

**Norman Koren**

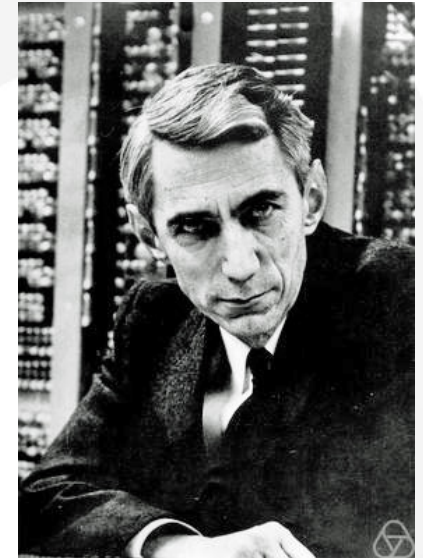
**Imatest LLC, Boulder, Colorado**

**Electronic Imaging 2020**

Image quality is depends on both sharpness and noise, but how do we weigh them? Which is more important?

The classic Shannon information capacity equation, well-known in electronic communications but not in photography, suggests a relationship.

$$C = W \log_2 \left( 1 + \frac{S}{N} \right) = W \log_2 \left( \frac{S + N}{N} \right)$$



**Claude Shannon**

$C$  is information capacity;  $S$  is signal power,  $W$  is bandwidth (related to sharpness),  $N$  is noise. How should they be measured?

To measure  $S$  and  $N$ , the well-known slanted-edge seems like an obvious choice, *but*

- For JPEG images from cameras, sharpening near edges (where  $S$  is high) increases the apparent bandwidth  $W$ .
- Noise  $N$ , measured in smooth areas (where  $S$  is low), is often reduced by bilateral filtering, leading to exaggerated  $C$ .
- Clipping (saturation) and aliasing artifacts may increase measured  $W$ , but they do not increase actual information  $C$ .

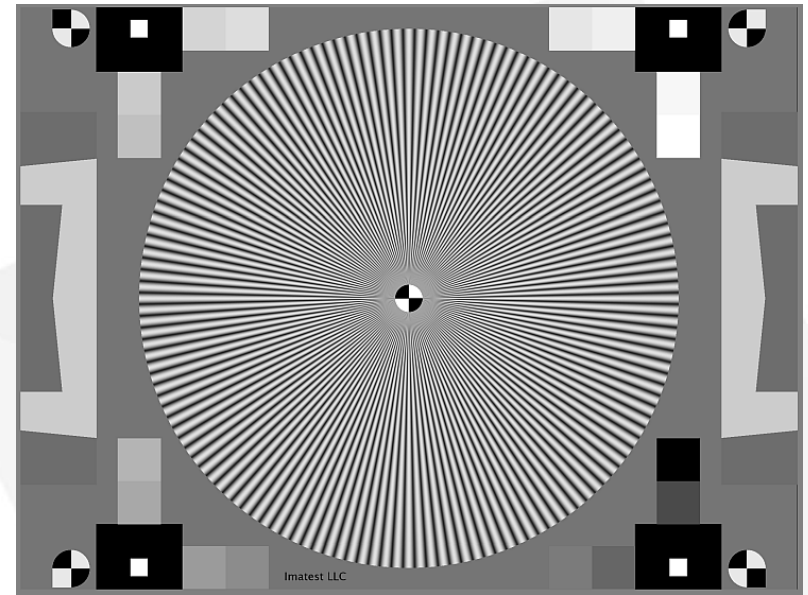


We would like to find a chart pattern where

- signal and noise can be measured at the same location (so they have the same image processing),
- clipping and other artifacts to not increase measured information,  $C$ .
- is a familiar industry standard

## In the ISO 12233:2017 standard (s-SFR measurement; Annex E, F)

- 50:1 contrast (minimum for standard; highest for matte media) covers a wide tonal range
- $n_{cycles} = 144$  or  $72$ , depending on camera resolution
- $f = n_{cycles}/2\pi r$ . Nyquist frequency,  $f_{nyq} = 0.5$  C/P is located at radius  $= r = 46$  pixels for a 144-cycle star and 23 pixels for a 72-cycle star
- Central registration mark diameter is 1/20 of the total star diameter.
- Analyzed in 32 or 64 radial segments and 8, 16, or 24 angular segments.



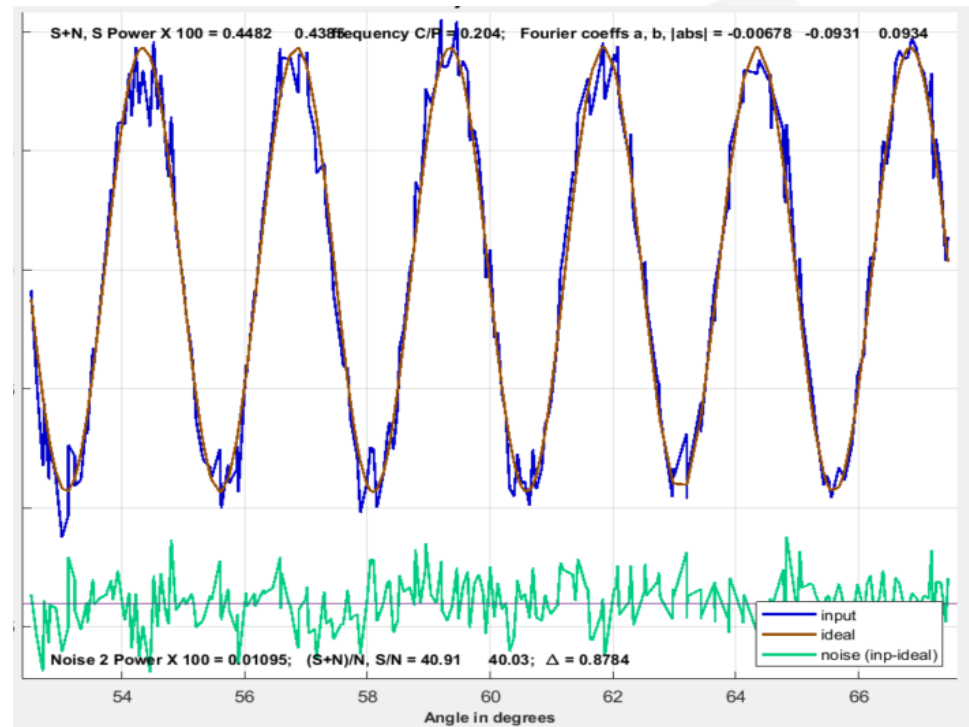
$S_{input}(\varphi)$  is the actual (noisy) signal in the segment, shown as a **rough blue curve**.

$S_{ideal}(\varphi)$  is the ideal (original) signal (sine + 2<sup>nd</sup> harmonic), shown as a **smooth brown curve**.

The noise in the segment is

$$N(\varphi) = S_{ideal} - S_{input}(\varphi)$$

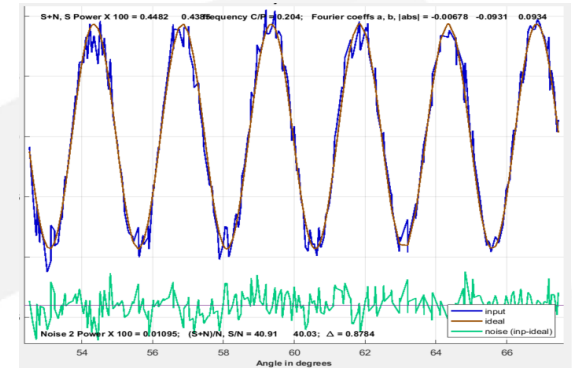
Shown in **green at the bottom**.



**Signal and noise are measured in the same location.**

The ideal (original) signal in the segment consists of a sine function + 2<sup>nd</sup> harmonic),

$$S_{ideal}(\varphi) = \sum_{j=1}^2 a_j \cos\left(\frac{2\pi j n \varphi}{P_{seg}}\right) + b_k \sin\left(\frac{2\pi j n \varphi}{P_{seg}}\right)$$



$a_j$  and  $b_j$  are calculated as Fourier Transform coefficients, which is very fast and meets the intent of the ISO standard.

$$a_j = \frac{2}{P} \int_P S_{input}(x) \cos\left(\frac{2\pi j n x}{P_{seg}}\right) dx \quad b_j = \frac{2}{P} \int_P S_{input}(x) \sin\left(\frac{2\pi j n x}{P_{seg}}\right) dx$$

Now we come to the integral form of the **Shannon Capacity equation**, from Shannon's second paper (1949). Noting that  $f = n_{cycles}/2\pi r$  for angular segments at radius  $r$ .

$$C = \int_0^B \log_2 \left( 1 + \frac{S(f)}{N(f)} \right) df = \int_0^B \log_2 \left( \frac{S(f) + N(f)}{N(f)} \right) df$$

This equation doesn't scale correctly because it is **one-dimensional**, while image pixels (which store information) are **two-dimensional**. It must be transformed into a double (2-dimensional) integral.

$$C = \iint_0^B \log_2 \left( \frac{S(f_x, f_y) + N(f_x, f_y)}{N(f_x, f_y)} \right) df_x df_y$$

The double integral looks intimidating, but there is a trick...



We evaluate the double integral by transforming it into polar coordinates.

$$C = \int_0^{2\pi} \int_0^B \log_2 \left( \frac{S(f_r, f_\theta) + N(f_r, f_\theta)}{N(f_r, f_\theta)} \right) f_r df_r df_\theta$$

Since  $S(f_r, f_\theta)$  and  $N(f_r, f_\theta)$  are only weakly dependent on  $\theta$ , the equation for  $C$  can be rewritten in one-dimension.

$$C = 2\pi \int_0^B \log_2 \left( \frac{S(f) + N(f)}{N(f)} \right) f df$$

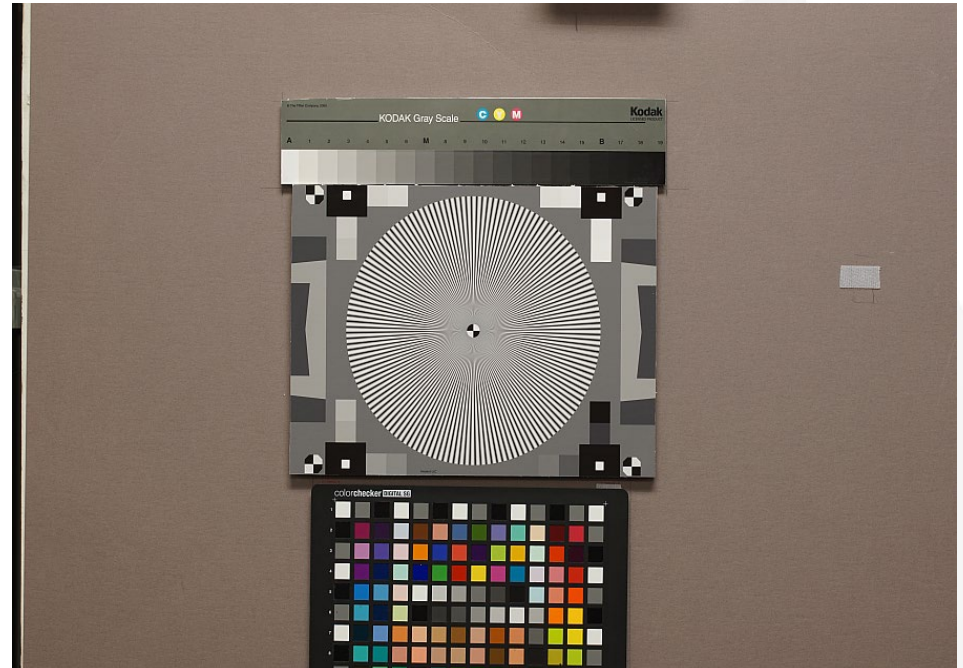
Good news! No more equations in this talk. 😊

$C$  differs from the original 1D equation by a factor of  $2\pi f$ . This little trick—converting from one to two dimensions and back—is the key to correctly calculating  $C$  and ensuring that it scales properly.

- Image should be well-exposed.
- It is linearized prior to analysis.
- For  $n_{cycles} = 144$ , the diameter of the star in the image should be 1400-1750 pixels so  $f_{Nyq} < f_{max} \leq 1.3f_{Nyq}$ .
- Many existing Siemens star images should be usable.

We tested three cameras that produced both raw and JPEG output.

- An older 10.1-Mpxl compact camera with  $2.14\mu\text{m}$  pixel pitch
- A 24-Mpxl Micro Four-Thirds camera with  $3.88\mu\text{m}$  pixel pitch
- A 42-Mpxl full-frame camera with  $4.5\mu\text{m}$  pixel pitch, BSI sensor



**Typical image for 24-Mpxl camera**



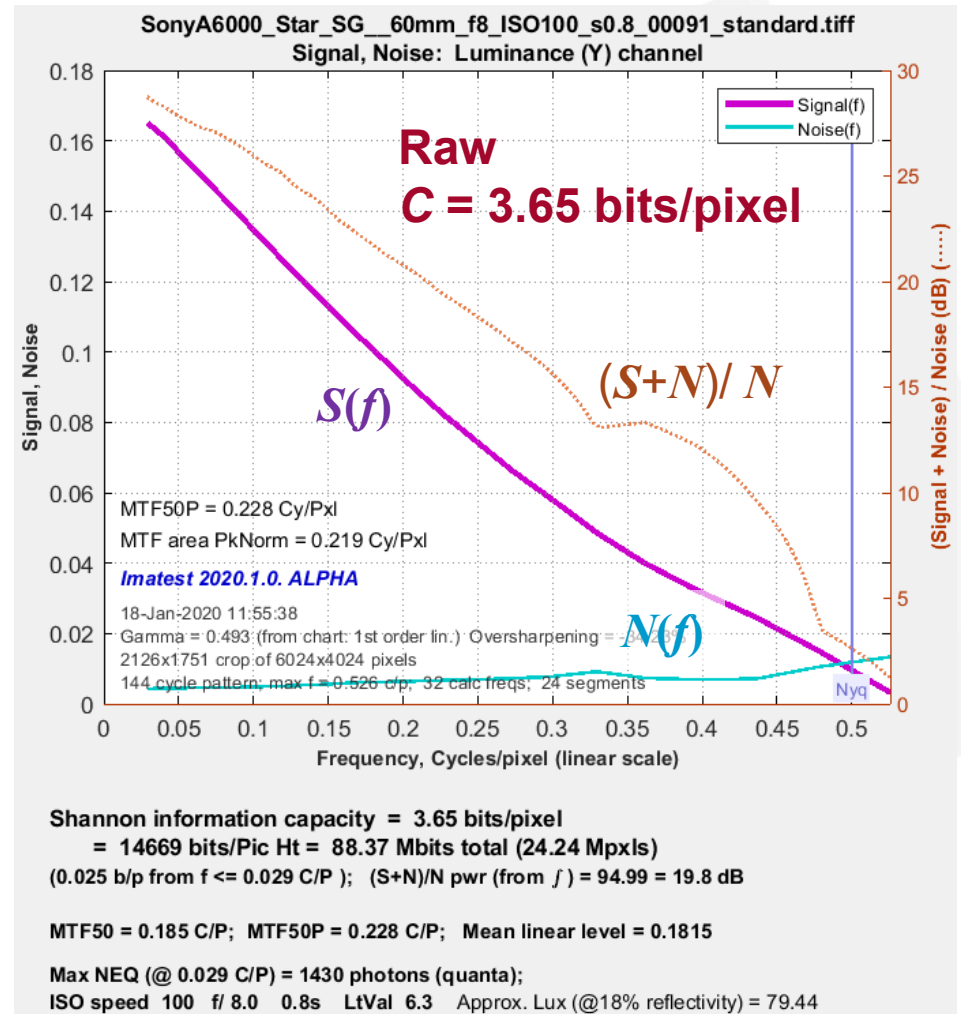
Results from **raw** image from the 24-Mpxl Micro 4/3 camera at ISO 100.

**Information capacity has units of bits/pixel.**

3.65 bits/pixel is excellent performance.

Signal  $S(f)$  (magenta line) is proportional to MTF (but normalized differently).

$N(f)$  is cyan, and  $(S+N)/N$  is brown.

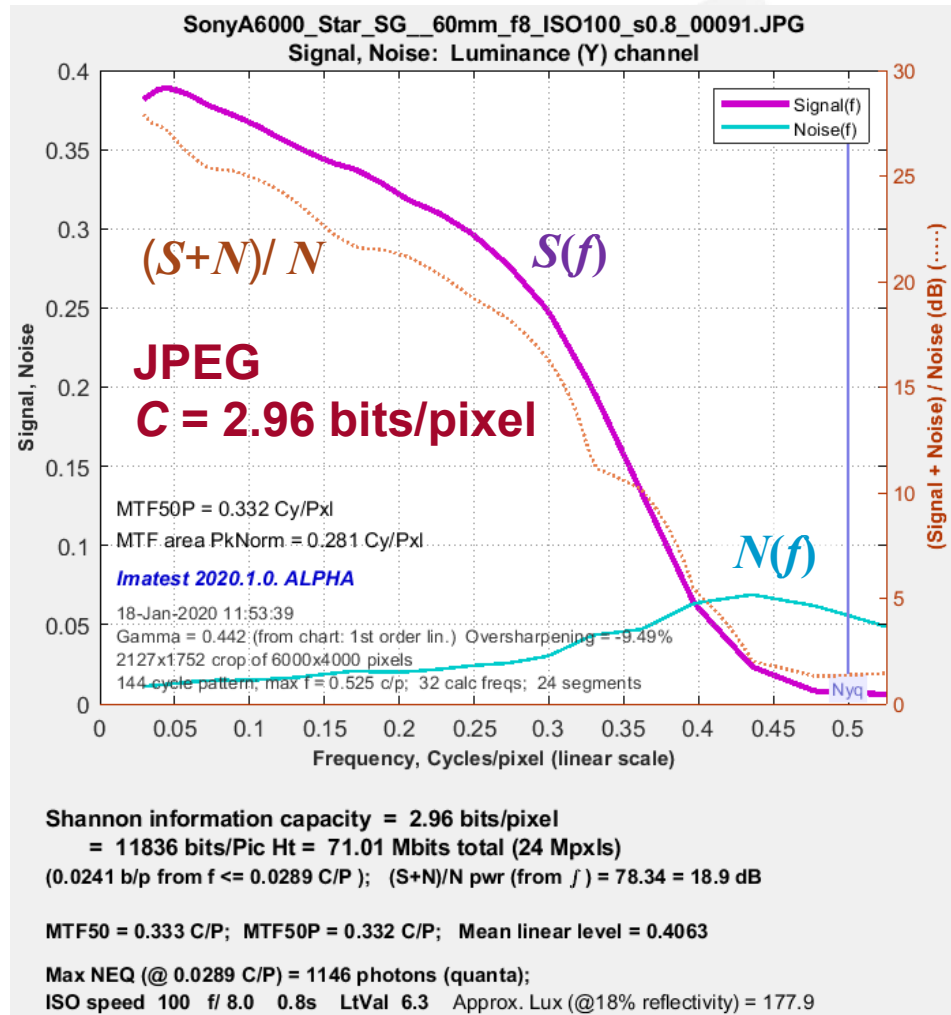


Results from **JPEG** image from the same 24-Mpxl camera at ISO 100.

2.96 bits/pixel lower than for unsharpened raw image, because sharpening increases high frequency noise; decreases SNR.

Table, showing results of sharpening (USM) and gaussian blurring

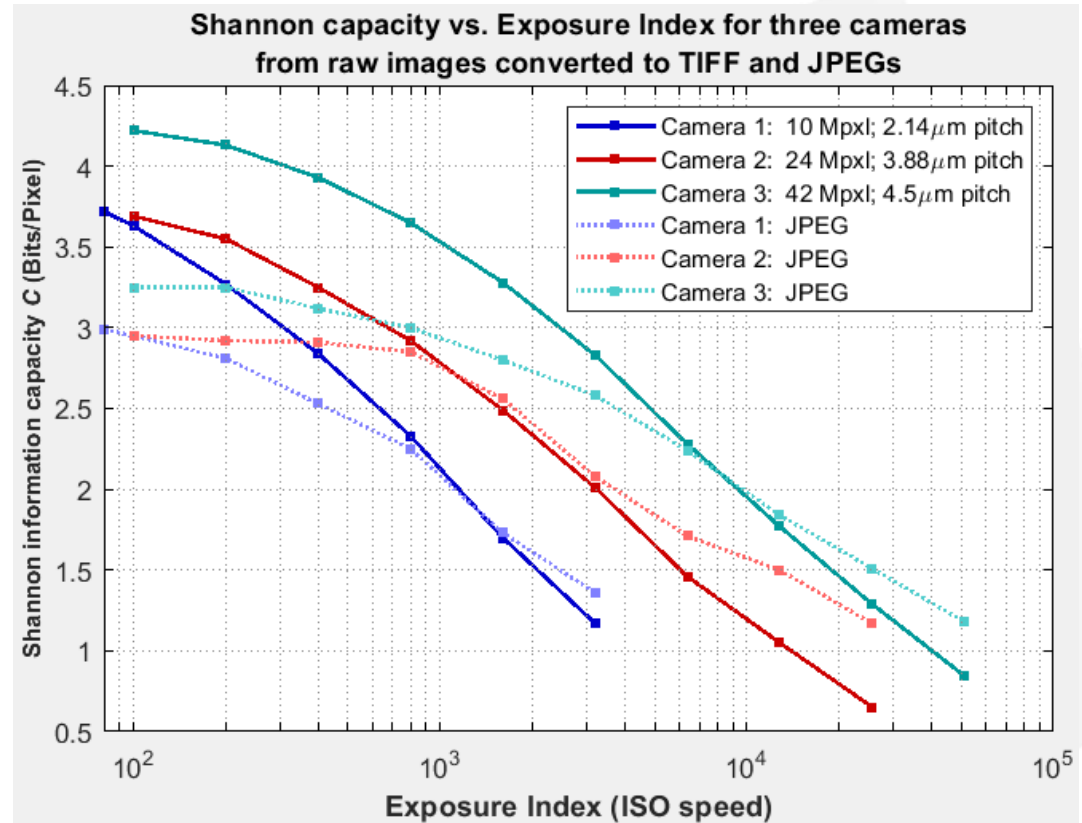
Image	C	MTF50 (c/p)	MTF50P (c/p)
Baseline	3.69	0.22	0.229
USM R2 A1	3.65	0.345	0.323
USM R1 A2	3.63	0.407	0.397
Gaussian 0.7	2.99	0.162	0.168
Gaussian 1.0	2.25	0.138	0.143
USM R2A1, Gaussian 0.7	3.06	0.241	0.239



Results for the three cameras (10, 24, 42 Mpxls) over a range of ISO speeds (Exposure Indexes)

Raw images (solid lines) have higher information capacity at low ISO speeds.

Reverses at high ISO speeds because of bilateral filtering (selective noise reduction) in the JPEG images. The greatest difference is only 0.5 bits/pixel.

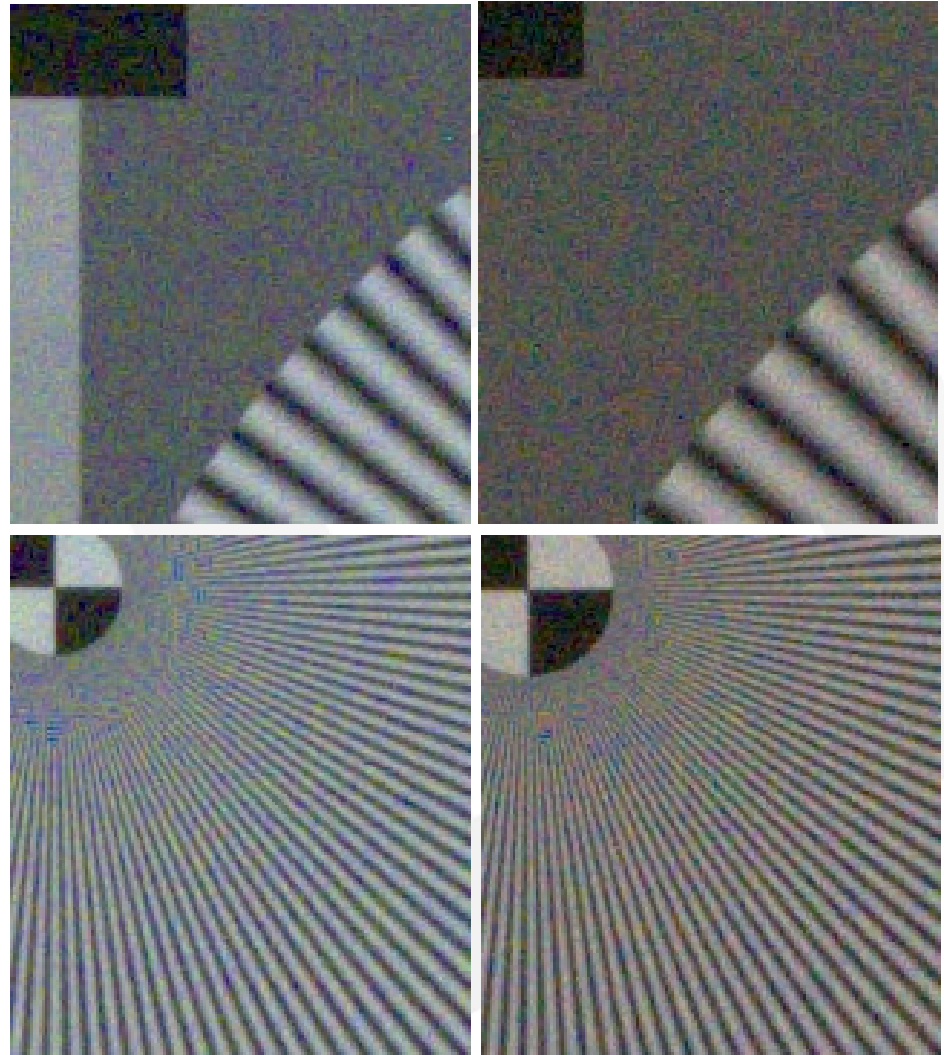


**Camera 3** has especially good performance because it has a Back Side-Illuminated (BSI) Sensor, which has much better SNR than standard sensors with equivalent pixel size.

Results from raw images from two different cameras at different ISO speeds, but with similar Information capacity  $\cong 1.7$  bits/pixel (much lower than for ISO 100, where noise would be difficult to see).

The appearance is similar.

**Camera 1, ISO 1600 (Left)**  
**Camera 3, ISO 12800 (Right)**



A noise image can be displayed.

It is created by calculating

$$N(\varphi) = s_{ideal} - s_{input}(\varphi)$$

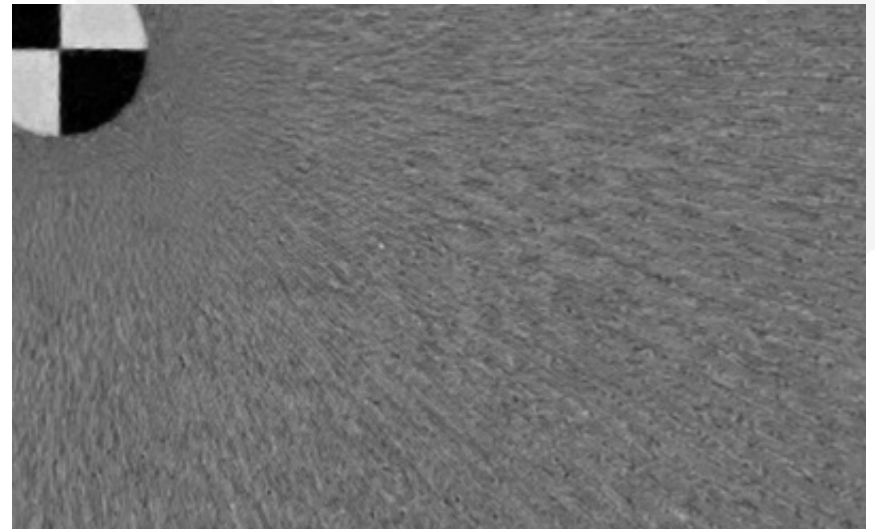
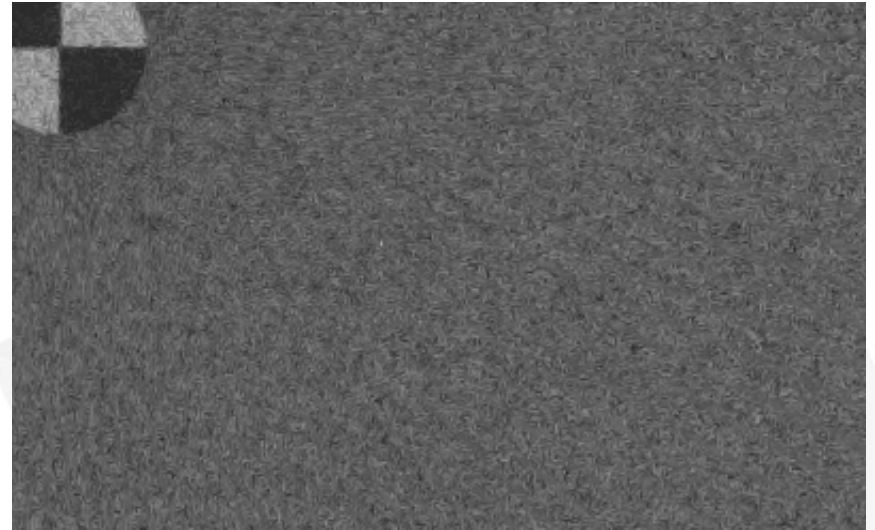
for all segments.

Contrast can be boosted to make noise visible at low ISO speeds.

**Camera 2, ISO 25600**

**Raw (top)**

**JPEG (bottom)**

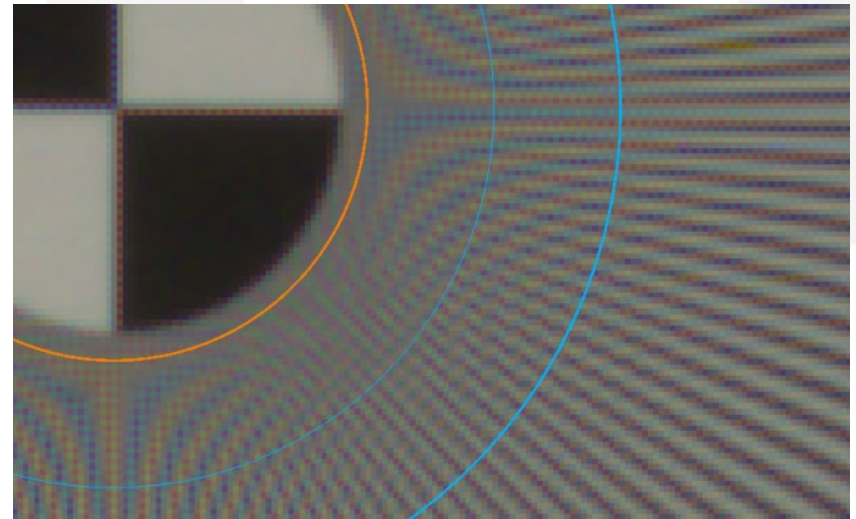
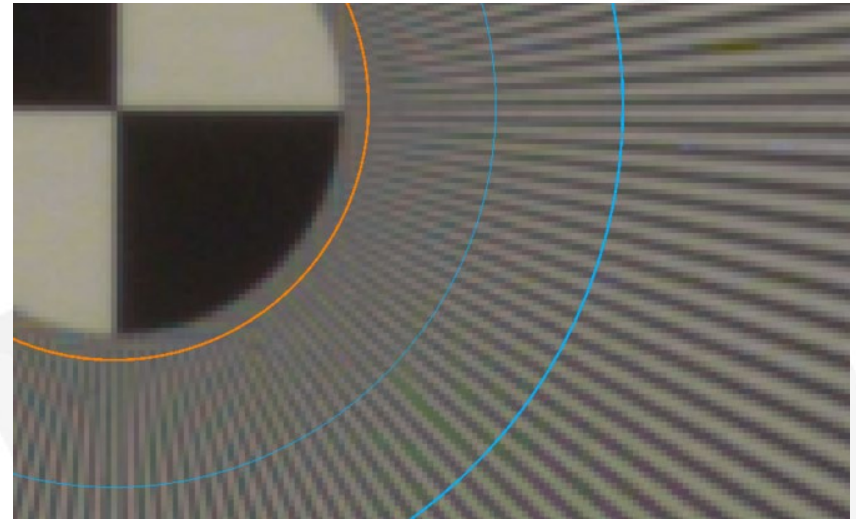




Demosaicing algorithms were analyzed in order of specified quality.

C correlated well with specified quality (better than MTF50P). Major differences were due to aliasing.

**AMaZE (best quality) (Top)**  
**Bilinear (poor quality) (Bottom)**



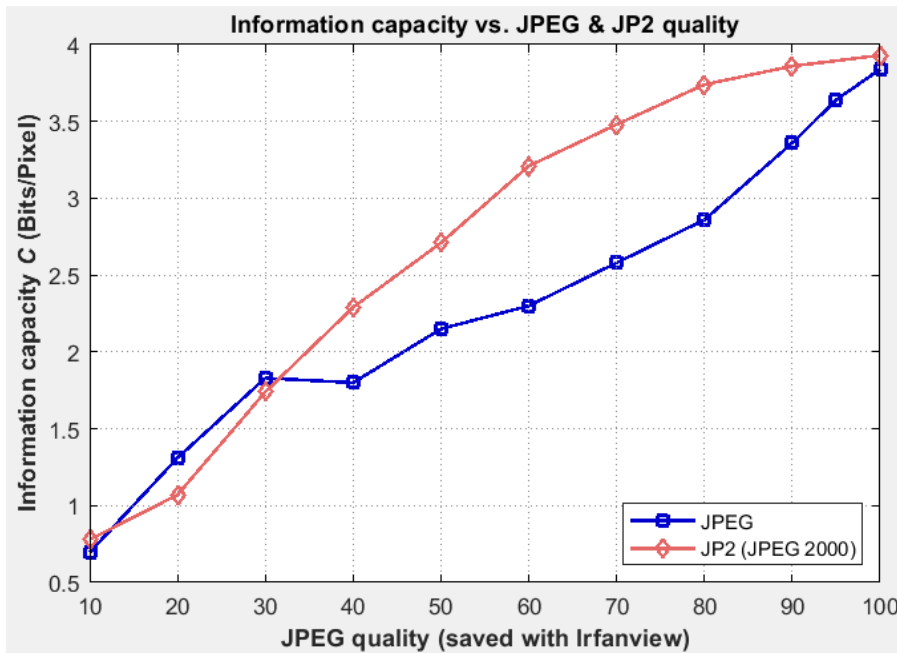
Demosaicing algorithm	C (bits/pixel)	MTF50P (C/P)
<b>dcraw bilinear</b>	1.8	0.191
<b>dcraw VNG</b>	2.51	0.219
<b>dcraw PPG</b>	3.14	0.229
<b>dcraw AHD</b>	3.69	0.229
<b>RawTherapee AMaZE</b>	3.95	0.236



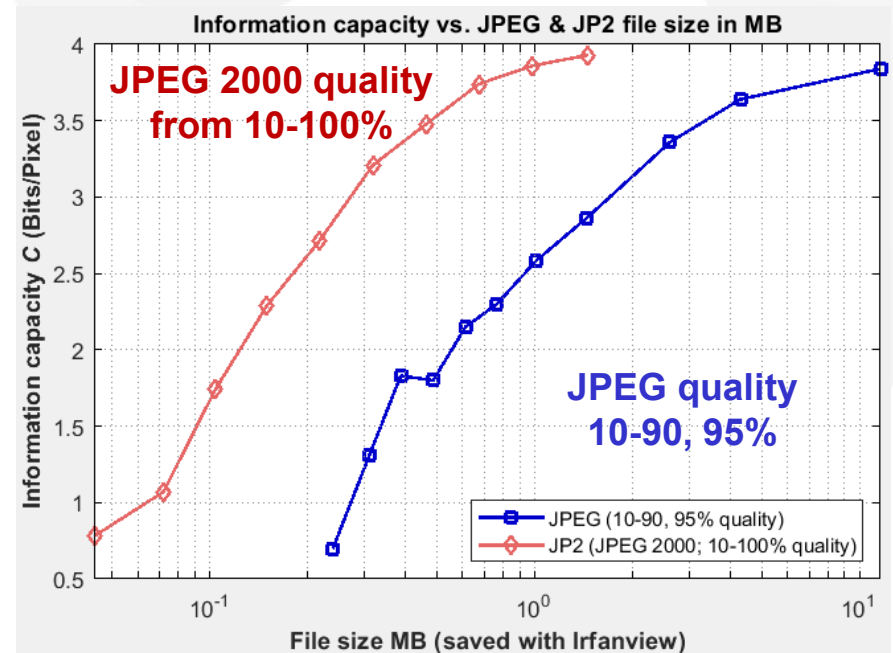
The 24-Mpxl ISO 100 raw image was saved as JPEG and JPEG 2000 for a range of quality levels.

JPEG 2000 was the clear victor. (So why hasn't it gotten traction?)

## Information Capacity C vs. Quality level

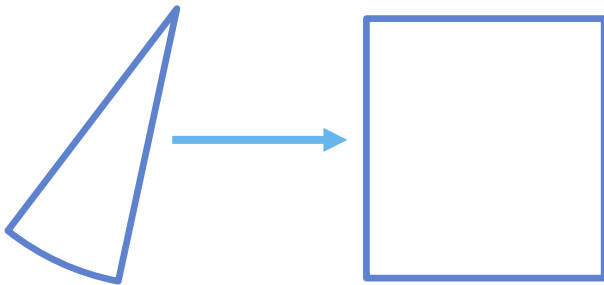


## Information Capacity C vs. file size

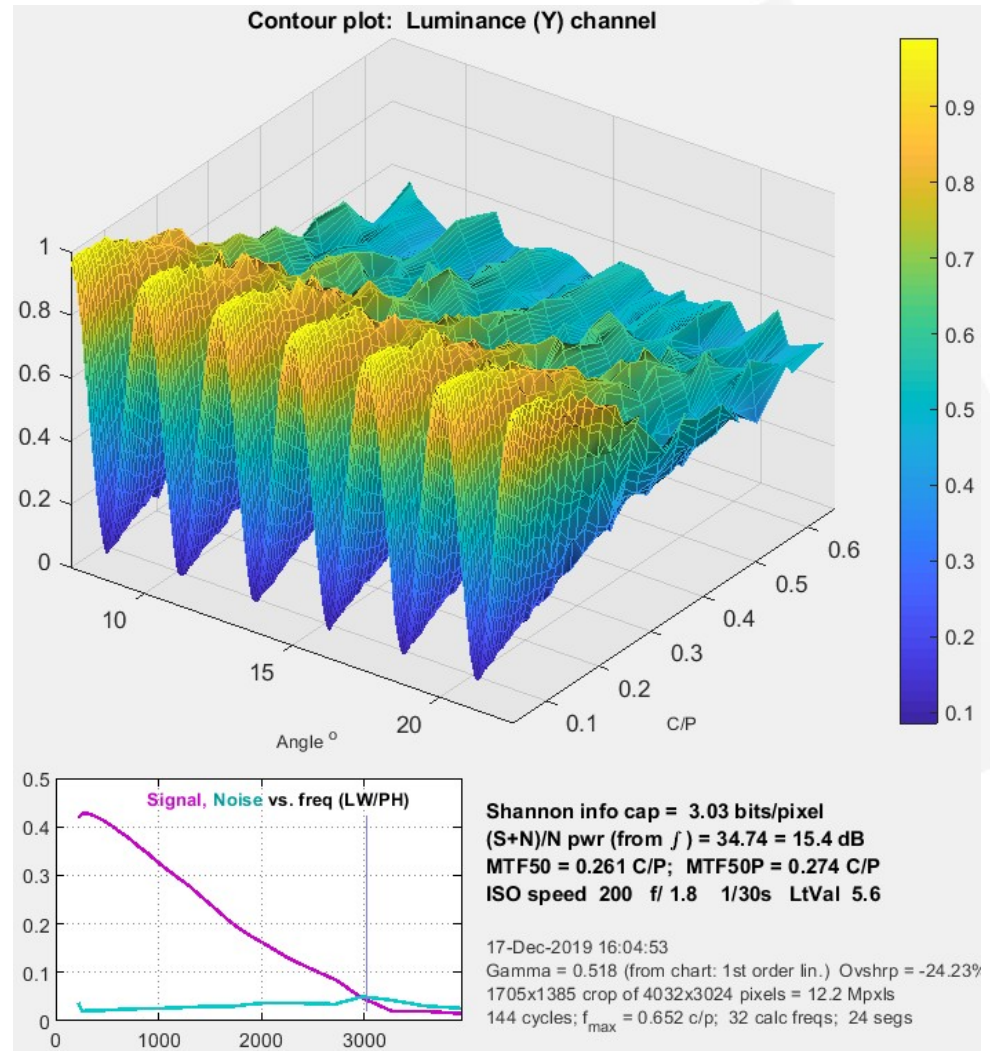


Raw (TIFF) image from iPhone 10 (captured with Adobe software)

A narrow pie segment has been turned into a rectangle.



Note that the information capacity (3.03 bits/pixel) is very similar to the highly-processed image in the next slide (3.10 bits/pixel).

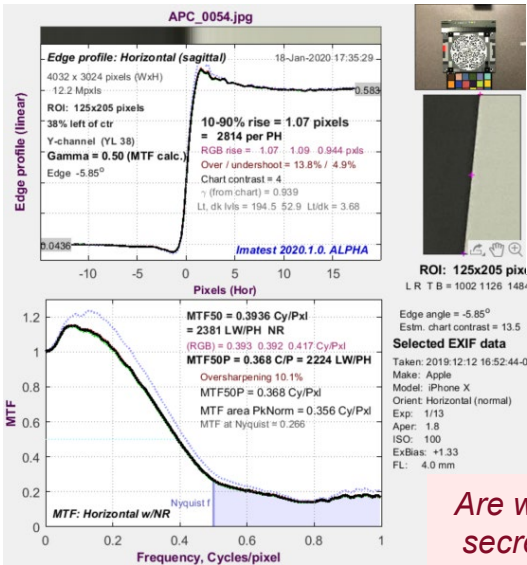


## JPEG image from iPhone 10

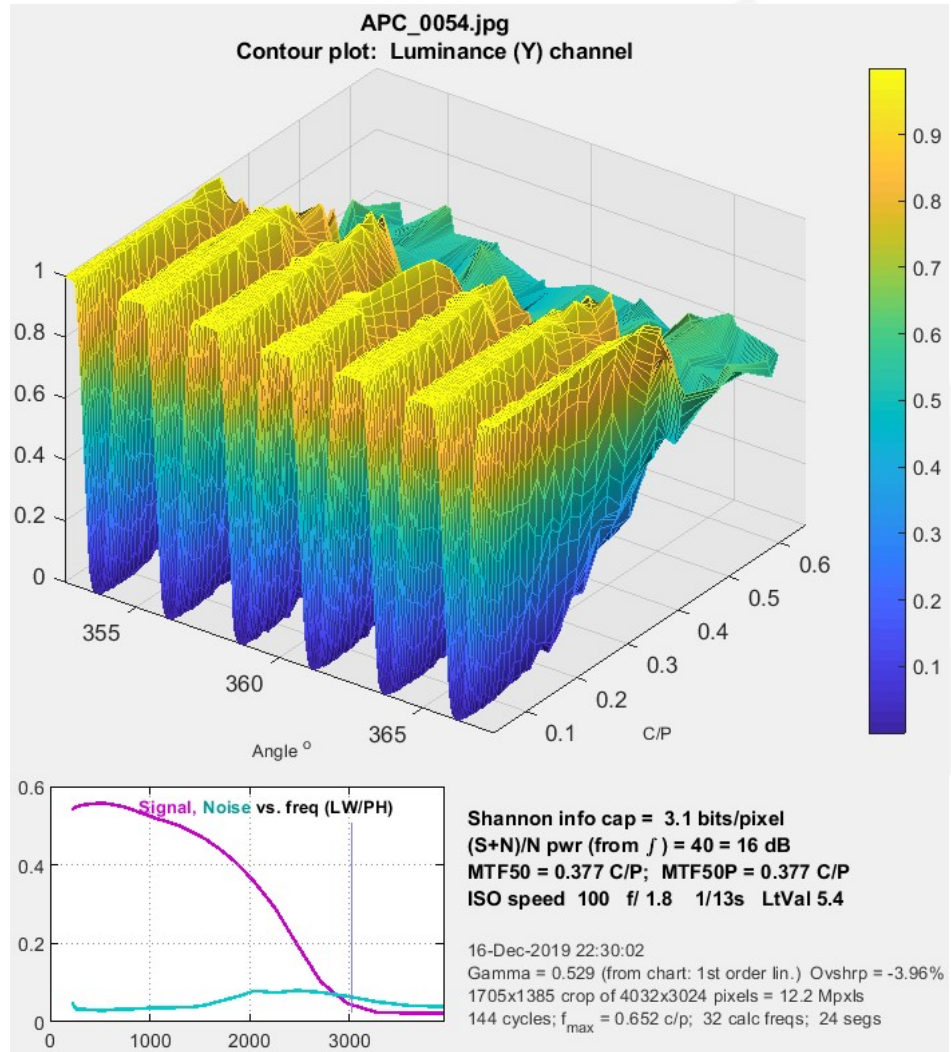
Some rather extreme mid-frequency contrast boost may make the image look more “snappy”.

**Mystery:** The clipping is not visible in SFR results from a 4:1 slanted-edge

(perhaps because contrast is lower than the star (???)



Are we seeing Apple's secret (apple)sauce?

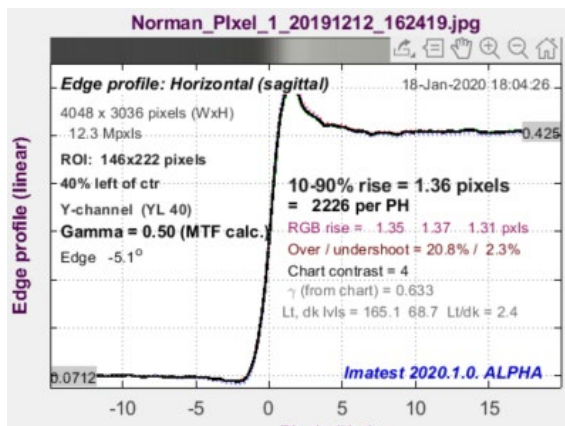




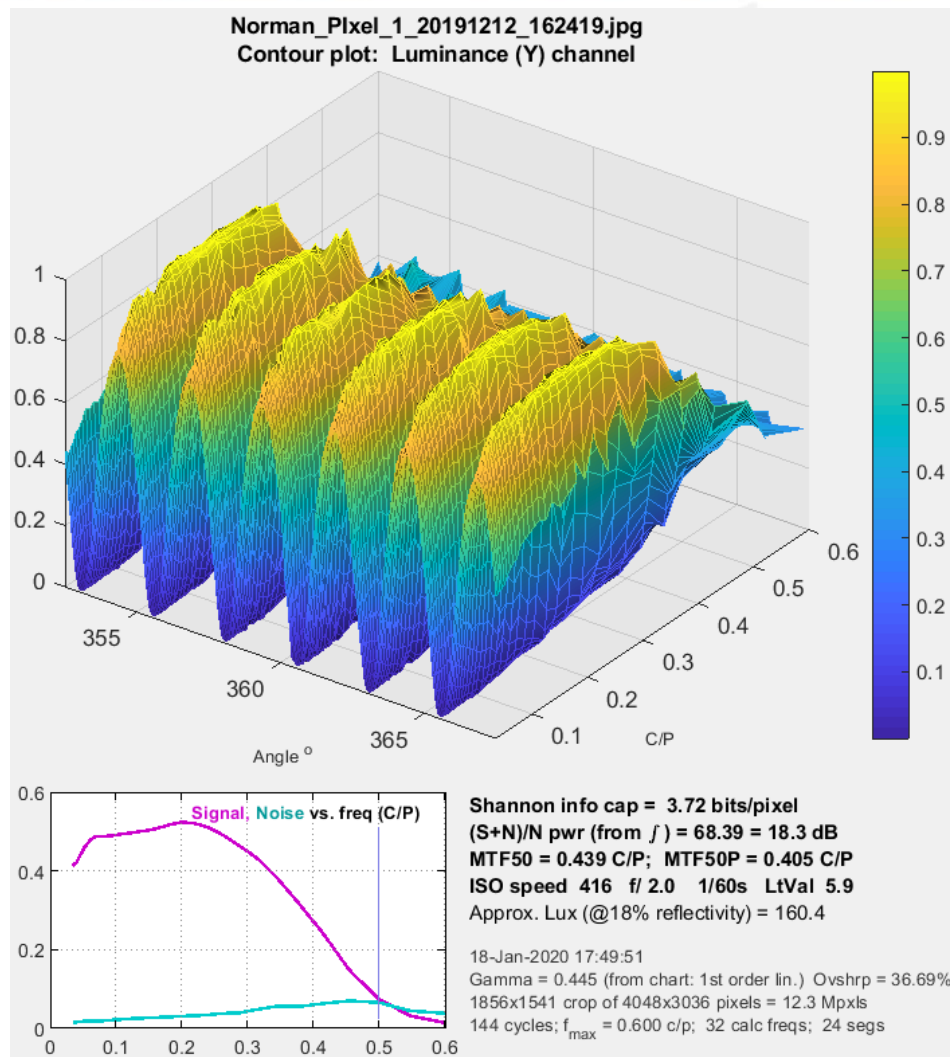
## JPEG image from Google Pixel phone

Sharpening is present, but the clipping noted in the iPhone 10 JPEG is absent. The image may be less “snappy”.

Information capacity (3.72 bits/pixel) is excellent.



4:1 slanted-edge results



## Other measurements

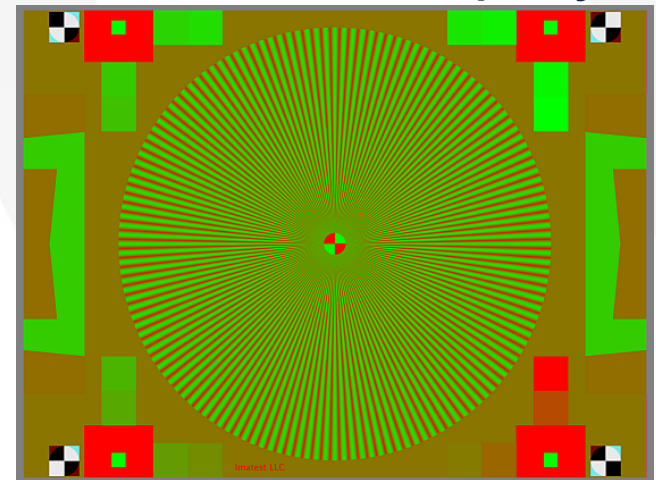
$s(f)$  and  $n(f)$ , derived from the Siemens star, can be used for other measurements (most of which we haven't tested extensively).

- SNRI, for detecting small “difference objects”  $SNRI^2 = \int \frac{|G(f)|^2 S(f)}{N(f)} df$   
where  $G(f)$  is the Fourier transform of the difference object.
- Noise Equivalent Quanta  
 $NEQ(f) = S(f)/N(f)$

All results above are for the Luminance (Y) channel. We measured C for R, G, and B channels separately (no surprises).

We plan to measure color (or chroma) information capacity using special versions of the Siemens star (G-R or G-B).

color information capacity

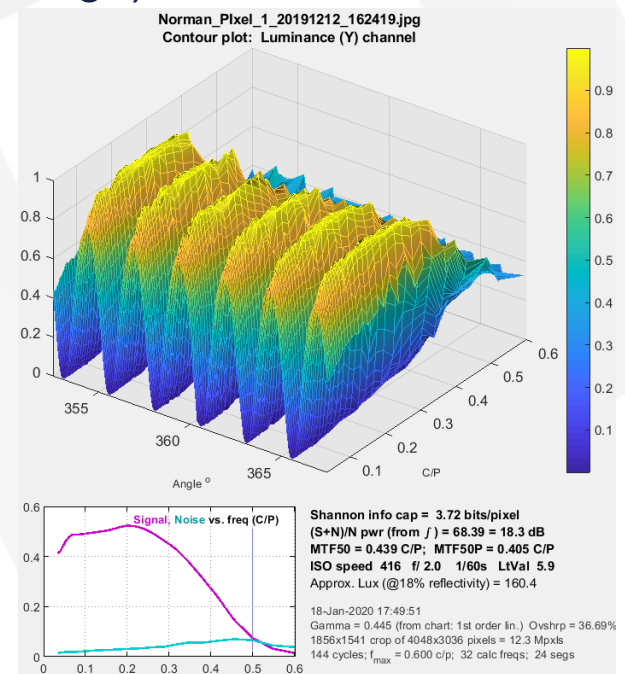


**Information capacity  $C$** , measured in bits per pixel (or bits per total image) at a specified ISO speed or illumination, combines sharpness (bandwidth; MTF) and noise using a classic approach from information theory.

It indicates the amount of information per pixel (or total image).

**This makes it potentially very valuable for evaluating the performance of cameras for Machine Vision and Artificial Intelligence (AI) systems, which operate on information (*not* just pixels).**

We will work with companies or academic institutions who can test this hypothesis.





Our method of measuring information capacity  $C$  from images of the Siemens star is fast, convenient, and reliable. Signal  $S$  and noise  $N$  are measured from the same locations for best accuracy and reliable scaling.

**We stress that information capacity  $C$  is new and unfamiliar to most engineers. But the units— information bits per pixel— are intuitive and easy to understand.**

**We believe it is a strong candidate to become a standard Key Performance Indicator (KPI) in the imaging industry.**

But before that can happen it will need to be standardized.

*Thank you*