In-flight refocusing and MTF assessment of SPOT5 HRG and HRS cameras

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ABSTRACT

The MTF (Modulation Transfer Function) is a means of characterizing the spatial resolution of the instruments. So, the MTFs of HRG and HRS cameras are parts of image quality parameters assessed during the in-flight commissioning phase. Vibrations during the launch and transition from air to vacuum may defocus the HRG cameras and degrade their MTF. Therefore, SPOT5 HRG cameras are refocused before measuring their MTF. The paper first describes the HRG focusing procedure that uses both cameras viewing the same landscape: the focus of one camera is changed while the other is fixed and used as a reference. Results are given for each camera in terms of best focus and focus variation in the field of view. These results are compared to those provided by an autotest system, on-board each HRG camera, that images a high frequency periodic pattern while the focus is changed. Then, MTF measurements are presented. The MTF of HRG cameras is measured by imaging a spotlight that aimed at the satellite; the results are compared with pre-flight measurements. Besides, the MTF of HRS cameras is assessed by imaging landscapes with edge patterns; the main objective is to compare the two HRS cameras.

Keywords: SPOT5, HRG, HRS, MTF, PSF, camera focusing

1. INTRODUCTION

The MTF (Modulation Transfer Function) is a means of characterizing the spatial resolution of the instruments. Restitution of the landscape contrasts viewed through the instrument is related to the MTF that is the Fourier transform of the impulse response (response at a point source or PSF). The MTF results from the cumulative effects of the instrumental optics (diffraction, aberrations, focusing error), integration on a photosensitive surface, charge diffusion along the array and image motion induced by the movement of the satellite during imaging. Thus, the MTFs of HRG and HRS cameras are parts of image quality parameters assessed during the commissioning phase. Moreover, an accurate knowledge of MTF is useful to adjust deconvolution filters used in the THR mode. Vibrations during the launch and transition from air to vacuum may slightly defocus the HRG cameras and degrade their MTF. Therefore, SPOT5 HRG cameras are refocused before measuring their MTF.

In the first section, we will describe the HRG focusing procedure, then we will present the results of focusing for each camera. We will discuss an alternative method too.

The second section concerns the relative and absolute MTF measurements. We will present the MTF measurements methods and some first results.

The third section concerns the MTF assessment of HRS cameras. As these cameras are used to produce stereoscopic views, an important requirement is the similarity of MTFs. Therefore, the main objective is to measure the MTF difference rather absolute MTF. An attempt to directly compare the HRS camera will be discussed.

2. HRG REFOCUSING

As for their predecessors, HRV aboard SPOT1, 2 & 3, and HRVIR aboard SPOT4, both HRG instruments are equipped with a refocusing mechanism. On the ground, this mechanism is positioned on the best step measured in a vacuum. Nevertheless, possible movement during launch may upset this focusing so that the position of each mechanism has to be checked and, if necessary, altered.

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2.1 Method

The refocusing method[1,2] uses the two HRG cameras simultaneously viewing the same target. Several couples of scenes with many details, such as urban areas, are selected from the refocusing image sequence. The focus of one camera is left fixed and is used as reference while the refocusing mechanism of the other camera is varied around its initial position. For each couple of scenes, we calculate the ratio of the Fourier transforms of corresponding images. The best focus is reached while maximizing this spectrum ratio, which varies as a near-parabolic function near its vertex. In order to improve the accuracy, a defocusing model can be fitted on measurements by a least-square optimization. The vertex of this curve gives the best focus position. Column-wise and row-wise spectrum ratios are computed to characterize camera astigmatism. Moreover, the method is performed in three areas of the field of view: the center and the two edges.

This refocusing is performed in the panchromatic mode. An examination of the first images acquired in this mode revealed that there was no significant defocus. In order to choose which camera to start with, we compared their MTFs (§3.1). In-flight measurements show that they were equivalent, so the choice is rather arbitrary. We chose to refocus HRG1 first because of a slightly greater uncertainty in its initial focusing.

We moved first the mechanism +/- 8 steps around its current position p_0. This is a very small defocusing value, about 9.5 µm. Therefore, we can test the focusing mechanism without reaching large defocusing values. If the vertex of the curve is not included between p_0-8 and p_0+8, the vertex position is extrapolated from the measurements. Therefore, the best focus determination can be inaccurate. Then, the mechanism is operated again with a sufficient walk to overpass the best focus.

The global best focus is a weighted average of the best foci for the different field areas and both measurement directions (rows and columns). Once its best focus is determined, the first camera is focused and can be used as a reference for the second one.

2.2 Results

An example of best focus determination is shown hereafter for the field center of HRG1 (Fig. 1) and HRG2 (Fig. 2). The whole of results is shown in Table 1. Finally, the HRG1 focus mechanism was set to p_0-12 and the HRG2 focus mechanism was set to p_0-7.

When comparing ground and in-flight focus measurements (Table 2), we observe the in-flight astigmatism is slighter. We observe also the HRG1 defocus is –11 steps and the HRG2 defocus is –9 steps.

HRG1			
Field area	Left	Center	Right
Rows	-12.8	-16.6	-13.0
Columns	-5.9	-10.0	-8.7
Mean	-9.4	-13.3	-10.8
Astigmatism	-6.8	-6.6	-4.3

HRG2			
Field area	Left	Center	Right
Rows	0.7	-8.7	-14.6
Columns	2.6	-5.3	-7.1
Mean	1.7	-7.0	-10.8
Astigmatism	-1.9	-3.4	-7.5

Table 1: Best focus position with respect to initial position p_0

HRG1		
	Ground	In-flight
Rows	-6.7	-16.6
Columns	1.3	-10.0
Mean	-2.7	-13.3
Astigmatism	-8.0	-6.6

HRG2		
	Ground	In-flight
Rows	-1.6	-8.7
Columns	5.3	-5.3
Mean	1.9	-7.0
Astigmatism	-6.9	-3.4

Table 2: Ground and in-flight best focus position of field center with respect to position p_0

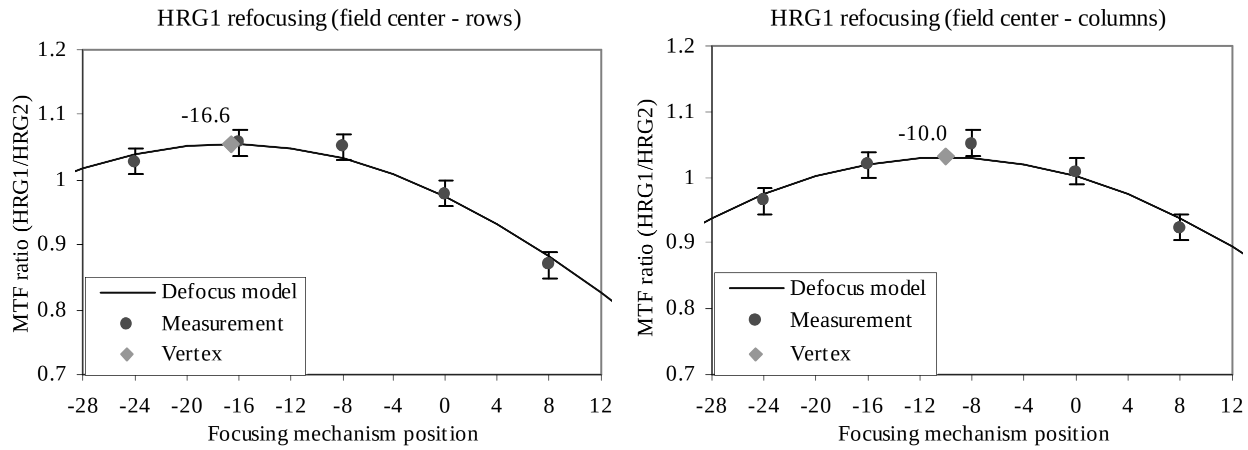

Fig. 1: Defocus model fitting on HRG1 field center measurements

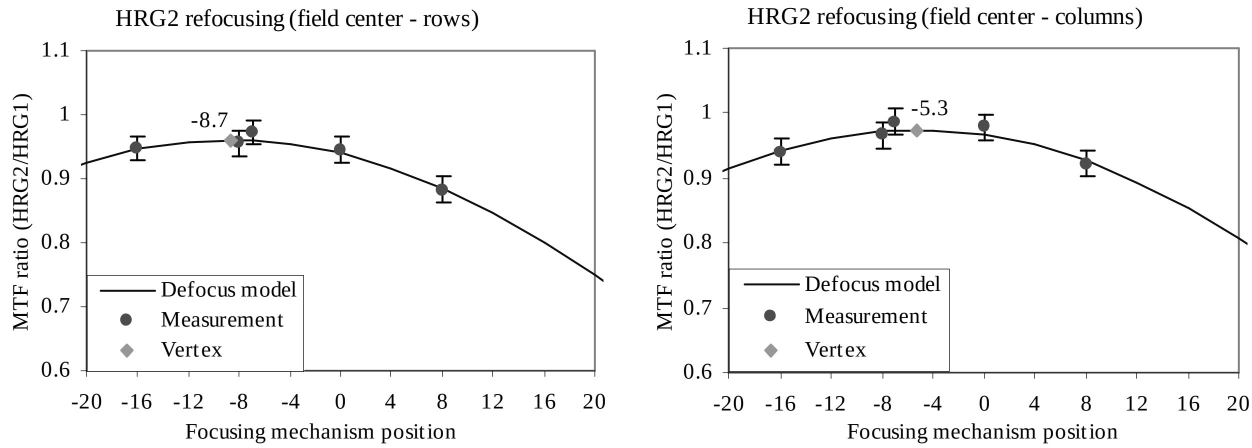

Fig. 2: Defocus model fitting on HRG2 field center measurements

2.3 Autotest

The best focus position can slightly move in the beginning of satellite life, due to desorption. The focusing method described above gives accurate results, but it requires a number of images. Therefore, it is rather heavy to check the focusing from time to time. An alternative method could be to use the so-called "autotest" periodic test pattern that is located in the focal plane at the end of the B2 CCD array. The steering mirror can image this pattern on the HM array by autocollimation. The principle is to acquire a set of autotest images for different positions of the focusing mechanism.

The best focus is reached while maximizing the contrast of the pattern image, which varies as a near-parabolic function. So, a parabola is fitted on the contrast measurements. The vertex position gives the best focus. In fact, the pattern is not exactly in the same plane as the array. There is a difference Δ of a few micrometers between the two planes. In consequence, the parabola vertex position is not the same as the best focus position of the camera. Nevertheless, once we have determined this difference, it is sufficient to use the autotest method and to add the difference to the autotest focus position to know the best focus position of the camera. Note that because of autocollimation the mechanism movement should be $\Delta/2$.

The pattern spatial frequency is 71 mm^{-1} while the Nyquist frequency is 77 mm^{-1}. As the pattern is parallel to columns and its frequency is near the Nyquist frequency, there is a moiré effect in the image (Fig. 3). An algorithm allows searching the area where there is a maximum contrast.

This method was played on HRG1 at the end of the focusing measurements. The focusing mechanism was moved 16 steps around the best position, i.e. from p_0-28 to p_0+4. The determined autotest focus position is p_0+12, that is to say, the parabola vertex is extrapolated from measurements and the vertex position is not quite accurate. The difference between the two mechanism positions is 24 steps. To obtain a more accurate measurement of autotest focus position, the mechanism should be moved from its good position p_0-12 up to p_0+12. This movement is thought too significant and critical. Consequently, the autotest focusing method is given up.

A new method is currently studied. It consists in merely measuring the contrast of autotest image without any focusing mechanism movement. A contrast change should point a variation of camera focusing. We need to evaluate the sensitivity of this method.

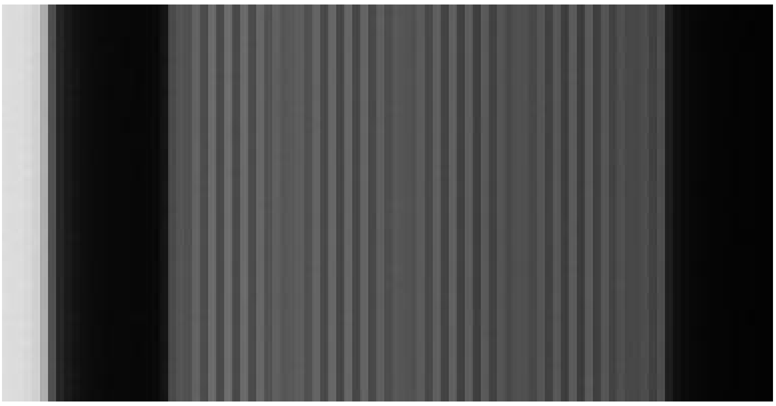

Fig. 3: Image of autotest periodic pattern

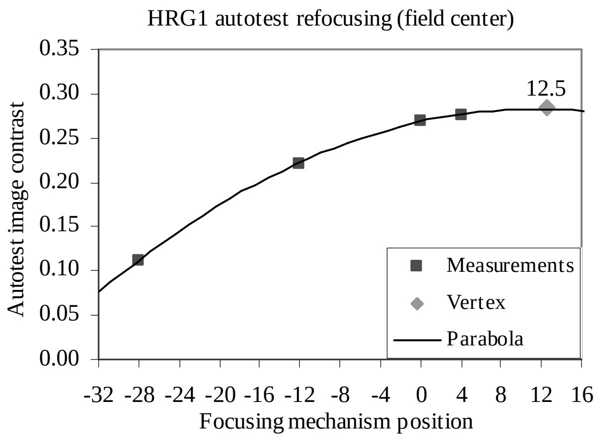

Fig. 4: Parabola fitting on HRG1 autotest contrast measurements

3. MTF MEASUREMENT OF THE HRG CAMERAS

3.1 Relative MTF

The spectrum comparison tool used for refocusing can also compute the MTF ratio of the two cameras near the frequency 0.3 f_e (f_e = frequency sampling rate). We can directly compare one instrument with the other when both instruments view the same landscape. As for the focusing measurements, the comparison can be done versus the field area (left, center and right). We want also compare the MTF in the field of one instrument. With this aim, we need couple of images where the same landscape is viewed by the field center of one instrument, e.g. HRG1, and a field edge of the other instrument, e.g. left field of HRG2. Thus, we can successively obtain the MTF ratio for both HRG center fields and for HRG2 left field against HRG1 center field. We easily deduce the ratio of MTF HRG2 left field to MTF HRG2 field center and, in the same way, all other ratios. The method is used for both directions (rows and columns) and for every spectral band. The accuracy of such a comparison of image frequency contents is estimated by the measurement dispersion, that is 2% (see error bars in Fig. 1 and Fig. 2).

The first results show that both cameras have equivalent MTFs and have a uniform quality in the field of view.

3.2 Absolute MTF

In spite of its accuracy, the method of comparison only gives relative MTF measurements. Several methods were performed in order to compute absolute MTF.

3.2.1 Methods

Images of a spotlight aimed at the satellite were acquired. The spotlight is located in the middle of a grassy field, i.e. in a uniform area (Fig. 6). The spotlight stands for a Dirac distribution, thus its image is the camera point spread function (PSF). In a general case (e.g. HM or XI modes), the sampling pitch is too large to get the MTF directly by computing a Fourier transform. Then, we can get the results in two ways. The first way[3] consists of 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 an oversampled PSF from which the MTF can be computed without undesirable aliasing effect. For the panchromatic band of HRG, we have a peculiar case where the THR mode directly gives a sufficiently sampled image.

Another method[5] uses a natural or artificial target with sharp transitions between dark and bright uniform areas. If the transition is slightly inclined with respect to the row wise (or column wise) direction, one can interleave the successive rows (or columns) in order to get an oversampled response to the Heaviside function and then the 1-D MTF. However, this method needs uniform areas. Such natural areas may be difficult to select and the method is not used with HRG. There is an artificial target at Salon-de-Provence in the south of France. Due to its dimension, it can be used only with THR mode.

3.2.2 First results

The spotlight images acquired during the commissioning period are currently processed. We present an example of results for HRG1 (Fig. 5). These results should be confirmed with other images; however, we can do a preliminary comparison with ground measurements and camera requirements (Table 3). We observe the in-flight MTF values are higher than the ground MTF values and very higher than requirement values.

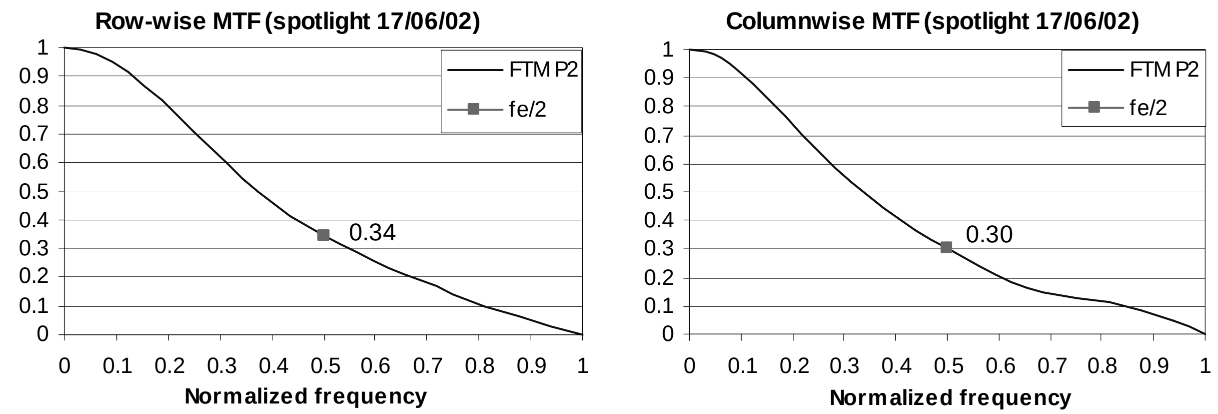

Fig. 5: HRG1 MTF (Panchromatic band)

HRG1	In-flight Measurement	Ground Measurement	Requirement
Across the track MTF	0.34	0.31	0.25
Along the track MTF	0.30	0.26	0.23

Table 3: First in-flight HRG1 MTF measurements

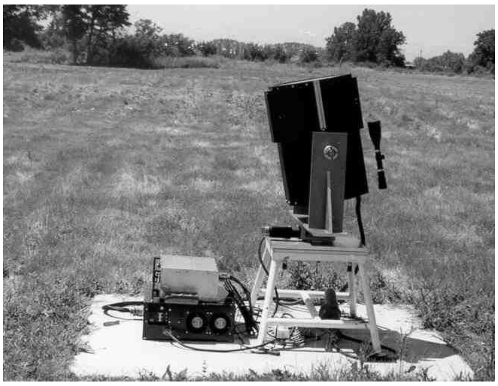

Fig. 6: Spotlight located on a grassy area near Toulouse

4. MTF MEASUREMENT OF THE HRS CAMERAS

4.1 Overview of the HRS system

The High Resolution Stereoscopic (HRS) system is constituted by two identical cameras. The view angle of the first camera is +20° along the track as the view angle of the second one is -20° (Fig. 7).

Usually, the pixel size and the sampling pitch are the same. For HRS, the pixel size and the sampling pitch across the track remain fixed by detector size, focal length and altitude and are equal to 10 meters. However, the pixel size along the track is larger than 10 meters due to the 20° view angle while the sampling pitch is chosen to be equal to 5 meters.

The swath is 120 km and the images are acquired in the panchromatic band (0.49 to 0.69 µm).

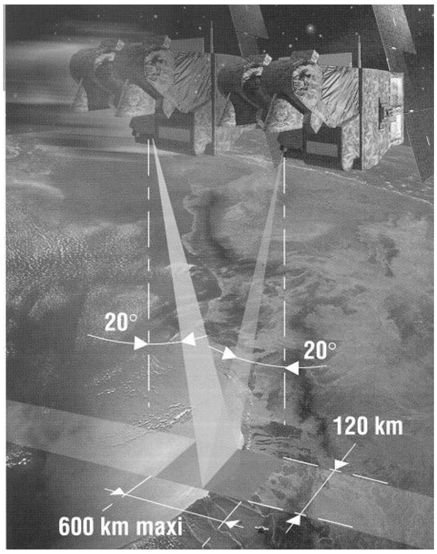

Fig. 7: HRS

4.2 The HRS comparison

Besides the usual MTF requirements (MTF above 0.18 at 0.05 m^{-1}), the HRS were required to have an MTF difference lower than 0.05. This requirement should be checked using the usual frequential comparison performed also for the HRG cameras (§ 3.1). The method accuracy was supposed to be spoiled by the parallax, but we have no idea of the magnitude of this degradation.

Several big cities have been imaged by HRS1 and HRS2. For each couple of images, several couples of smaller areas were extracted and for each couple, the ratio of the frequential content was computed.

For each couple of images, the standard deviation of the frequential contents was small (less than 5%), but the variation of the frequential content between couples of images has risen up to 50%! No correlation was found between the ratio of the frequential content and the solar position. The conclusion was drawn: the parallax fully spoiled the results and the method should be given up…

4.3 The MTF assessment

The decision was taken to measure the MTF of both HRS cameras, then to derive the comparison of the cameras from these measurements. The main method to measure the MTF relies on natural edge images[5,6,7].

Some edges were extracted from images near Phoenix and Mexicali. After 2D and 1D visualization, only few ones were kept and used for the MTF assessment. For each edge, a model MTF is fitted to MTF curve. The results obtained are shown in Table 4 and Table 5. An example of curve is presented in Fig. 8**.**

An attempt was made to use the artificial edge built near Salon-de-Provence. The size of the artificial target is definitely too small for the across track direction, but hope existed for the along track direction. Two measurements were done for HRS2. For HRS1, the MTF was clearly lower than for HRS2 and, as the blur increases, the target appears too small. The results are also in Table 5 and compared to ground measurements.

For HRS2, in-flight measurements are fully in agreement with ground values. For HRS1, the in-flight measurements are no longer showing the same astigmatism noticed for ground measurements.

For this reason, a new measurement using another and independent method was planned. We chose the point source method using the same spotlight as for HRG (§3.2). A spotlight is lighted and aimed at HRS1, then HRS2. A difficulty is we have to alter the orientation of the spotlight between the viewing by HRS1 and HRS2. We have only 90 s to do this. In order to overcome the undersampling of the image in the along rows direction, a model must be fitted on the Line Spread Function derived from the image[3]. The MTF in the concerned direction is computed by FFT of the values of the model. We not yet have HRS spotlight images, due to bad weather. There is only one opportunity to overpass the spotlight location every 26 days.

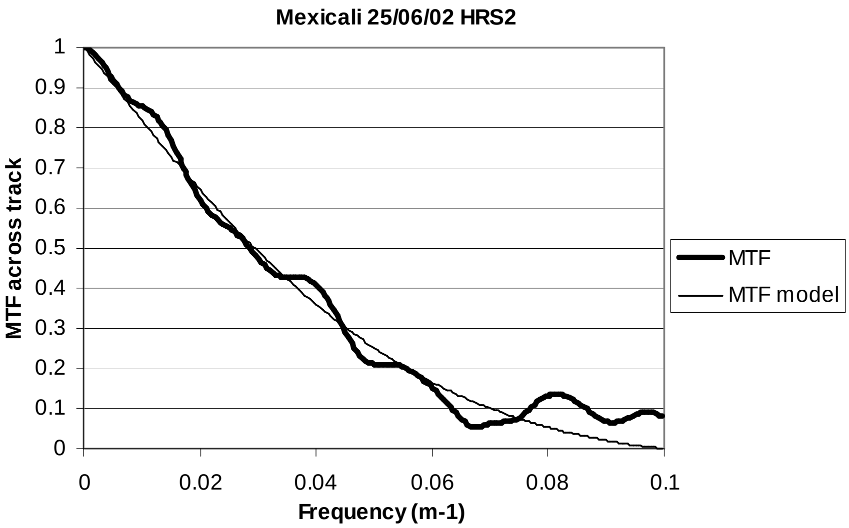

Fig. 8: example of HRS MTF curve

Along the track MTF	Measurement	**Model**	Ground defocus +1σ	Ground	**Ground defocus -1σ**
HRS1 col. 3315 to 3362 (Phoenix 10/06/02)	0.17	**0.20**	0.29	0.27	**0.24**
HRS2 col. 3390 to 3438 (Phoenix 10/06/02)	0.26	**0.29**	0.34	0.35	**0.33**
HRS2 col. 5830 to 5846 (Salon 23/06/02)	0.26	**0.31**	0.32	0.33	**0.31**
Disparity between HRS1 and HRS2	0.09	0.09	0.05	0.08	0.10

Table 4: HRS MTF results at $0.05m^{-1}$ (along the columns)

Across the track MTF	Measurement	**Model**	Ground defocus +1σ	Ground	**Ground defocus -1σ**
HRS1 col. 10007 to 10045 (Phoenix 10/06/02)	0.14	***0.21***	0.28	0.28	0.27
HRS1 col. 3840 to 3879 (Mexicali 25/06/02)	0.19	***0.22***	0.28	0.29	0.29
HRS1 col. 5301 to 5336 (Phoenix 06/07/02)	0.3	***0.23***	0.25	0.27	0.29
HRS1 col. 3916 to 3953 (Phoenix 06/07/02)	0.09	***0.18***	0.28	0.29	0.29
HRS2 col. 10072 to 10113 (Phoenix 10/06/02)	0.23	**0.30**	0.31	0.31	**0.29**
HRS2 col. 3899 to 3941 (Mexicali 25/06/02)	0.21	**0.26**	0.33	0.33	**0.31**
HRS2 col. 5379 to 5412 (Phoenix 06/07/02)	0.32	**0.26**	0.29	0.31	**0.31**
HRS2 Col. 3837 to 3878 (Phoenix 06/07/02)	0.21	**0.24**	0.33	0.33	**0.31**
Disparity between HRS1 and HRS2 (near col. 10100)	0.09	0.09	0.03	0.03	0.01
Disparity between HRS1 and HRS2 (near col. 3900)	0.02	0.04	0.05	0.04	0.02

Table 5: HRS MTF results at $0.05m^{-1}$ (along the rows)

4.4 HRS conclusion

The in-flight MTF measurements confirm the clear difference between HRS1 and HRS2. However, the correlation algorithms used to compute the disparity map for DTM production are not sensitive to this difference For the HRS1 astigmatism, results from spotlight measurements are requested to be able to draw a conclusion.

For the methods, the main conclusion concerns the usual frequential content comparison that is fully spoiled by the parallax. Happily, two independent direct MTF measurement methods were available. This enables to conclude to the actual in-flight HRS performances.

5. CONCLUSION

Both HRG cameras were refocused during the in-flight commissioning of SPOT5. The HRG MTF measurements have begun when the cameras were focused. The measurement methods, specially the spotlight method, were satisfactory. The first results show a high MTF quality. The requirements are amply carried out. It remains to process some images before to give final results.

The HRS MTF measurements confirm the clear difference between the cameras. Further measurements with the spotlight method would be useful to strengthen the results.

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