

The square plotted in dot lines is the THR reciprocal cell and the curves represent the MTF contour levels with level values 0.35;0.15;0.05. MTF maximum value outside from the reciprocal cell is 0.15 and aliasing is dramatically reduced.

Panchromatic band was initially specified with minimum linewise (0.25) and columnwise (0.23) MTF values at Nyquist frequencies for the 5m classical mode. This induces a MTF value of 0.09 at Nyquist frequency for the quincunx mode along the 45° frequency direction. This direction corresponds to $\left(\left(f_x, f_y\right) = \left(\frac{1}{5\sqrt{2}} m^{-1}, \frac{1}{5\sqrt{2}} m^{-1}\right)\right.$, where aliasing is maximum for THR mode. This value of 0.09 was low enough to assure that THR would be nearly alias free but the counterpart was a rather blurry image at the system output.

However, through improvements brought to the telescope development, the final results were much higher : (0.34,0.30) for 5 m mode and 0.15 for THR mode as quoted before.

To conclude this chapter, SPOT 5 THR panchromatic was specified considering image quality as a (MTF, SNR, sampling grid) triplet.

- MTF : 0.09 at THR Nyquist frequency
- SNR : 110 et L2=118 $Wm^{-2}Str^{-1}mm^{-1}$
- Sampling grid specifications put constraints upon the offset between the two 5m grids, concerning both the two line detector realization and high frequency attitude disturbances since there is a time delay of 2.2ms between the successive acquisitions by the two linear arrays.

The static offset had been specified to lie within (0.45pixel;0.55pixel) and the unknown offset due to attitude disturbances was limited to 0.1 pixel.
As in flight commissioning pointed it out (cf [4]), each of these specifications were met with margins and made THR mode the first example of sampling/MTF adaptation, thus leading to a global optimization of SPOT 5 HRG instrument.

2. SPOT 5 INSTRUMENT

Derived from the SPOT series, the SPOT 5 instrument, called HRG will perform Earth mapping with considerably improved resolutions : 5 m and 2.5 m (after processing) in the panchromatic band, to be compared with 10 m for the SPOT 1 to SPOT 4 camera series. This improvement is obtained with a new focal plane concept and with significant telescope enhancements.

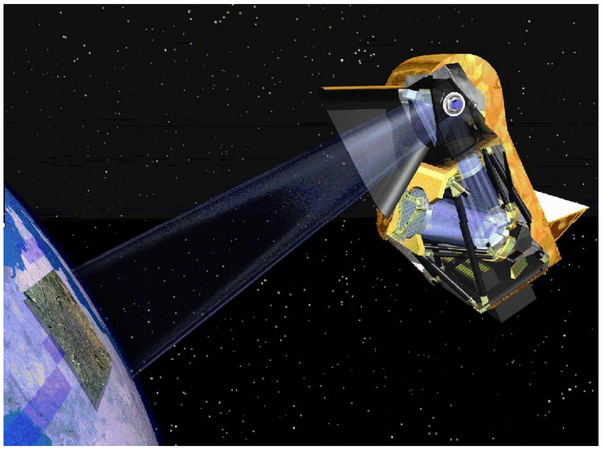


Figure 2. Artist view of the HRG

This chapter describes how the optical quality of the SPOT 5 camera has been improved for meeting the new resolution requirements, while still using the same type of telescope as SPOT 4.

2.1 Instrument overview

The SPOT instruments concept is based on a catadioptric telescope. The optical formula is an on-axis Schmidt combination optimized for a +/-2.1 degrees cross track field of view with a focal length of 1082 mm for a pupil diameter of 334 mm.

The light coming from Earth radiance first hits a flat folding mirror. This mirror is driven by a stepper motor allowing of track-pointing within a range of +/-27 degrees. The optical beam is then reflected towards the front Schmidt corrector made of two aspherical lenses, located at entrance pupil level. Afterwards, a fixed flat mirror folds the light beam to reduce the overall size of the telescope. Then, a concave spherical mirror focuses the light for ensuring the focal length of the formula. Lastly, a refocusing mechanism supports the two field lenses, and permits in orbit focusing of the telescope. After a spectral separation performed by dichroic prisms, four visible and one middle infrared monolithic CCD lines collect the light in order to form the image of the earth.

2.2 Focal plane improvement

Thanks to the pupil diameter of 334 mm, the theoretical telescope resolution power is about one meter resolution (400cycles/mm at the focal plane).

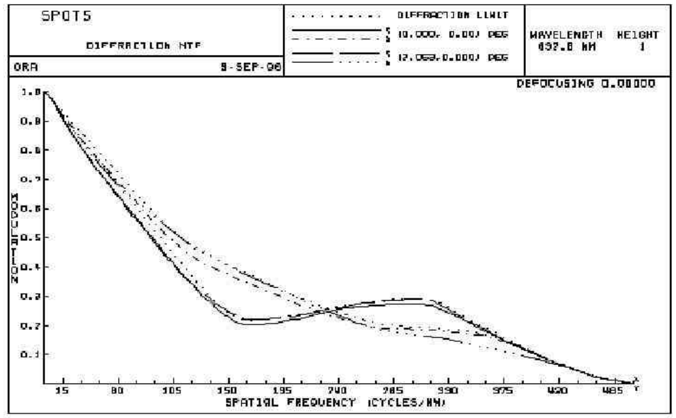


Figure 3. Theorical diffraction MTF of the HRG telescope

The first improvement was to design a focal plane with a CCD pixel size of 6.5 µm, instead of 13 µm for SPOT 4. This leads to a resolution of 5 meters. The resolution of 2.5 meter is achieved with a special configuration of this detector. It is composed of 2 CCD lines of 12000 pixels each, separated by 22.5 µm, and both on the same chip.

The flux losses due to the reduction of the pixel size are partly balanced by the increase of the spectral band (B2 for SPOT 4 and PAN for SPOT 5), by the abandon of the SPOT 4 line prism coupler (50% of losses) and by the optimisation of the telescope transmission.

2.3 Telescope structure improvement

Even with an adequate focal plane, the SPOT 4 telescope quality is not sufficient to achieve the spatial resolution.

The first aberration which limits the resolution is the shift of focus due to the telescope structure instability. The structure of the SPOT 5 camera is based on the same recurrent concept for all the instruments of the SPOT series. This is an hyperstatic design composed of two sets of beams made of carbon fiber with titanium tips. The main sources of instability come from the moisture release and from the control of the thermal expansion of the beams .

The Coefficient of Moisture Expansion (CME) has been optimized to minimize the focus variation and to reduce the outgazing time constant, in order to reach stable performances as quickly as possible (i.e. in the first months of the mission). Those objectives have been achieved by taking the commonly used composite of cyanate fiber M55J, with the RS3M resin. The performances have been refined also by optimizing the fiber draping. For the SPOT-5 camera the maximum defocus value is 3 µm (20 µm for SPOT 4 camera). This stability ensures a negligible MTF degradation.

Figure 4. The SPOT series structure

2.4 Thermal control refinement

The thermal control of the HRG instrument is based on the same principle as the previous models : A passive thermal control ensures an average temperature of the instrument of 20°C, whereas an active regulation deals with the critical areas.

Since the HRG optical MTF is very sensitive to optics distortion induced by gradients, the thermal design has been improved by increasing the number of the items to be controlled from 16 for SPOT-4 to 26 for SPOT-5. Furthermore, the regulation threshold have been also brought closer to reach a temperature control accuracy of +/-0.3°C, compared with +/-0.6°C for the previous models.

Thanks to these improvements, the thermal instability was divided by two.

2.5 Mirror Fixation Device (MFD)

Once the structure is stable, the main problem is to keep the mirrors at the right place, without any deformation and without sensitivity to the gravity release effect. This is devoted to the mirror fixation devices (MFDs). Each mirror of the SPOT series camera is mounted on a barrel with 3 MFDs; this ensemble is then fixed to the telescope primary structure on an interface base plate.

On the previous SPOT models, these mirror fixations were achieved by 3 blades with spherical bearings. These hyperstatic MFDs induce too much mirror deformation (about 10µm of astigmatism) and position instability (about 20µm). A new concept of isostatic mounts was developed. The maximum degradation induced by these MFDs is better than 10nm RMS for each mirror, including gravity effects and the position stability is better than 1µm

The insensitivity of the telescope to the gravity has been checked with “+1g” and “–1g” interferogram acquisitions ; the derived “0g” map presents a difference of only a few nanometers with respect the “1g”; besides the map analysis shows that no constraints are injected in the mirrors, which demonstrates the MFDs filtering efficiency.

2.6 Optical alignment improvement

Once the optical elements are well maintained in position, it is possible to achieve a very precise optical alignment. From SPOT-1 to SPOT-4, telescope alignment was performed on the base of theodolite pointings. The optical performance achieved by this method is about 50 nm RMS. For the HRG instrument, this process has been drastically improved. The wave front error of the telescope is deduced from interferogram acquisitions. The analysis of the measured maps provides the displacements to be applied to chosen compensators for correcting the telescope misalignments. Special optics adjustment devices have been developed, with a motion resolution of a few dozens of microns, for meeting the wave front specification of 32 nm rms.

Furthermore, the refocusing mechanism was also significantly modified for reaching a step resolution of 0.7 µm, to be compared with 5 µm for the previous series. This highly contributes to reduce the focus error of the detection module.

2.7 Optics improvement

Once the structure is stable, and the telescope perfectly aligned, the latest aberrations which limit the optical quality are due to spherical aberration and to the polishing quality of the mirrors and the lenses. So the optical formula was re-optimized principally by introducing asphérisation of the Schmidt corrector. The resulting MTF of the telescope in the panchromatic band is greater than 63%.

The commonly achieved mirror wave front error is very close to 15 nm rms. For meeting the very demanding 32 nm rms requirement, a computer assisted polishing method was developed. The principle is based on the re-shaping of the first surface of the first front lens, located at the entrance pupil for compensating residual manufacturing aberrations. This reshaping is obtained by the analysis of the wave front maps of the whole align telescope, measured under vacuum. A quick converging iterative process allows to remove the latter distortions and provides spectacular performances improvement. After telescope alignment, the specification of 32 nm rms is successfully met.

2.8 MTF simulation

To quantify these improvements on the optical quality, we have simulated the effect on the MTF of these improvements, step by step. The starting point is the SPOT 4 telescope, with the focal plane of SPOT 5. It shows firstly that even if the performance is good at 10 meters with the SPOT 4 design, the performance is almost zero with the focal plane of SPOT 5. In second, we can notice that all improvements are necessary to fulfill the specification.

	MTF	
SPOT 4 Begin of life	31%	10 meters resolution
SPOT 4 with SPOT 5 focal plane	3%	5 meters resolution
Structure and thermal control improvement	14%	
MFD improvement	17%	
optical alignment with computer	21%	
Aspherisation and reshaping of the whole telescope	25% 5%	5 meters resolution 3 meters resolution

table I : From Spot 4 to Spot 5, impact of the improvements.

2.9 Acknowledgement

The HRG camera study and development have been carried out on the behalf of CNES under the responsibility of ASTRIUM, with the participation of SAGEM-REOSC for the telescope optics, MATRA Bae Dynamics for the structure with MBS for the cyanate beams, ALCATEL for the video electronics, SODERN for the focal plane assembly and THOMSON TCS for the detectors.

3. SPOT5 INSTRUMENT IN-FLIGHT PERFORMANCES

The image quality performances have been assessed during commissioning phase and are monitored along the routine period. To reach this goal, the CNES team uses specific target programming in order to compute image correction parameters described in [5] and estimate the performance, at system level, of the image processing chain. The radiometric quality of the corrected images is quantified by several signal-to-noise ratio measurements. Numerical counts observed on uniform landscapes images are not strictly constant : apart from the onboard 8-bits digitization that induces maximum fluctuation of +/- 0.5 LSB, noise is caused by two separate phenomena :

- Column wise noise : caused by the Poisson fluctuation of the signal delivered by the CCD and various constant on-board chain noises.
- Line wise noise : normalization residues (radiometric model deviation) may cause visible “columns” on a uniform landscape. They are estimated to less than 0,1% of signal for SPOT 5 and 0,3% for SPOT 4.

For each image, the two noises are combined (root sum square) in a “image noise” that quantifies the variation of the numerical counts on a uniform landscape. The method used to assess the column wise noise eliminate the landscape contributions by using two images of the same site (snowy expanses) [6]. The signal–to-noise ratio (SNR) of the different channels is provided in table I. The SNR is calculated for the reference gain G3 and for a reference value of radiance L_{ref} ($W/m^2/sr/\mu m$). The SNR is compared with SPOT 4 instrument performances.

		SNR (SPOT 5)		SNR (SPOT 4)	
	Lref	column	image	column	image
HM/M	120	148	146	171	149

Table II : Signal-to-noise ratio

With the improvement of SPOT 5 ground resolution (5m x 5m) compared with SPOT 4 (10m x 10m), the signal is divided by 8, consequently the SNR also decreases. However, many improvements described in paragraph 2 limit the SNR degradation.

Restitution of the landscape contrasts viewed through the instrument is related to the Modulation Transfert Function (MTF) (Fourier transform of the response to a point source or PSF). Images of a spotlight aimed at the satellite were acquired : these give the camera point spread function (PSF). Because the sampling rate is too large to get the MTF directly by computing a Fourier transform, we can get the results in two ways [7]. The first way consists in using one spotlight image and fitting to a PSF parametric model in order to compute two parameters : one for the MTF shape, the other one for the sub-position on the sampling grid. The second way uses a combination of several images with different sub-positions on the sampling grid in order to rebuild on over-sampled PSF from which the MTF can be computed without undesirable aliasing effect. Another method [8] uses a natural or artificial target with sharp transition between dark and bright uniform areas. An artificial target at Salon-de-Provence in the south of France has been used with HM mode (5m x 5m). The absolute MTF of HM mode is provided in table III.

	In-flight measurement	Ground measurement	Requirement
Across the track	0,34	0,31	0,25
Along the track	0,30	0,26	0,23

Table III : HRG1 absolute MTF of HM mode

The SPOT 5 success opened a new way to build efficient instrument. But to achieve sub meter resolution, new compromises have to be find by giving more optimised image specifications.

4. PLEIADES RADIOMETRIC IMAGE QUALITY SPECIFICATIONS

The aim is to define the image quality requirement at system level and to find the best trade-off between the overall satellite + ground segment cost and the final performances. Taking ground processing into account in system design is a relatively new concept in the field of resolution. The first operational application is on SPOT 5 with THR mode [2]. Pleiades-HR system design is chiefly determined by the specifications for radiometric image quality in the panchromatic band which supplies the images with the highest resolution. The radiometric image quality is defined by :

- The sampling interval : It is set at 70 cm for nadir viewing.
- The MTF : It must be quite high over the interval [-fe/2, fe/2] and vanish beyond fe/2 (fe is the sampling frequency).
- The SNR : It must be sufficient to maintain the high frequencies transmitted by the MTF and the sampling.

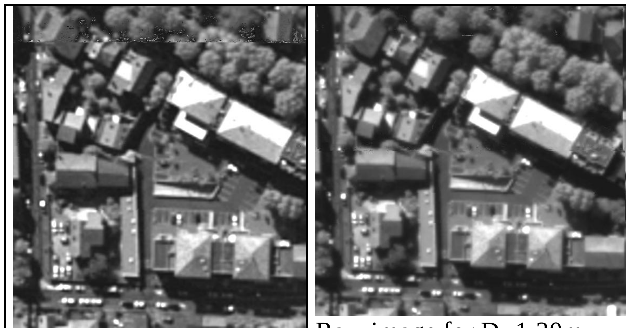
The MTF is considered after ground processing. As for SPOT 5 THR deconvolution, we define a higher MTF_{target} than the real instrument MTF, whose variations are realistic i.e decreasing according to spatial frequencies. The filter D = MTF_{target}/MTF is called a deconvolution filter and restores the image contrasts. The operation is linear filtering which is legitimate since the image is correctly sampled. For a sampling frequency fe, a sampled image will be of good quality if its MTF is near zero at fe/2, which comes down to saying that the finest details visible on the sampled image (spatial frequencies close to fe/2) are blurred. Deconvolution raises the high frequencies in the image but amplifies the noise (particularly in high resolution images that are very often noisy because of lack of signal). So a denoising process must be run. The ground processing planned on Pleiades is inherited from the work conducted on the SPOT 5 satellite. The main design parameter is the SNR x MTF product, which determines the useful support of the MTF and hence image resolution. It is nevertheless understood that for the same value of this product, all the pairs (MTF, SNR) do not correspond to images of the same quality. This is because the information attenuated by a near zero MTF cannot be used, even if the SNR is very high. On the other hand, a detail submerged by excessive noise cannot be restored, even if it was transmitted in the sharpest manner by a very high MTF. We consider the full specification of the instrumental MTF and the SNR to be written as follows, at the given frequency f_0 :

$\forall |f| \leq fo$, MTF(f) $\geq$ MTF threshold
SNR $\geq$ SNR threshold
MTF(f).SNR $\geq$ MTF*SNR threshold

To determinate the value of these thresholds, we consulted a group of users to whom we submitted several simulated images that are representative of the on-board acquisition system and the ground processing [9]. The specification in the panchromatic band was established at the following values :

$\forall |f| \leq fo$, MTF(f) ≥ 0.07
SNR ≥ 90
MTF(f). SNR ≥ 7

With these specifications, the panchromatic Pleiades-HR restored image quality is better than a non-restored image that would have been acquired by a camera diameter D~1,3m (twice larger than Pleiades HR diameter). The following simulated pictures show how panchromatic image restoration can improve the raw image quality :



Pleiades restored image (D=0.65m)

Raw image for D=1.30m

Figure 5 : enhancement due to the restoration

The raw image for D=1.3m can't be restored because it is polluted by the substantial aliasing due to high MTF near the Nyquist frequency.

These radiometric Pleiades-HR specifications achieve the on-board/ground design compromise and allow to propose a cheaper instrument adapted with ground processing to the requirement of users.

5. The Pleiades-HR instrument

The image quality requirements for PLEIADES-HR (high resolution) together with newly available technologies lead to an instrument completely different from SPOT-5's HRGs (even though it is also a push-broom instrument).

First, due to the high spatial resolution that reduces the integration time, it is no longer possible to use the supermode sampling scheme. The SNR can only be met by slowing down the satellite's ground speed for instance by a pitch motion, or by electronically increasing the integration time with a TDI (time delay and integration) detector. With the newly available detectors, the latter solution is the most practical, so it has been retained for PLEIADES-HR. As these detectors come as area arrays with small numbers of rows, they cannot be placed close together in the field of view as is required for stability needs with the HRG's supermode sampling.

These TDI detectors also have larger pixels, which means that the telescope must have a larger focal length. In our case, the 13-µm pixel pitch yields a 13-m focal length. It has to be recalled here that another main driver for the PLEIADES-HR satellite dimensioning is a large imaging capacity. The HRG has a pointing mirror for this purpose. It is no longer possible first because the telescope is wider and would implies a still larger pointing mirror, but also because a two-axis pointing is needed. So the satellite is designed for high agility:

- small spacecraft, i.e. small instrument (of course, launch cost is also a major driver for this),
- small inertia, which is obtained by placing the instrument near the center of gravity, inside the platform.

If a classical MTF criterion was to be taken (see § 1), it would yield a 1.3-m pupil diameter, which cannot be combined with the focal length unless the field of view becomes uselessly small. This was one reason to look for looser MTF requirements. As shown on Fig. 5, the 650-mm pupil leads to restored images with the same quality as raw 1.3-m telescope images. Furthermore, at this low speed (f/20), the telescope is more tolerant and can be made more compact than a f/10 telescope with regard to its focal length: it then implies that it is not necessary to achieve much smaller pixels (6.5 µm for instance).

Compared to the spatial resolution, the swath is very wide (21 km; 5 detector must be butted to get the 30 000 corresponding pixels): telescopes of the Korsch type (on-axis or off-axis) represent the best compromise with simplicity and compactness. In order to lower the polishing difficulties, already highly demanding, the retained configuration is the on-axis one, with a 90°-folding after the secondary mirror. With high magnification at intermediate images, it still requires high stability (a few µm for the distance between the primary and secondary mirrors). This leads to the choice of C/C composite for the main structure and zerodur for the mirrors.

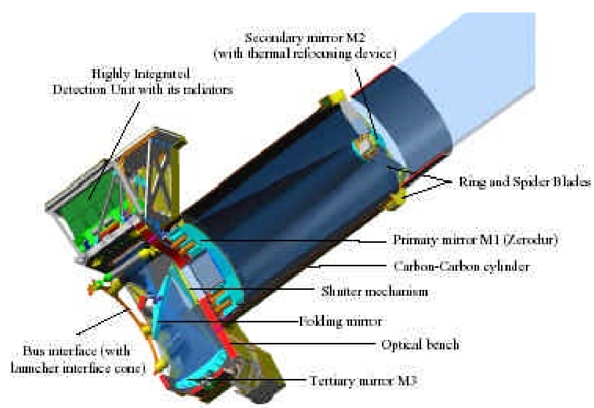


Figure 6. PLEIADES-HR instrument exploded view.

The main drawback comes from the exit pupil position, which imposes high ray incidence at the focal plane: it creates a rather high distortion, which has an impact on the MTF in the case of a TDI detector. But thanks to its good quantum efficiency, the SNR performance can be achieved with a relatively small number of rows, which yields a reasonably small MTF loss. This high incidence also makes it more difficult to accommodate the filters for the different spectral bands.

Thanks to advances in the technology and image processing fields, it has been possible to design an instrument that has good optical quality without exceeding the size and mass limits imposed by the small satellite constraints.

Readers who would like to know more about the details of this instrument should refer to [10].

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