Introduction

Star Chart, which uses the Rescharts interface, measures SFR (Spatial Frequency Response) or MTF (Modulation Transfer Function) from the sinusoidally-modulated Siemens star chart proposed for inclusion in a future release of the ISO 12233 standard, as described in A Pilot Study of Digital Camera Resolution Metrology Protocols Proposed Under ISO 12233, Edition 2. The Siemens star chart has been strongly promoted by Image Engineering, a supplier of test charts and hardware located near Köln, Germany. Their paper, Digital Camera Resolution Measurement Using Sinusoidal Siemens Stars, is a useful reference.

Charts with 144, 72, and 48 cycles can be analyzed in 8, 12, or 24 segments around the circle. The value of gamma used to linearize the chart can optionally be determined from the 16 small square patches near the edge of the chart or it can be measured externally and entered.

Creating and photographing the chart and running the program

Star Chart measures MTF using calculations similar to Log Frequency. The principal difference is that is measures it for a range of angles (in 8, 12, or 24 segments) using a sinusoidally-modulated pattern along the radii of a circle. This method is more direct than the slanted-edge method, but may be slightly less accurate. Because calculations are performed on circles of known spatial frequencies, the calculation can be made more robust against noise than Log Frequency.

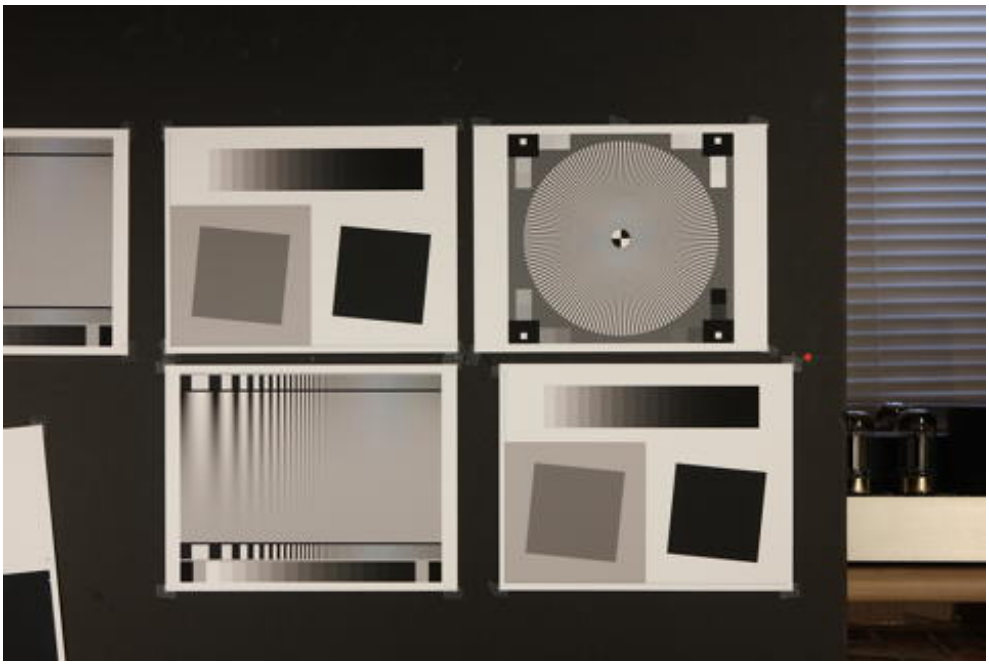


Image with star chart (upper right)

The image above used to illustrate the Star chart module and to compare results with Slanted-edge SFR and Log Frequency. It was captured with a Canon EOS-40D camera, 24-70mm f/2.8L lens set at 50mm, f/5.6, ISO 100. It includes Star, Log Frequency-Contrast and slanted-edge charts with high and low contrast (20:1 and 2:1).

Purchase test charts from Image Engineering or **create** them using Imatest Test Charts, then print the

chart on a high quality inkjet printer. Recommended Test Charts options are **PPI: 720** (Epson inkjets) or **600** (HP or Canon inkjets), **Height (cm)** (as required), Highlight color: White, Contrast ratio: 40, Type: Sine, Gamma: 2.2, Star pattern bands: 144 or 72, Chart lightness: Lightest, ISO standard chart: **Yes** or **Yes (small inner circle)** (inner circle has 1/10 or 1/20 the diameter of the outer, respectively).

Number of chart cycles Ideally the maximum spatial frequency (just outside the inner circle) should be around 0.6 to 1.0 cycles/pixel. The diameter of the inner circle d_i is 1/10 or 1/20 times the diameter d_P of the circular sine pattern, depending on the chart (selectable in Test Charts). The smallest diameter for analysis is $0.11d_P$ or $0.056d_P$. For an image of P pixels (width or height) of a star with N cycles, where the pattern circle diameter d_P takes up a fraction g of P ($d_P = gP$; $d_i = 0.11\ gP$ (or $0.056\ gP$)) , the maximum spatial frequency in cycles/pixel is

$f_{max} = N / (0.11\ \pi\ d_P) = N / (0.11\ \pi\ g\ P)$ (inner circle 1/10 the diameter of the outer)
$f_{max} = N / (0.056\ \pi\ d_P) = N / (0.056\ \pi\ g\ P)$ (inner circle 1/20 the diameter of the outer)

Example: for a 3000 pixel wide image where the pattern circle d_P takes up $g = 0.25$ (25%) of the image and the inner circle has 1/10 the diameter, $f_{max} = 0.555$ cycles/pixel for a 144-cycle pattern; $f_{max} = 0.278$ cycles/pixel for a 72-cycle pattern. The 144-cycle pattern is indicated. 72-cycle patterns are most suitable for low resolution cameras (~2 megapixels or less).

Mount the chart on a flat dark board— 1/2 inch foam board works well; thinner board warps more easily. Depending on the number of horizontal pixels in the chart to be analyzed, the chart should occupy 1/3 to 1/4 of the horizontal frame. Other charts can be mounted along with it.

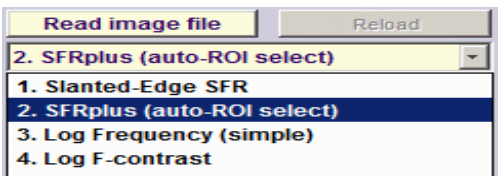
Orientation. The pattern should be oriented horizontally, i.e., in landscape orientation (it is slightly wider than high).

Photograph the chart using the sort of lighting described in Imatest Lab or How to test lenses, taking care to avoid glare. Save the image in any one of several high quality formats, but beware of JPEGs with high compression (low quality), which will show degraded quality, unless, of course, you are testing JPEG degradations.

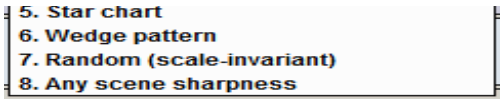
Because resolution varies over the image for most cameras and lenses, the star chart should not take up too much of the frame— in most cases its diameter should be no more than 1/3 of the image height.

Open Imatest, then click on . The Rescharts window is described in the Rescharts page.

Select a pattern to analyze (in this case, **Star Chart**) by clicking on the appropriate entry in the popup menu below or by clicking on if **Star Chart** is displayed. The button and popup



menu (shown on the right) are highlighted (yellow background) when Rescharts starts.

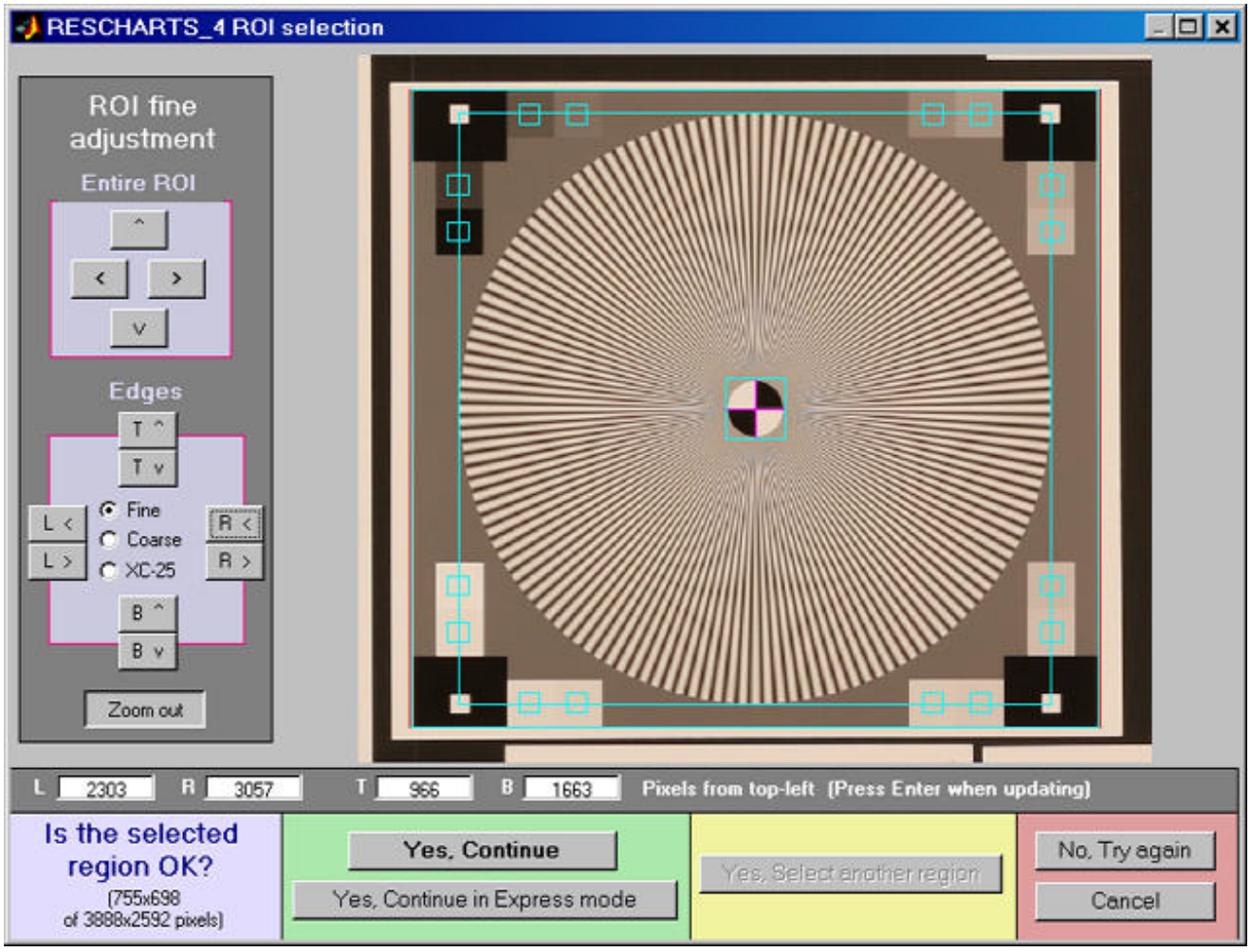


Select the image to read. If the pixel size is the same as the previous Star Chart run, you'll be asked if you want to use the previous ROI, adjust the previous ROI, or crop anew. If the folder contains meaningless camera-generated file names such as IMG_3734.jpg, IMG_3735.jpg, etc., you can change them to meaningful names that include focal length, aperture, etc., with the View/Rename Files utility, which takes advantage of EXIF data stored in each file.

Cropping ***The initial crop should include the entire pattern, including the outside of the black rectangles*** (with the small white squares inside). It doesn't have to be precise because it will be refined in the ROI fine adjustment window, shown below. **The ROI fine adjustment window may be maximized to facilitate fine selection.**

In the ROI fine adjustment window the pattern should be cropped so

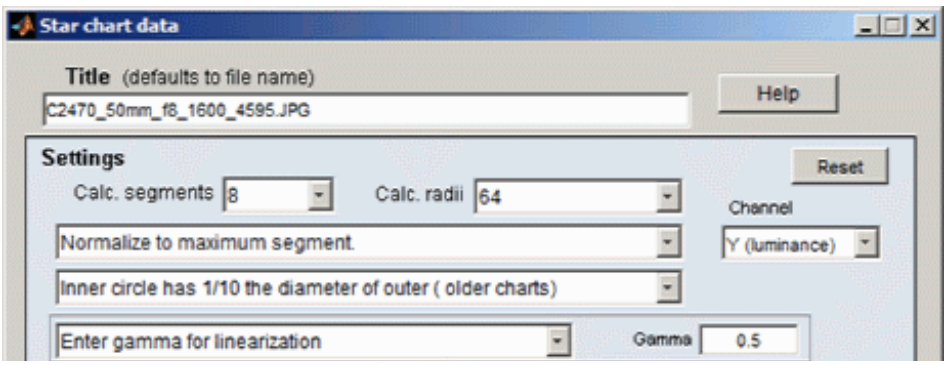
- the middle cyan square is at the bounds of the large star pattern circle (or slightly inside if there is distortion),
- the inner cyan square is on the inner circle (which consists of four quadrants— two white, two black) for inner circles with 1/10 the diameter of the outer. (The inner circle will be well inside of the inner cyan square for small inner circles, which have 1/20 the diameter.),
- the magenta crosshair inside the inner circle is well-centered. If it is slightly off Imatest will automatically correct it.



ROI fine adjustment window showing the cropped Star Chart image
Canon EOS-40D camera, 24-70mm f/2.8L lens
set at 50mm,
f/5.6, ISO 100.
Click on image to load full-size test image.

If **Express mode** is ***not*** selected, the input dialog box shown below appears. Some buttons such as SQF Options are inactive: they are holdovers from other modules reserved for future use. This dialog box can be at any time by pressing the button.

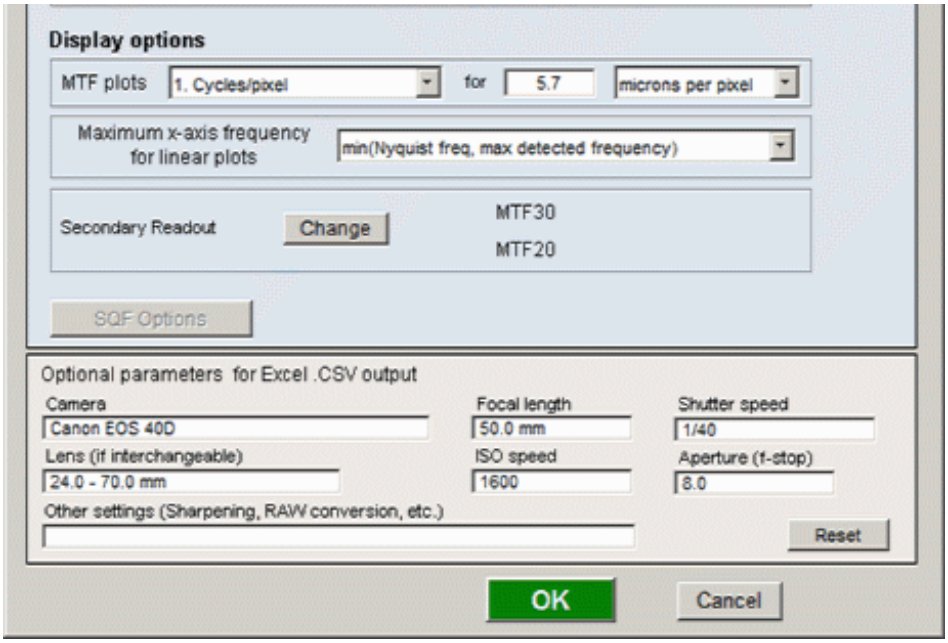
Image settings & options dialog box



Settings

Calc segments is the number of segments around the circle to

display in the analysis. 8, 12, and 24 are supported. 8 is the default.



Calc. radii is the number of radii on the circle used for the MTF calculations. It was 32 prior to version 2.7.2. 64 is considerably more accurate but slightly slower (it's the new default). 128 is slightly more accurate and slower still.

Normalization selects the MTF normalization method (where to set MTF to 1.0):

1. normalize to the outer MTF value for each segment (the default),
2. normalize to the maximum outer MTF value in all segments, or
3. normalize to the difference between the lightest and darkest of the square patches near the pattern edge.

(1) may be slightly better when illumination is nonuniform. (2) may be slightly better when actual MTF varies between segments. (3) is simetimes better because the lowest spatial frequencies in the star may not be low enough approximate zero spatial frequency.

Channel is R, G, B, or Y (luminance; the default).

Inner circle May have either 1/10 or 1/20 the diameter of the outer. Should match the chart. Affects the maximum spatial frequency of the analysis.

Enter or calculate gamma Choose between **Calculate gamma & linearize from chart patches** or **Enter gamma for linearization**. If **Calculate gamma…** is selected, the 16 small square patches at the periphery of the star chart are used to determine the value of gamma for linearizing the chart, **Gamma** (below) is disabled, and the displayed value of gamma includes the indicator **(chart)**.

Gamma is used to linearize the test chart when **Enter gamma…** (above) is selected. It can be measured by Stepchart, Colorcheck, or Multicharts. 0.5 is a typical value for color spaces intended for display at gamma = 2 2 (sRGB, Adobe RGB, etc.). If gamma is entered (rather than calculated), the displayed value of gamma includes the indicator (input).

Display options

MTF plots selects the x-axis scaling. If Cycles/inch or Cycles/mm are selected, the pixel spacing (um/pixel, pixels/inch, or pixels/mm) should be entered.

X-axis scaling for linear plots selects the maximum spatial frequency to be displayed in linear plots.

Secondary readout allows up to two secondary redouts (MTFnn, MTFnnP, or MTF at a specified spatial frequency) to be displayed on the MTF plots. Details here.

Don't worry about getting all settings correct: You can always open this dialog box by clicking on in the Rescharts window.

After you press , calculations are performed and the most recently-selected display appears.

Output

The **Display** box in the Rescharts window, shown below, allows you to select any of several displays. Display options are set in boxes that appear below Display. All displays except **Exif data** have a channel selection option (Red, Green, Blue, or Luminance (Y) (0.3R + 0.59G + 0.11B).

Display	Description
MTF (original and linearized)	MTF for up to 8 segments of the star. Both linear and logarithmic frequency displays are available.
MTFnn or MTFnnP	Display MTFnn (the frequencies where MTF equals nn % of the low frequency values) and MTFnnP (the frequencies where MTF equals nn % of the peak value) for nn = 70, 50, 30, 20, and 10. Both polar (spider) and rectangular plots are available.
MTF contours (rectangular)	Display MTF contours in a rectangular plot with linear or logarithmic frequency display. Similar to the MTFnn rectangular plot.
MTF contours (polar)	Display MTF contours in a polar plot whose geometry duplicates that of the target.
EXIF data	Show EXIF data if available as well as linearization curves (used to calculate gamma from the chart).

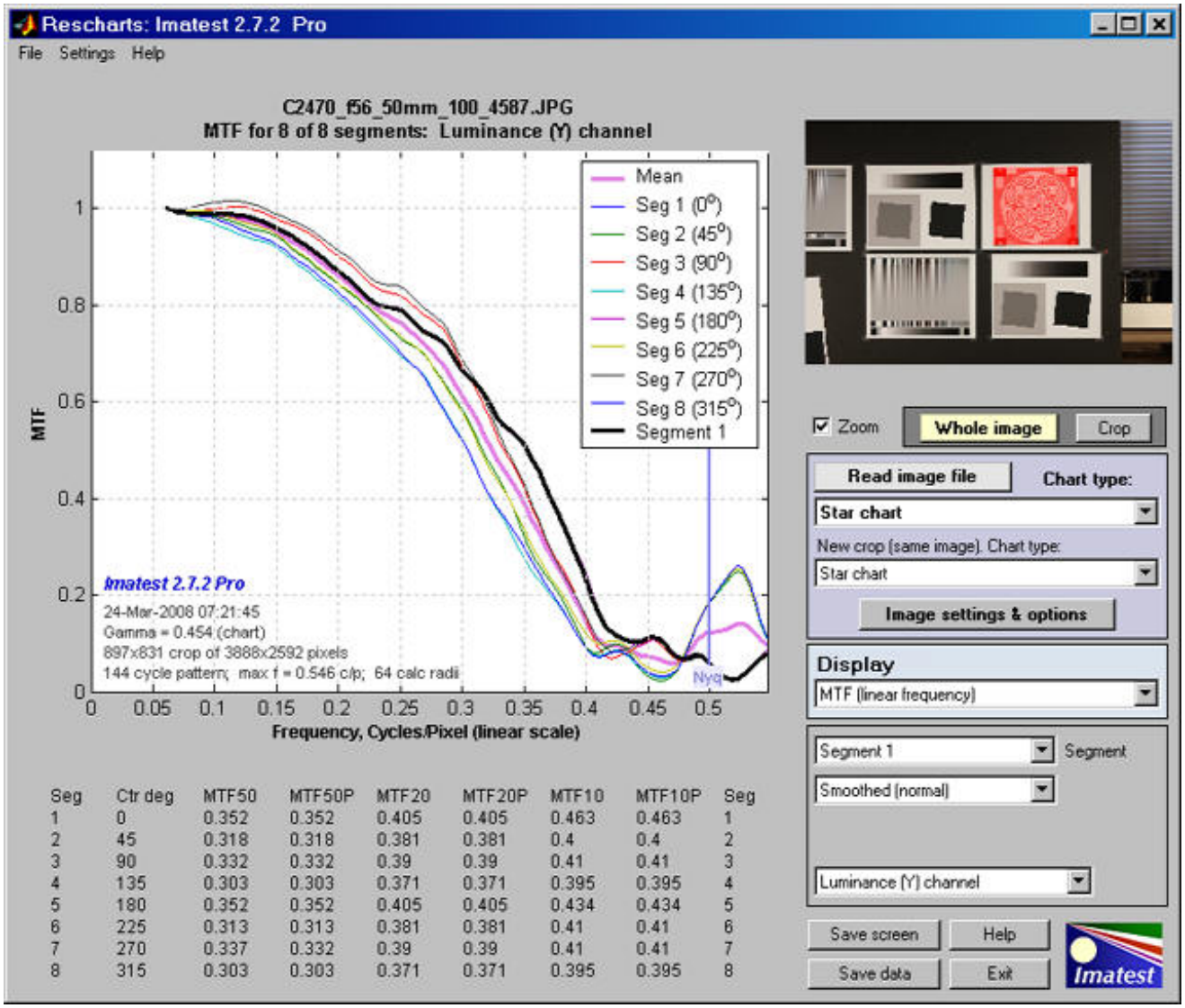
In addition to the displays, two buttons allow you to save results.	
	Saves an image of the Starchart window as a PNG file. If you check Display screen in the Save screen dialog box, the image will be opened in the editor/viewer of your choice. (Irfanview works well, and it's free.)
	Saves detailed results in a CSV file that can be opened by Excel and also in an XML file.

The spatial frequency is automatically calculated from the image, under the assumption that log frequency increases linearly with distance. The number of chart cycles is also determined automatically.

MTF

The MTF (Spatial Frequency Response) can be displayed on a linear or logarithmic frequency scale. You can select between showing the first 8 segments equally weighted, or emphasizing any of the segments (Segment 1 is shown as a thick black line below). The average response is a thick magenta-gray line. Smoothed, interpolated response is normally displayed, but uninterpolated, unsmoothed (raw) response is available as an option.

Normalization: MTF is normalized (set to 1.0) using either (1) MTF at the outer radius of each segment, (2) the maximum value of MTF at the outer radii of all segments, or (3) the difference between the lightest and darkest square near the pattern edge. Neigher case (1) nor (2) is ideal because the minimum spatial frequency is not as low as it should be for correct normalization. (The high to low spatial frequency ratio is only 10 or 20 for the star chart — *much* lower than for the Log Frequency or Log F-Contrast charts.) In general, normalizing MTF to the outer radius of the star *increases* MTF slightly above its true value. MTF should ideally be normalized to a lower spatial frequency. Case (3) should only be used with maximum contrast patterns.



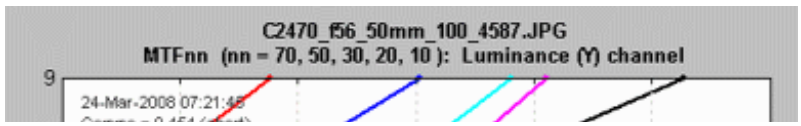
MTF (linear frequency scale) for 8 segments of the Star pattern

The entire Rescharts window is shown. The original 64 radii are linearly interpolated to 101 frequencies, then smoothed to eliminate response roughness caused by calculation artifacts and noise. Gamma = 0.454 (chart) at the lower left of the plot indicates that gamma was calculated from the 16 small square patches at the periphery of the chart. If it were calculated elsewhere and entered into Star Charts, (input) would be displayed instead of (chart).

MTF50, MTF50P, MTF20, MTF20P, MTF10, and MTF10P for the first 8 segments are displayed in a table below the plot for this and several of the output plots (but not shown below).

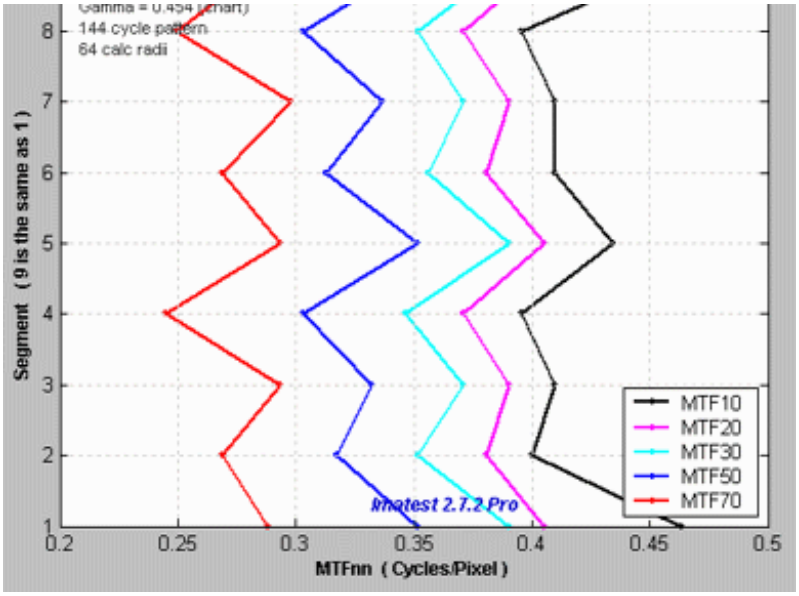
MTFnn, MTFnnP

The plot on the right shows MTF70 through MTF10 (spatial frequencies where MTF = 70,, 50, 30, 20, and



10%) on a linear frequency scale displayed in rectangular (Cartesian) coordinates. Frequency is displayed in cycles/pixel, but Line Widths per Picture Height (LW/PH), cycles/inch, or cycles/mm can be selected by pressing the button. The full circle is shown: segment 9 corresponds to segment 1: (0 degrees center angle).

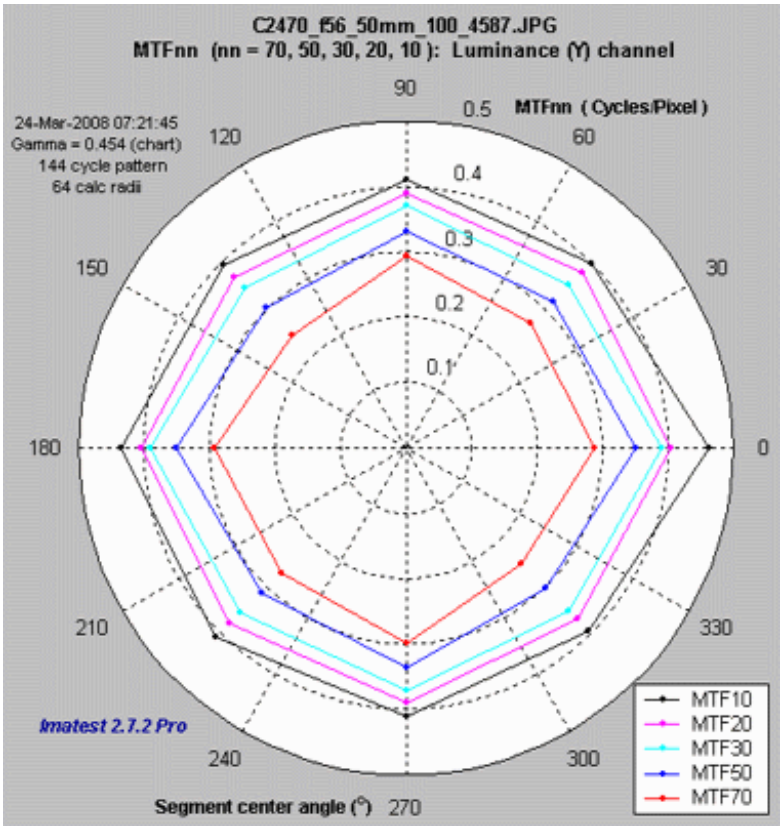
The legend (the box on the right) has been moved using the mouse to uncover the MTF10 (blue) line.



MTF70 – MTF10: Rectangular (Cartesian) coordinates, Linear frequency scale.

The plot on the right shows MTF70 through MTF10 displayed in polar coordinates. Spatial frequency (cycles per pixel in this case) increases with radius. (This is the opposite of the image itself, where spatial frequency is inversely proportional to radius.)

This plot is most similar to the spider plot shown in Image Engineering digital camera tests and Digital Camera Resolution Measurement Using Sinusoidal Siemens Stars (Fig. 15), by C. Loebich, D. Wueller, B. Klingen, and A. Jaeger, IS&T, SPIE Electronic Imaging Conference 2007. MTF10 (the black octagon on the right) corresponds to the Rayleigh diffraction limit.

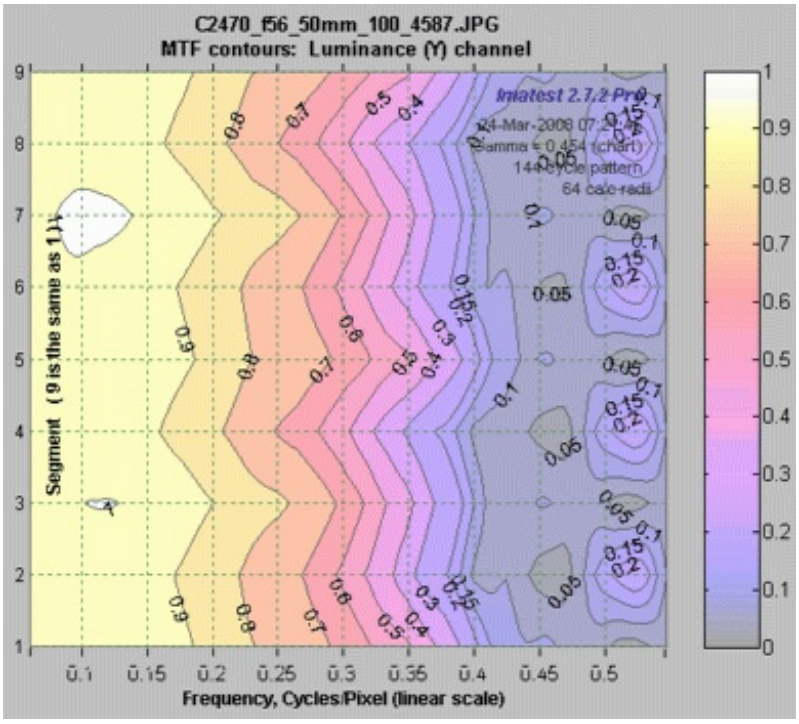


MTF70 – MTF10: Polar coordinates, Linear frequency on radius.

MTF contours: rectangular and polar

The plot on the right shows the MTF contours for each of the 8 segments. Spatial frequency is displayed on a linear scale, but a log scale may be selected and a color bar (see below) may be added.

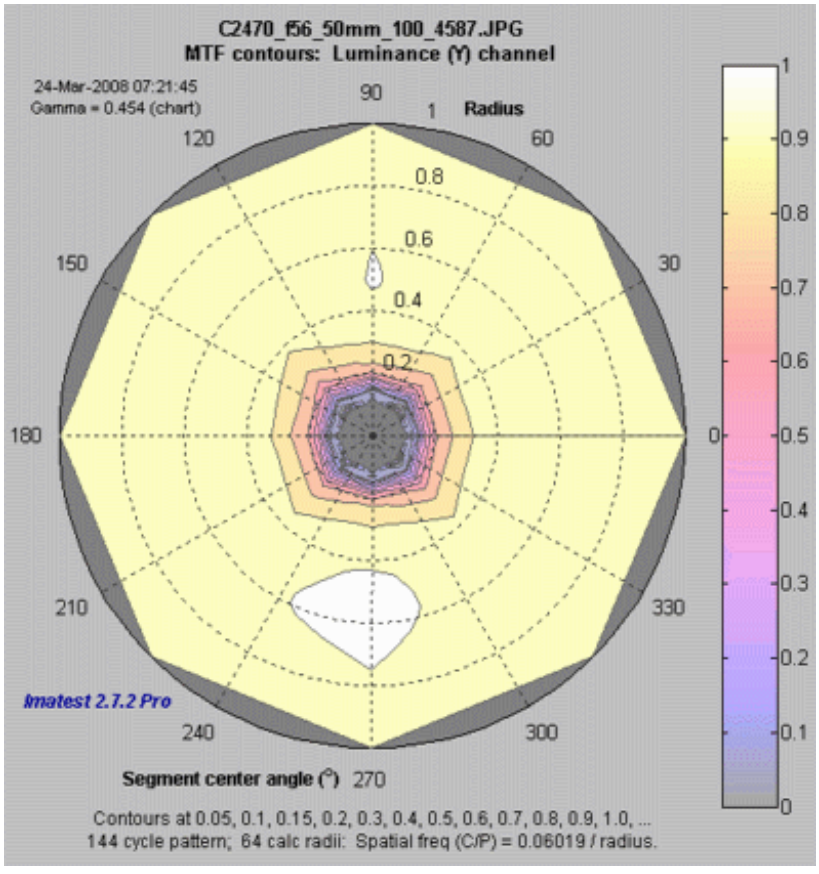
This plot contains information similar to the rectangular MTFnn plot, above.



MTF contours, rectangular display,
Linear frequency scale.

The plot on the right shows the MTF contours for each of the 8 segments, displayed on a polar scale, where location (radius) on the plot corresponds to the image. This is the *inverse* of the polar MTFnn plot, above, where spatial frequency is the inverse of image radius.

Most of the action in this image is near the center. If the **Zoom** box is checked you can zoom in by selecting a portion of the image or simply by clicking on it.



MTF contours, polar display.

Equations, algorithm, and issues

Equations for analyzing the Siemens star are given in Digital Camera Resolution Measurement Using Sinusoidal Siemens Stars by C. Loebich, D. Wueller, B. Klingen, and A. Jaeger, IS&T, SPIE Electronic Imaging Conference 2007. The algorithms used for ***Imatest Star Charts*** are similar, differing only in details. The 32, 64, or 128 radii r_i , located from just outside the inner circle to just inside the outer circle, are selected using a logarithmic scale that makes them more closely spaced near the inner circle. This makes the frequency spacing (proportional to 1/radius) more consistent than for uniformly spaced radii. For each of the 32 radii r_i , all points are located with radii between ($r_{i-1}+r_i$)/2 and (r_i+r_{i+1})/2 pixels. ($r_i-0.7$ and $r_i+0.7$ pixels, used prior to Imatest 2.7.2, caused significant bumps in the MTF response.) Spatial frequency is $1/(2\pi\, r_i)$ cycles/pixel. These points fit the curve,

$$I(\varphi) = a + b_1 \sin(2\pi/g)\, \varphi\,) + b_2 \cos(2\pi/g)\, \varphi\,), \text{ where } b = \text{sqrt}(b_1^2 + b_2^2)$$

$$\text{MTF} = b/a$$

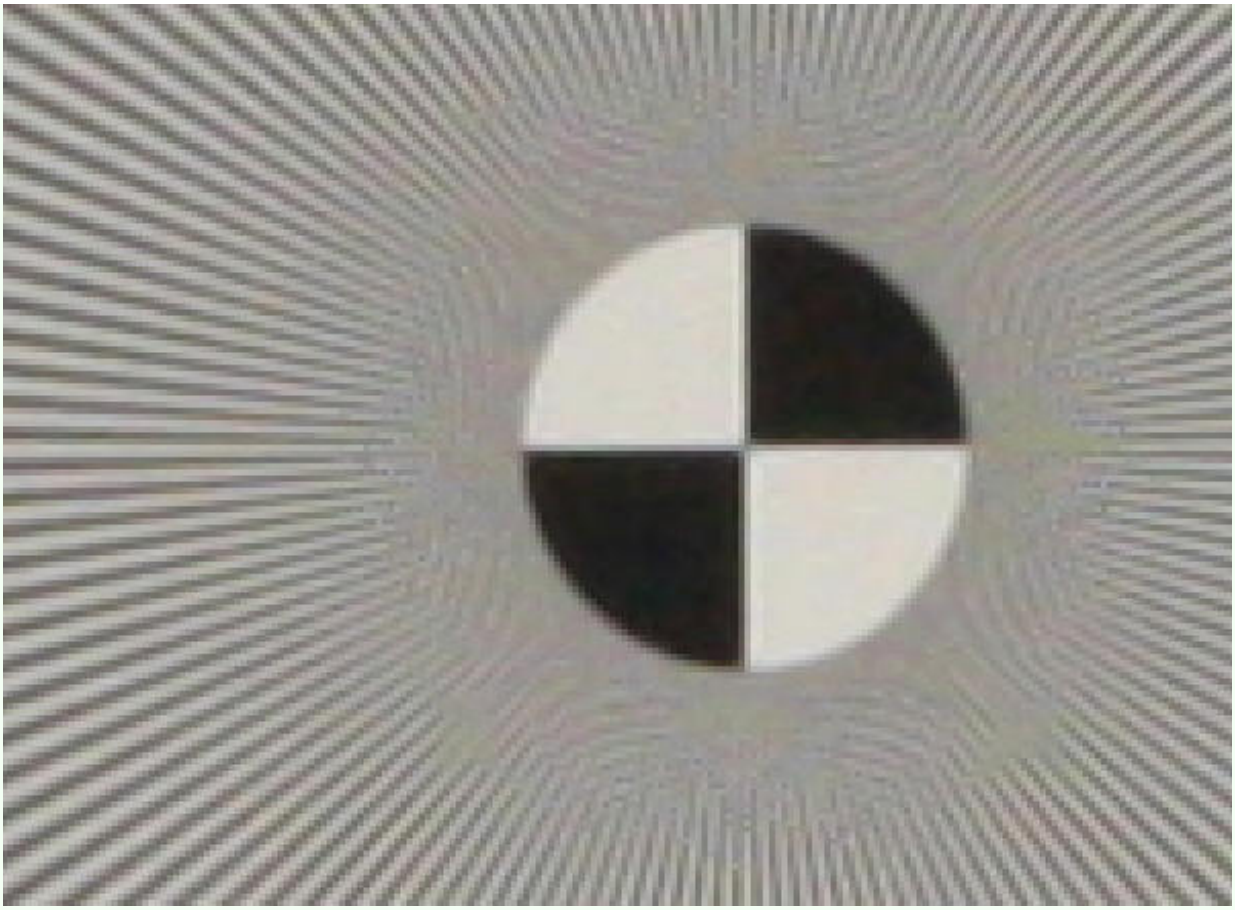
The equation for $I(\varphi)$ is recognized as a term in a Fourier series expansion, which can be solved using the standard Fourier series equation since each segment (there are 8, 12, or 24) has an integral number of cycles (of a total of 144, 120, 72, or 48 cycles on the chart).

$$b_1 = k\ \text{mean}(\ \sin(2\pi/g)\, I(\varphi)\ );\qquad b_2 = k\ \text{mean}(\ \cos(2\pi/g)\, I(\varphi)\ );\qquad a = \text{mean}(\ I(\varphi)\ )$$

Since MTF is normalized to 1 at the lowest measured spatial frequency for each segment, k drops out of the final result.

Algorithm issues

Bumps in the MTF response curve caused by aliasing are visible in the image below.



3x enlarged image of the center of a star pattern acquired on the Canon EOS-40D, 24-70mm f/2.8 lens set to 50mm, f/8 (a sharp setting)

Normalization: MTF is normalized using (1) MTF at the outer radius of each segment, (2) the maximum value of MTF at the outer radii of all segments, or (3) the difference between the lightest and darkest square near the pattern edge. Neither case (1) nor (2) is ideal because the minimum spatial frequency is not as low as it should be for correct normalization. (The high to low spatial frequency ratio is only 10 or 20 for the star charts — *much* lower than for the Log Frequency or Log F-Contrast charts.) In general, normalizing MTF to the outer radius of the star *increases* MTF above its true value. MTF should ideally be normalized to a lower spatial frequency, as with case (3), which should only be used with maximum contrast charts.