

On-orbit MTF and defocus assessment methods applied to SPOT5 cameras

Dominique Léger

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return on innovation

□ Objective

- **To maintain best image quality (sharpness)**
 - **Periodic assessment of cameras MTF during satellite life**
 - » **To verify cameras requirement specification**
 - **Assessment of possible slight defocusing**
 - » **To propose refocusing, if any**
 - **MTF assessment after refocusing**
 - » **To verify MTF increase**

Overview

- Spot 5 cameras outline
- MTF assessment methods
 - Absolute
 - Relative
- MTF results over the years
 - Field center, right field
- Defocusing assessment methods
- Results of defocusing assessment
- MTF results after refocusing
- Summary

SPOT 5 cameras outline

□ Main features of SPOT 5

- Two cameras (HRG)
 - Pointing mirrors to set viewing angle
- THR (2.5m), **HM (5m)** **B1**, **B2**, **B3** (10m), **B4** (20m)
 - HM used for MTF quality control
- Panchromatic mode HM : two linear arrays
 - HMA and HMB shifted 0.5 pixel (cross-track) and 3.5 pixels (along track)



MTF assessment methods

□ Absolute MTF

- Measurement of Modulation Transfer Function
 - MTF value at Nyquist frequency
- Slanted edge method
- Artificial target (checkerboard)

□ Relative MTF

- Comparison of two HRG cameras
 - Both cameras image the same landscape

Absolute MTF measurement method

- ❑ Artificial edge target
 - Salon de Provence (south of France)
 - 60m x 60m
 - White: $\rho = 0.50$ - Dark: $\rho = 0.05$
 - Inclination versus satellite track: $\sim 18^\circ$



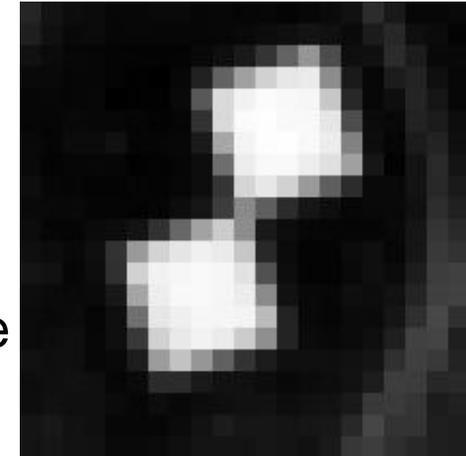
SPOT5 HRG1 (THR)



Absolute MTF measurement method

❑ Slanted edge method

- Due to inclination angle
 - 3 lines needed for oversampling purpose
- Due to the PSF width
 - Only 2 lines available without side effect from other squares or surrounding area
- One point out of three is missing in ESF
 - Missing points obtained by spline interpolation
- MTF obtained by calculating the ratio of FFT of ESF to FFT of Heaviside function
- Mean of upward and downward edges
- Mean of HMA and HMB results



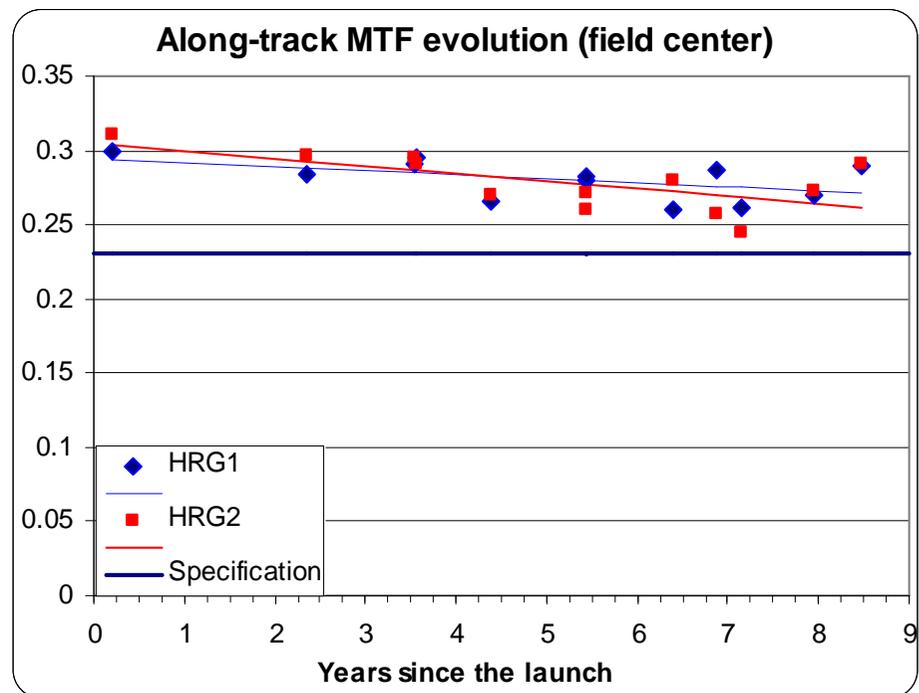
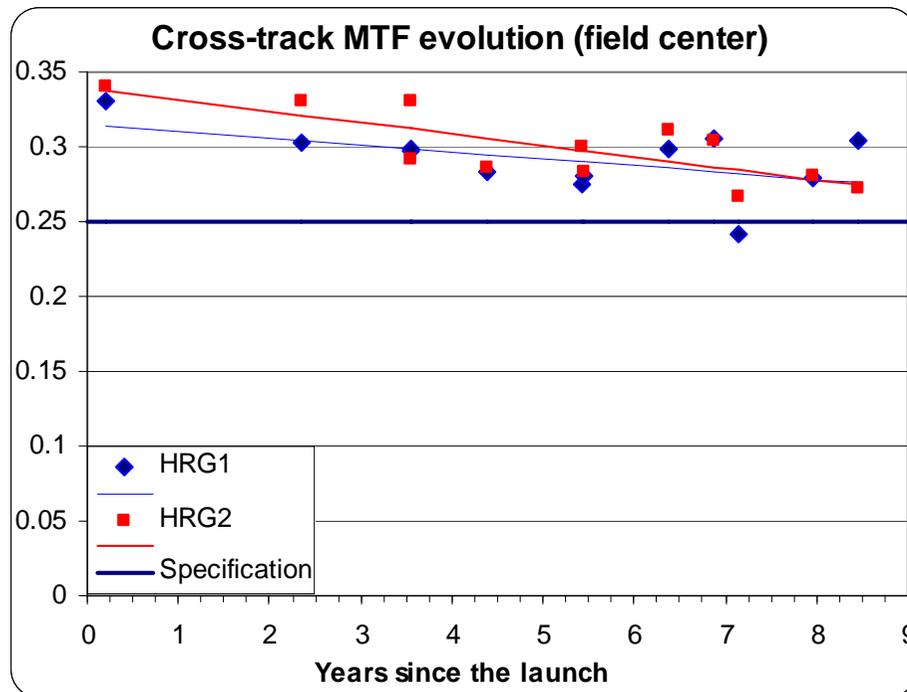
Relative MTF measurement method

- Comparison of frequency content of two HRG images
 - Both cameras image the same landscape
 - Landscapes with a large frequency content (e.g. big cities)
 - Frequency content comparison between homologous areas
 - Field center, field edges
- | | | | |
|------|---|---|---|
| | L | C | R |
| HRG1 | | | |
| HRG2 | | | |
- Integration of image spectra near $0.3 f_s$
 - » From $0.25 f_s$ to $0.35 f_s$
 - Calculation of MTF ratio HRG2/HRG1

MTF assessment results

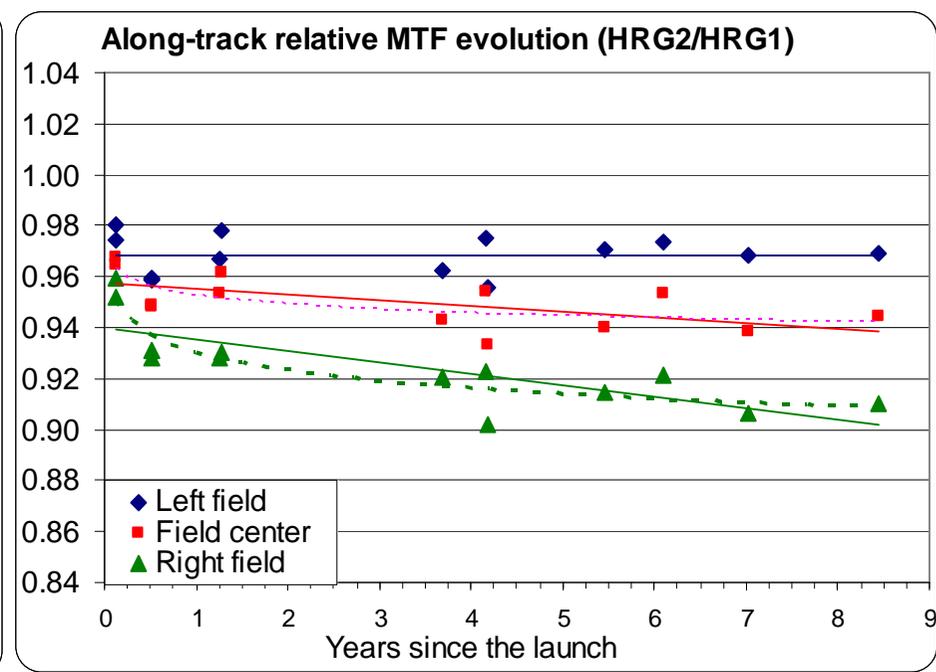
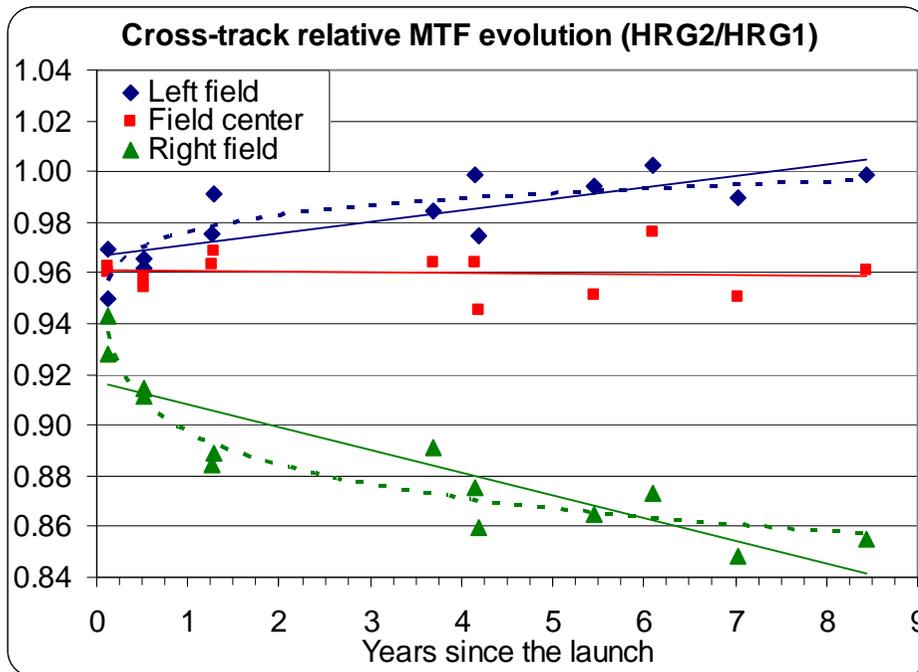
□ Absolute MTF – field center (2002-2010)

- Slight decrease since the beginning of life
- It remains above requirement specification



MTF assessment results

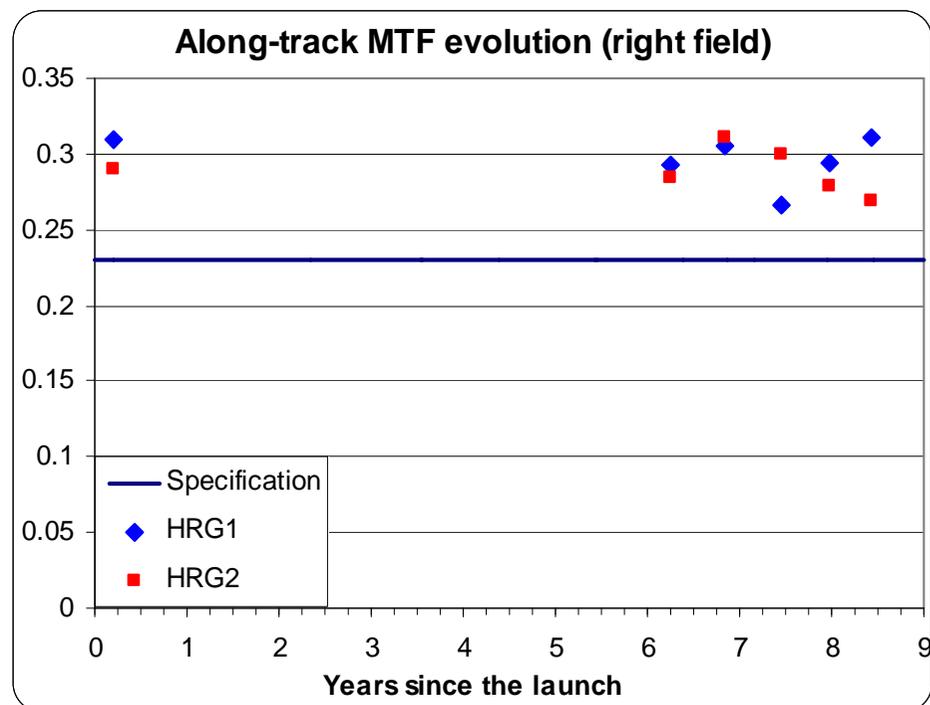
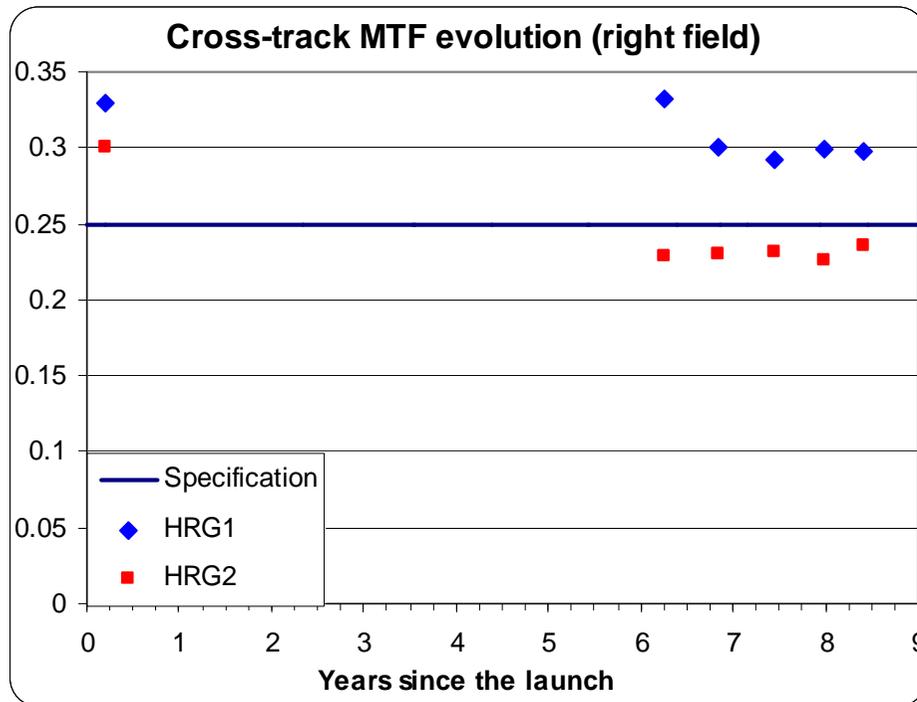
- Relative MTF – field center and two field edges
 - Decrease of right field value (cross-track direction)
→ Absolute MTF measurement since 2008



MTF assessment results

□ Absolute MTF – right field (2008-2010)

- Decrease in cross-track direction compared to the beginning of life
- It has become slightly under requirement specification
 - Blur is too small to be perceptible



Defocusing assessment methods

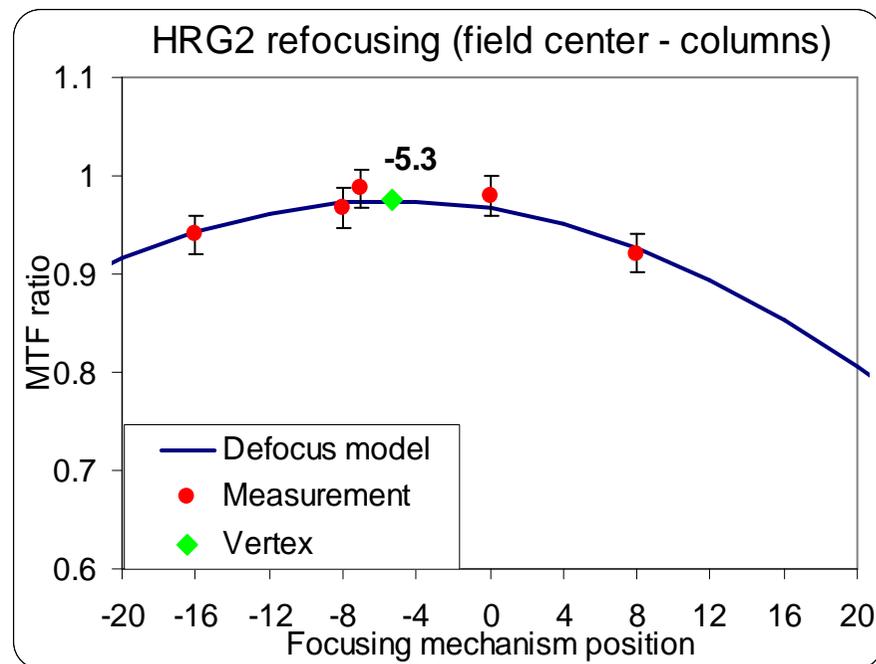
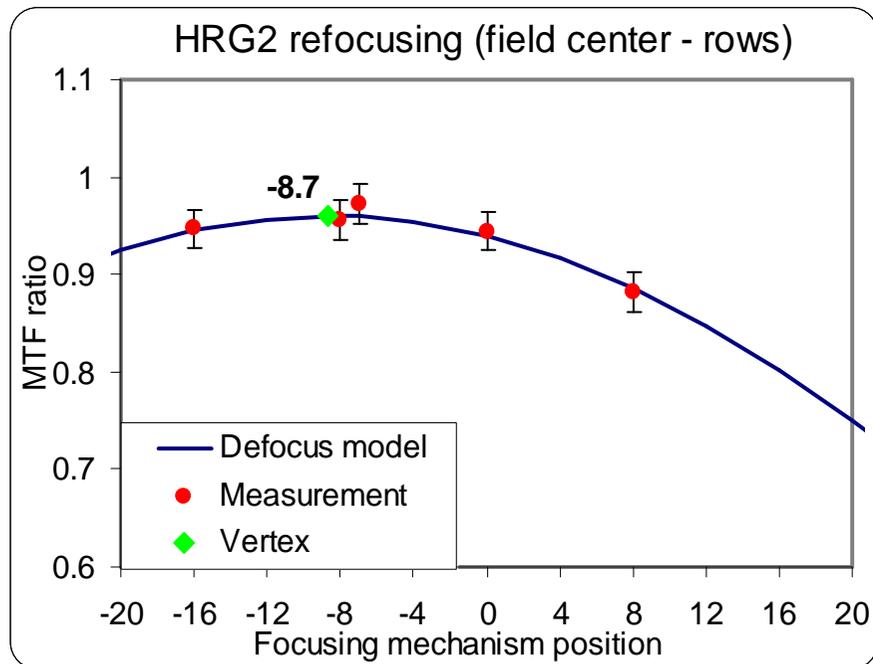
- ❑ With refocusing mechanism activation
 - Relative MTF for several mechanism positions of **one** camera
 - Method used in the commissioning phase
 - Precise measurements of best focus position
 - Too cumbersome in commercial context

- ❑ Without refocusing mechanism activation
 - Use of an onboard test target (autotest)
 - Defocus estimate using a focusing model
 - Combining initial focusing measurements and observed MTF decrease

Refocusing in the commissioning phase

□ Results of HRG2 refocusing operations (2002)

- Best focus (field center): $p_0 - 7$
 - Astigmatism: -3
(one focusing step = $1.2 \mu\text{m}$)



Refocusing in the commissioning phase (full results)

□ Best focus vs field area with respect to p0

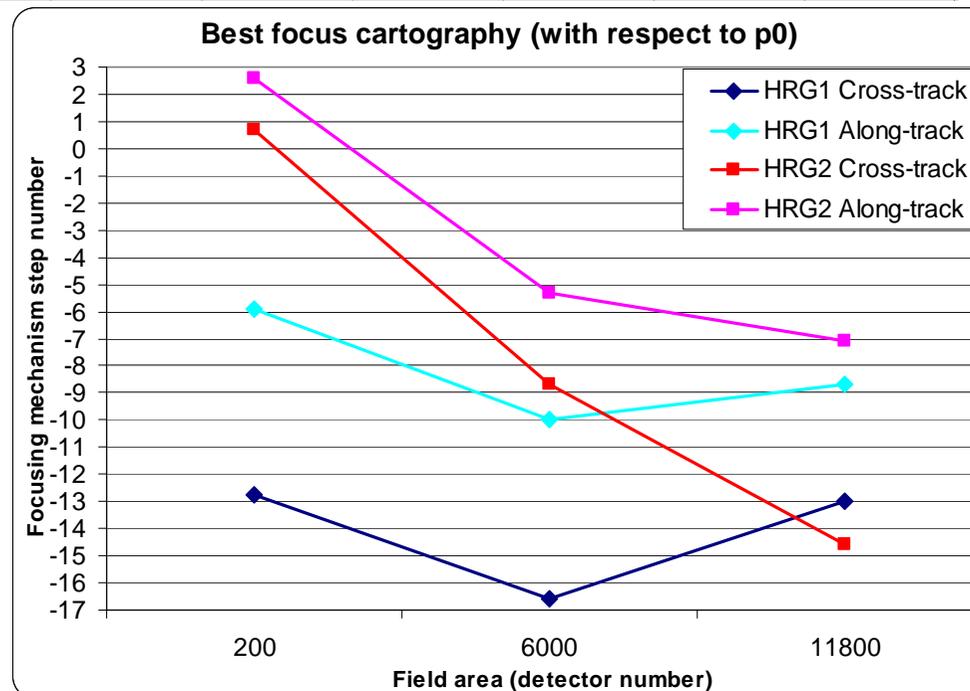
- Astigmatism and field curvature different between instruments

Field area	HRG1			HRG2		
	Left	Center	Right	Left	Center	Right
Cross-track	-13	-17	-13	1	-9	-15
Along-track	-6	-10	-9	3	-5	-7
Mean	-9	-13	-11	2	-7	-11

Final focusing

HRG1: p0-12

HRG2: p0-7

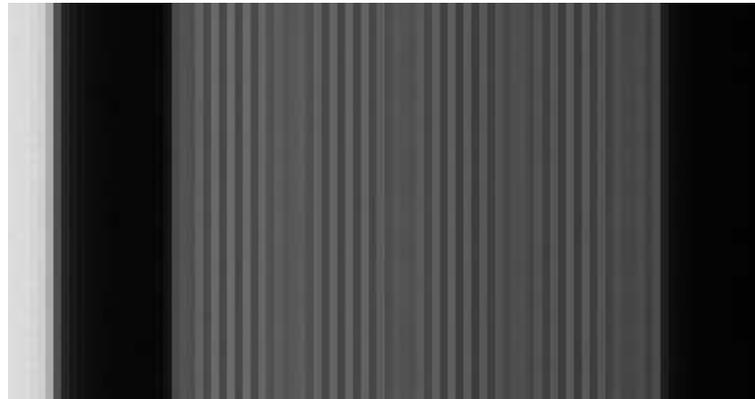


Defocusing assessment

- Defocusing assessment methods
 - HRG2 "Autotest"
 - Use of an on-board target
 - HRG2 absolute MTF
 - HRG1 and HRG2 relative MTF

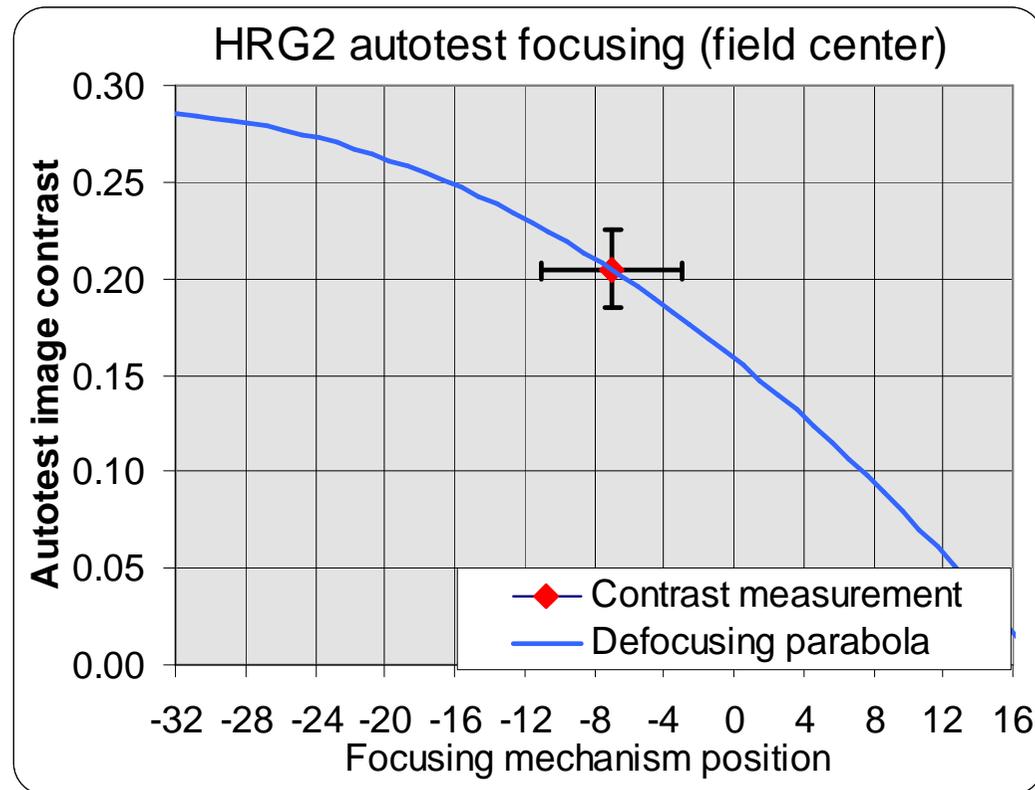
Defocusing assessment (autotest method)

- ❑ "Autotest" is a method to check the focusing monthly
 - a periodic pattern (autotest) located in the focal plane is imaged on the HM array
 - the image contrast is maximum for the best focus
 - as the pattern frequency is near to the Nyquist frequency, there is a moiré effect in the image
 - the maximum contrast area must be searched
 - the autotest is not exactly in the focal plane
 - difference between camera focusing and autotest focusing



Defocusing assessment (autotest method)

- The autotest pattern is imaged without any focusing mechanism movement
- We merely measure the autotest image contrast

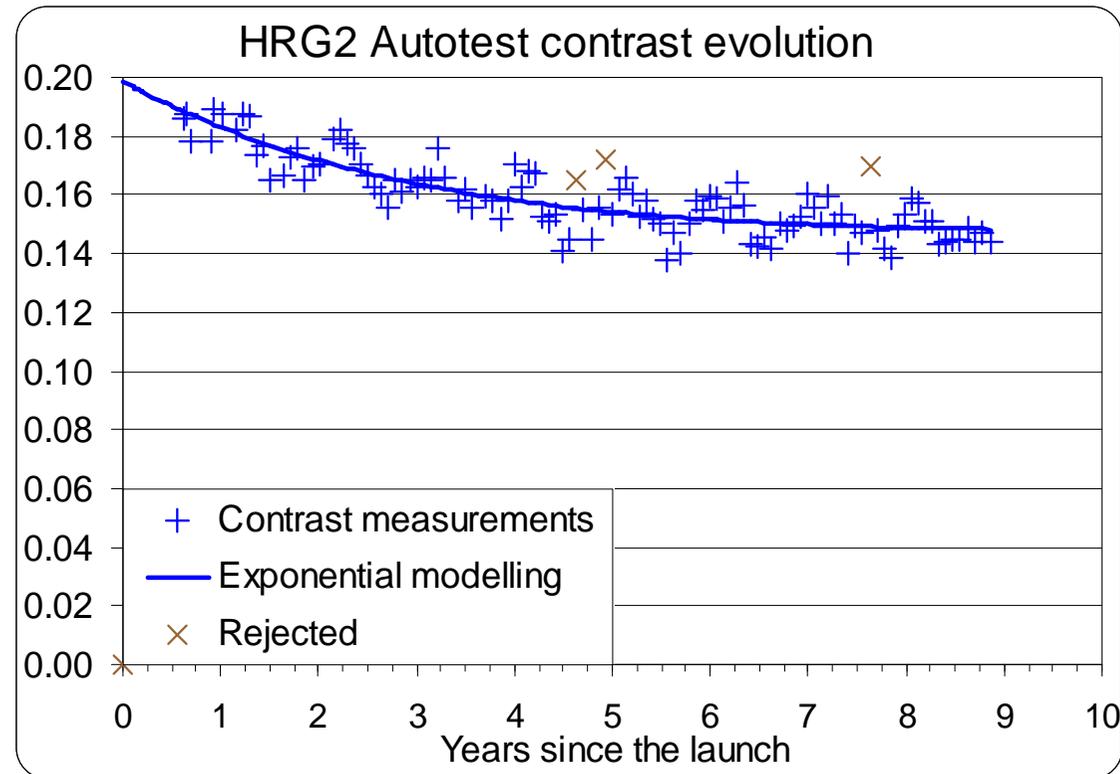


- A contrast change should point a variation of camera focusing
- The sensitivity is :
contrast variation 0.01
 \Leftrightarrow 2 focusing steps

Defocusing assessment (autotest method)

□ Evolution of autotest contrast

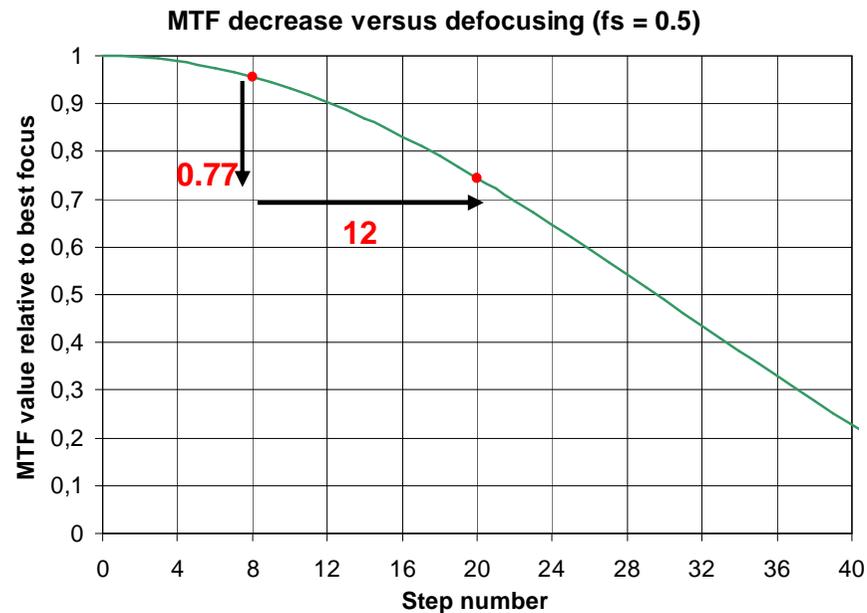
- Decrease 0.04 since the beginning of measurements
- Corresponding to 8 steps focusing change



Defocusing assessment (using HRG2 absolute MTF)

Best focus after initial focusing		
Field area	Center	Right
Cross-track	-2	-8
Along-track	2	0

MTF evolution (2002 – 2010)		
Field area	Center	Right
Cross-track	0.81	0.77
Along-track	0.86	0.99



Best focus evolution		
Field area	Center	Right
Cross-track	-15	-12
Along-track	-16	-4

Mean : -12

Some discrepancies

Defocusing assessment (using relative MTF)

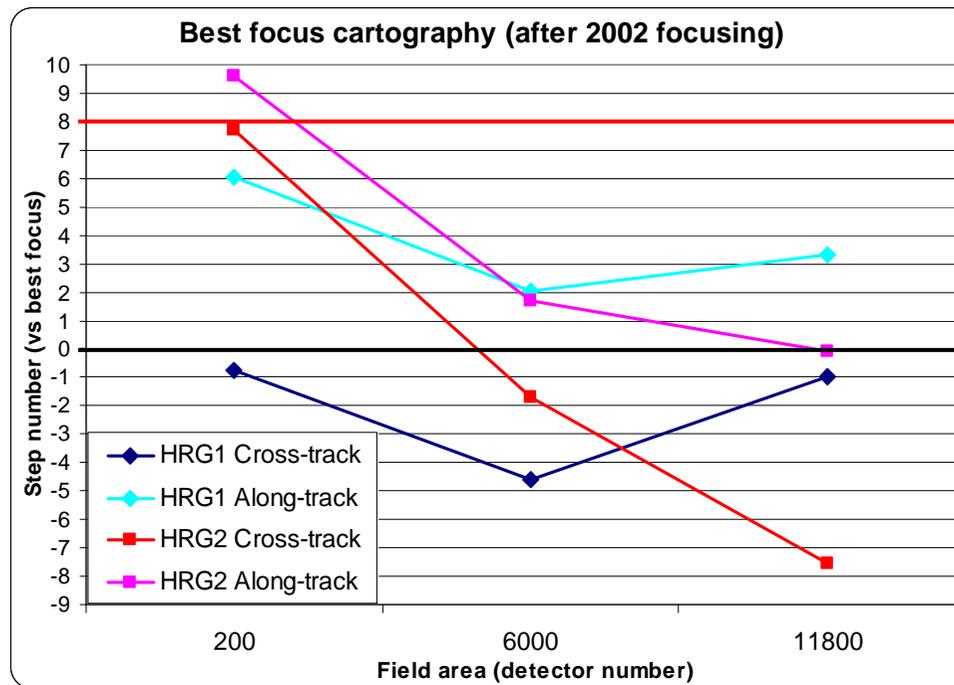
- ❑ Difficult to analyze two instruments together
- ❑ Need to have an hypothesis about HRG1
 - HRG1 absolute MTF shows also defocusing
 - Absolute MTF not precise enough to assess HRG1 defocusing
 - We do suppose similar defocusing for HRG1 and HRG2
 - Relative MTF evolution is observed because of differences between initial focusing due to astigmatism and field curvature

Defocusing assessment (using relative MTF)

- Best focus vs field area with respect to mean best focus after 2002 focusing

	HRG1			HRG2		
Field area	Left	Center	Right	Left	Center	Right
Cross-track	-1	-5	-1	8	-2	-8
Along-track	6	2	3	10	2	0
Mean	3	-1	1	9	0	-4

Best focus
HRG1: p0-12
HRG2: p0-7



8 step defocus

Best focus

Defocusing assessment (using relative MTF)

□ Evaluation algorithm

- Supposing mean defocus of p steps
- Calculating defocusing for each field area
- Calculating MTF evolution using defocus modelling
 - *Steel, W. H., Optica Acta (1956)*
- Calculating relative MTF
- Searching p for best fitting between calculated relative MTF and measured relative MTF

□ Result of assessment

- $p = -10$

Defocusing assessment (using relative MTF)

Defocus vs field area for $p = 8$

Field area	HRG1			HRG2		
	Left	Center	Right	Left	Center	Right
Cross-track	-9	-13	-9	0	-10	-16
Along-track	-2	-6	3	2	-6	-8

MTF evolution

Field area	HRG1			HRG2		
	Left	Center	Right	Left	Center	Right
Cross-track	0.977	0.959	0.977	1.019	0.972	0.945
Along-track	1.009	0.991	0.995	1.028	0.991	0.982

Calculated relative MTF evolution

Field area	Left	Center	Right
Cross-track	1.04	1.01	0.97
Along-track	0.95	0.97	1.00

Measured relative MTF evolution

Field area	Left	Center	Right
Cross-track	1.04	1.00	0.91
Along-track	0.99	0.97	0.95

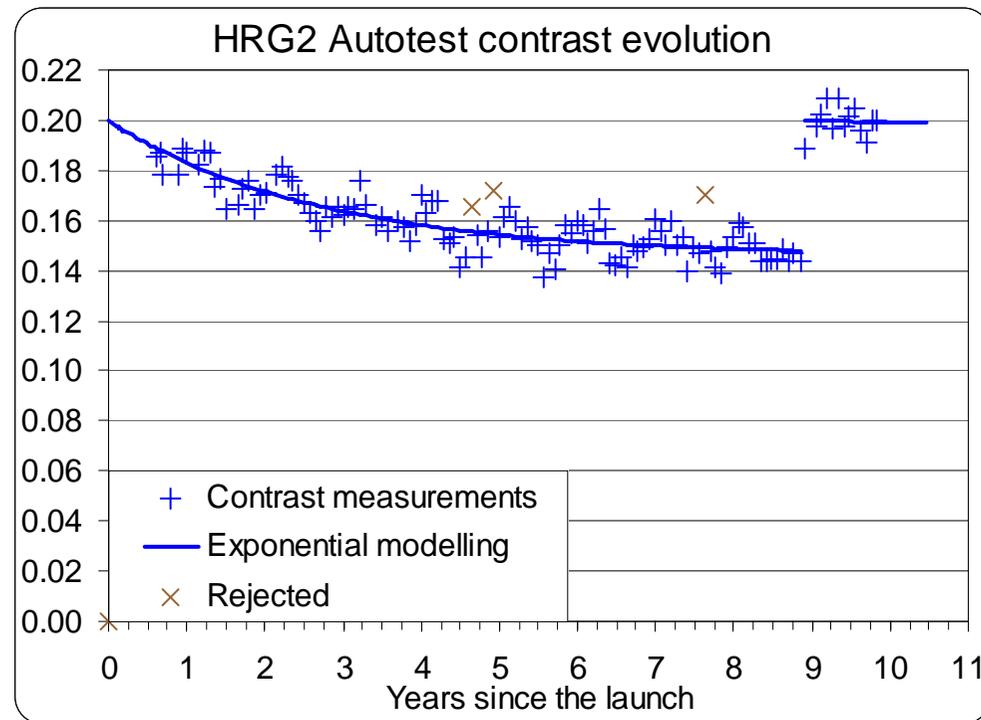
Defocusing assessment (synthesis)

- ❑ Three defocusing assessment methods
 - Results from 8 to 12 steps
 - Autotest contrast evolution → 8
 - Absolute MTF evolution → 12
 - Relative MTF evolution → 10
 - Each method not quite precise, but rather coherent results
- ❑ Decision about refocusing by CNES
- ❑ Strategy
 - Moving focusing mechanism cautiously
 - Minimum value refocusing
 - If not enough, second refocusing
 - Choice of refocusing HRG2 using a value of – 8 steps
 - HRG2 refocused 1st april 2011

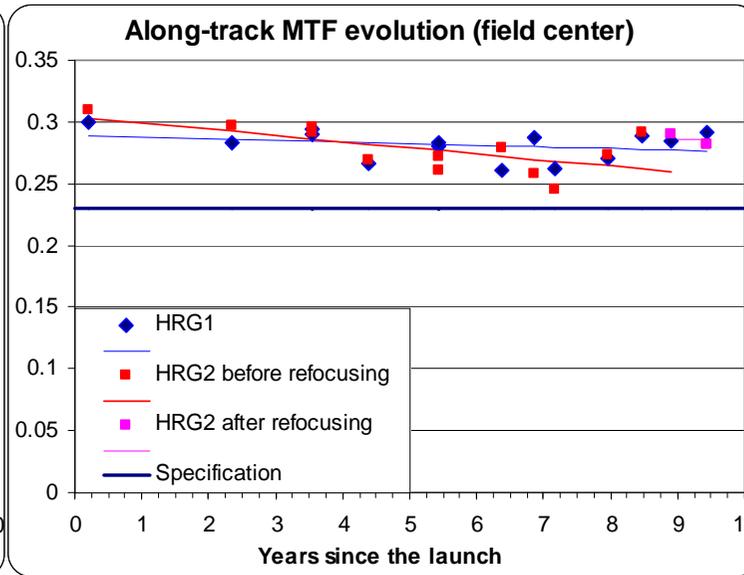
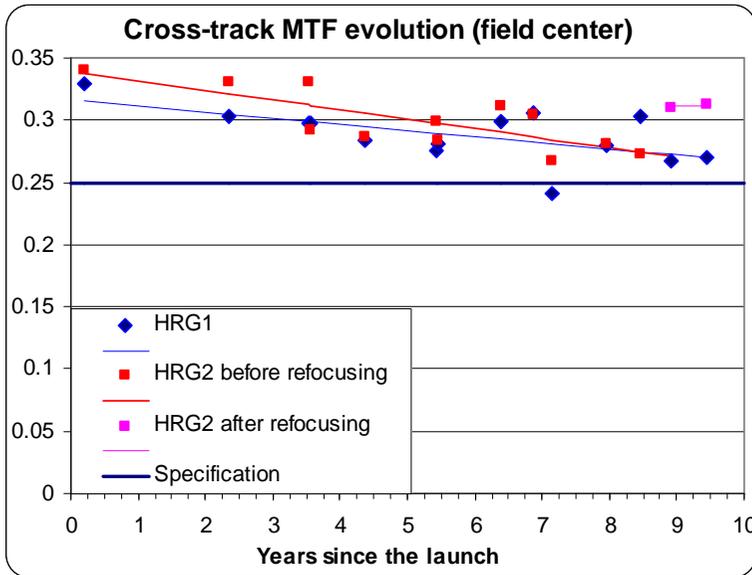
Refocusing results : autotest contrast

□ Evolution of autotest contrast

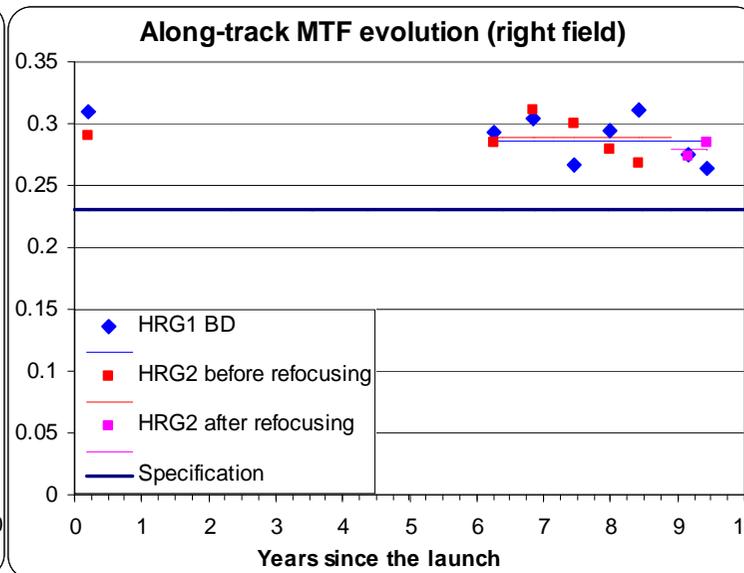
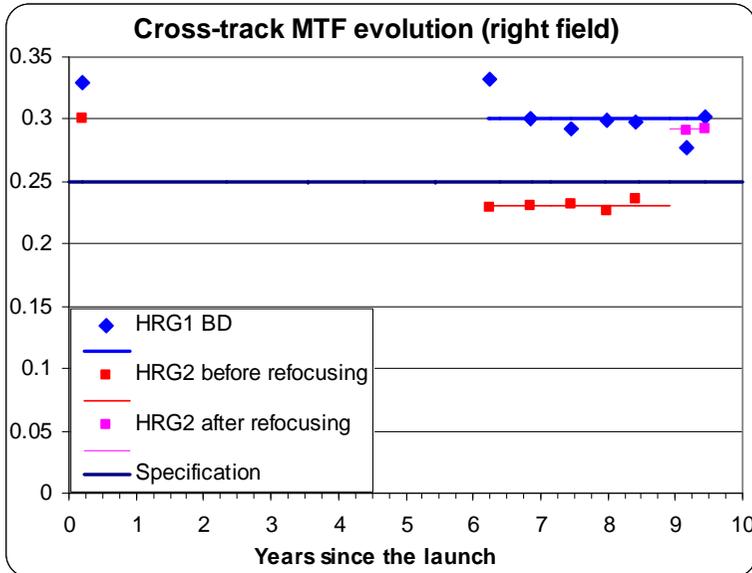
- Increase 0.05 after refocusing
 - Shows a small error about sensitivity
 - contrast variation 0.01 \leftrightarrow 1.6 focusing steps
- Return to initial level



Refocusing results : absolute MTF



Increase of field center MTF value

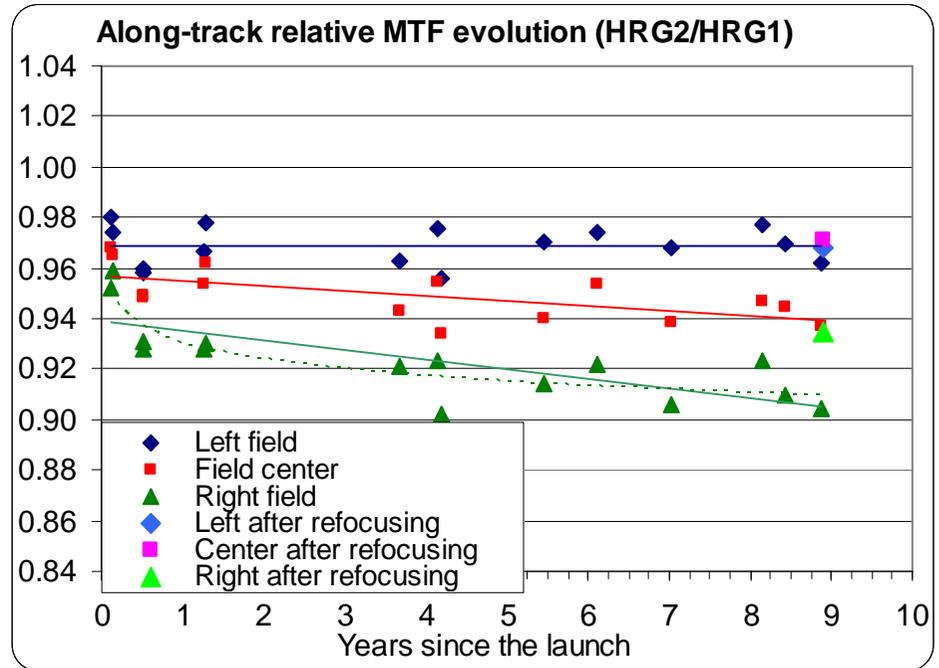
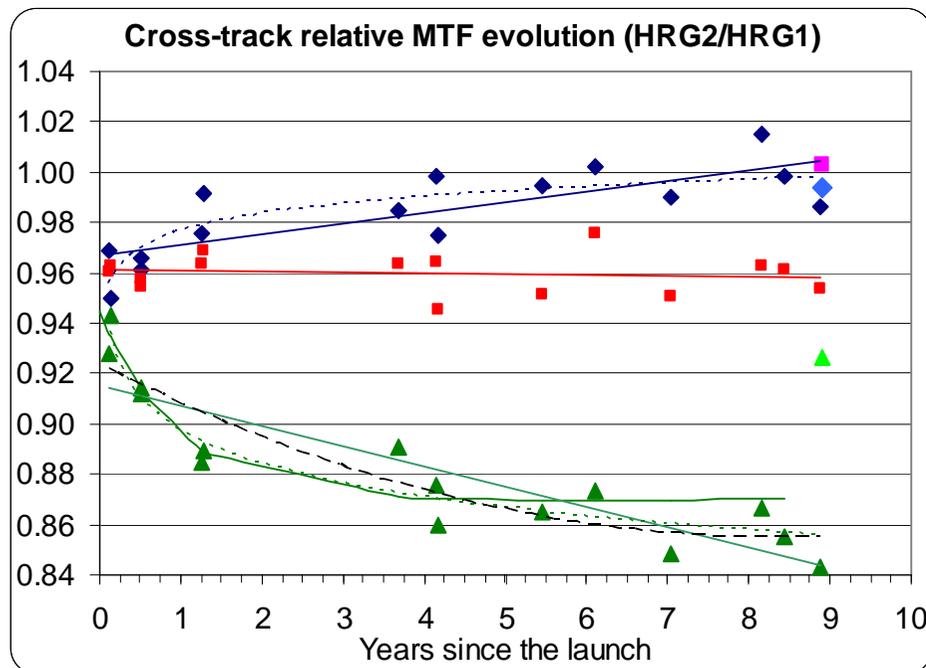


Return to initial level for cross-track right field MTF value
→ above specification

Refocusing results : relative MTF

□ Relative MTF – field center and two field edges

- Increase of right field value (cross-track direction)
- Also increase of field center value



Summary

- Periodic cameras MTF assessment showed a slight defocusing for HRG2 (2002 -2010)
- Defocusing value assessed combining several methods
- MTF assessment after refocusing shows refocusing is sufficient
 - HRG2 MTF specification is again satisfied in the whole field
- MTF HRG1 specification is satisfied, therefore no refocusing is needed
- Autotest method is specific to SPOT 5 satellite
- Relative MTF measurement is easy to use because of two cameras
- Relative MTF method could also be applied with nimble satellites, e.g. Pleiades

Acknowledgement - References

□ Contract

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□ Acknowledgement

- The author is grateful to Françoise Viallefont for all the works done together in the field of MTF and defocusing assessment

□ References

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Mr. Dominique Léger {Dominique.Leger@onera.fr}