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General Image Quality Equation (GIQE)

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General Image Quality Equation (GIQE)

- The General Image Quality Equation (GIQE) predicts NIIRS as a function of Ground Sample Distance (GSD), Relative Edge Response (RER), Signal-to-Noise (SNR), Convolver Gain (G), and Edge Overshoot (H).
  - The variables RER, G and H are defined after image enhancements are applied. Only SNR is independent of image enhancements.

- Latest two versions of the GIQE are:

GIQE4 NIIRS = 10.251 – a*log10(GSD) + b*log10(RER) + 0.656*H – 0.344*G/SNR

where

- $a = 3.32$ and $b = 1.559$ if $RER \geq 0.9$ or
- $a = 3.16$ and $b = 2.817$ if $RER < 0.9$

GIQE3 NIIRS = 11.81 + 3.32*Log10(RER/GSD) – 1.48*H – G/SNR

- GIQE4 is particularly problematical because it is dual sloped with GSD depending upon the RER.

GIQE History

- GIQE3 was released Dec 1994 to unmanned aerial vehicles/sensors community.
- GIQE4 was published Nov 1997 in Applied Optics Vol 36 No 32 pp8322-8328 for the developing commercial space imaging industry.
- Both IQEs were empirically determined.
- Both IQEs assumed hardcopy viewing.
  - The GIQE4 user's guide asserts that, on average, optimized softcopy provides a 0.2 NIIRS improvement over hardcopy.
- GIQE4 uses GSD defined in the ground plane. GIQE3 uses GSD defined in the plane orthogonal to the line of sight.
- Next generation GIQE (GIQE5) is being designed for softcopy.
- NIIRS scale has been revised to give a 2 to 1 slope with respect to log(GSD).
  - Each doubling of the GSD should reduce the NIIRS by one unit.
  - Previous version did not yield this 2 to 1 slope.

Why Softcopy GIQE should differ from Hardcopy GIQE

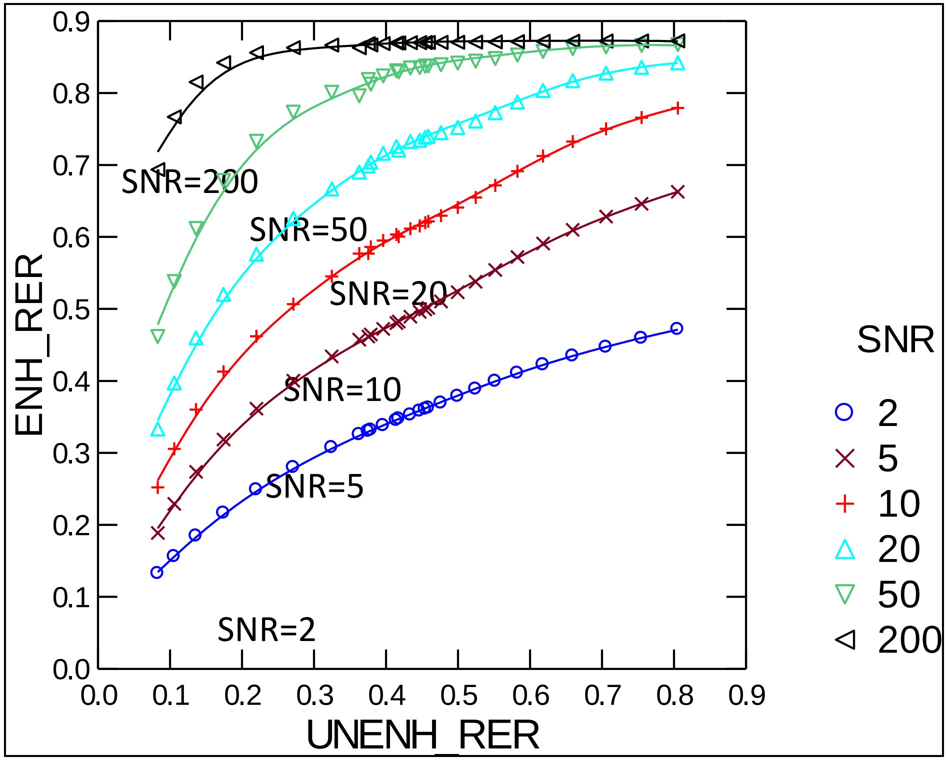
- For hardcopy, images are enhanced during the film development process and the user had limited ability to modify these enhancements (mostly magnification) during exploitation of the scene.
  - So a hardcopy GIQE can assumed RER, H and G are essentially fixed values, with only GSD changing from image to image.
  - For any particular imaging system, estimating the value the hardcopy RER, H and G was a one time—although not necessarily trivial—exercise.
- In contrast, softcopy is enhanced interactively by the image analyst when viewing digital images on a electronic light table (ELT).
  - ELTs typically provide interactive sharpening (MTFC), contrast adjustments through the use of dynamic range adjustments (DRA) and lookup tables (LUTs), magnification and rotation.
  - Interactive enhancement of softcopy images imply RER, G and H, as defined by GIQE3 and GIQE4, can no longer be considered fixed known constants.
- This suggests a softcopy GIQE should be defined using variables prior to enhancement that would predict the NIIRS of an image after enhancement.
  - That is, NIIRS would be a function of:
    - GSD
    - Unenhanced RER (RER_0)
    - SNR only
  - The unenhanced values of $G \cong 1$ and $H < 1$ would not be useful predictors of NIIRS

Enhanced vs Unenhanced Variables

- It is desirable that any new GIQE that uses unenhanced parameters be compatible with previous developed GIQEs that used enhanced parameters
  - This requirement means that the relationship between the unenhanced RER and optimally enhanced RER and G be defined
  - This, in turn, requires the optimized enhancement process be specified

- It will be assumed here that images will be enhanced using Wiener filtering
  - Wiener filtering has known optimal properties, but
  - Wiener filtering is not uniquely defined – several versions can be found in the literature
  - The version used here is a modified version of the one used by Thurman and Fienup "Application of the General Image-Quality Equation to Aberrated Imagery" Applied Optics, April 2010

Enhanced RER vs Unenhanced RER Using Wiener Sharpening



Summary of the Literature Review

- All reports reviewed (see Background Slides) found the dual slope associated with the GIQE4 GSD term a problem and that the equation did not well predict NIIRS.

- The Samuel T. Thurman and James R. Fienup papers found the GIQE3 predicted NIIRS very well when the H term was removed. They achieved an even better fit to the NIIRS data if the coefficient for the G/SNR term was re-estimated and increased from 1.0 to a value in the range (2.23, 2.57).
  - The dropping of the H term may be an artifact of the use of Wiener filtering which does not cause significant edge overshoot
  - Of course edge overshoot will not be a quality factor for unenhanced softcopy images. H will always be less than 1.0. This can not be assume true for hardcopy, as the photo-development process alone can enhance edges.

Approach

- The GIQE3 is a good predictor of NIIRS using the enhanced value of RER and the amount of gain applied G.
  - It will be assumed GSD is fixed at 21 inches (a nominal NIIRS 5 case) so only RER and G/SNR are relevant. H is ignored because the Wiener filter will not cause edge overshoot.
- Using the Wiener filter, a relationship between the unenhanced and the enhanced RER can be established (as shown earlier).
- The GIQE3 is then used to predict the NIIRS from the enhanced parameter values and then a model (GIQE5) will be identified and estimated that predicts the same NIIRS using the unenhanced parameters.
- This approach insures continuity between previous general image quality equations.
- Variation in image quality and its effects on NIIRS were assessed by first varying the value of Q and then by varying the value of the Waveform Error (WFE) Root-Mean-Square Error (RMSE) (see backup slides).

An Unenhanced Version of GIQE3

$$\mathbf{NIIRS = c0 + c1*log_{10}(GSD) + c2*(1 - e^{c3/SNR})*log_{10}(RER_0) + c4*log_{10}(RER_0)^4 + c5/SNR}$$

Where

c0 = 9.7

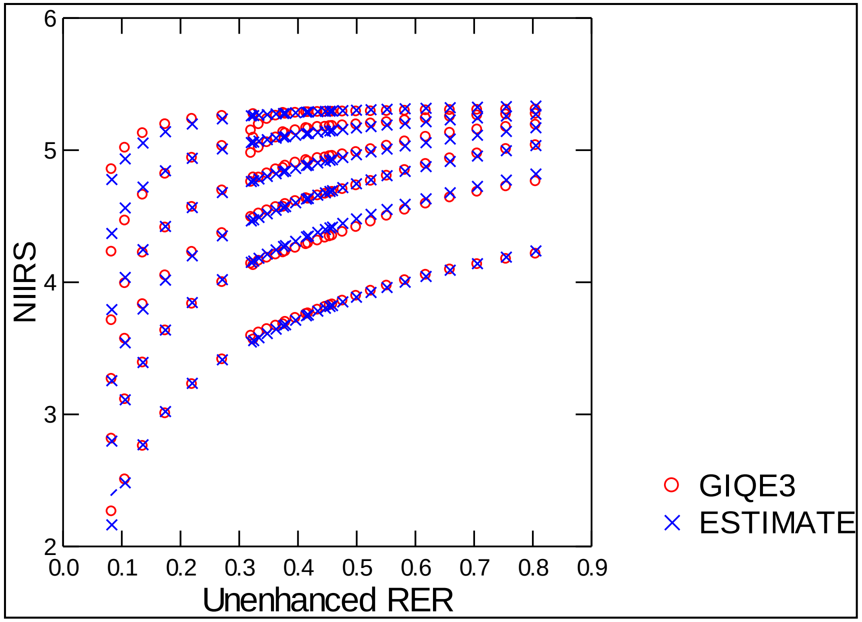
c1 = -3.32

c2 = 1.68

c3 = -17.3

c4 = -0.308

c5 = -1.92



- $R^2 = 0.999$
- The GSD coefficient, c1, is equal to -3.32 by definition.
- This analysis establishes the functional form of the GIQE5.
- Parameter values must be validated and possibly re-estimated from IA NIIRS data.

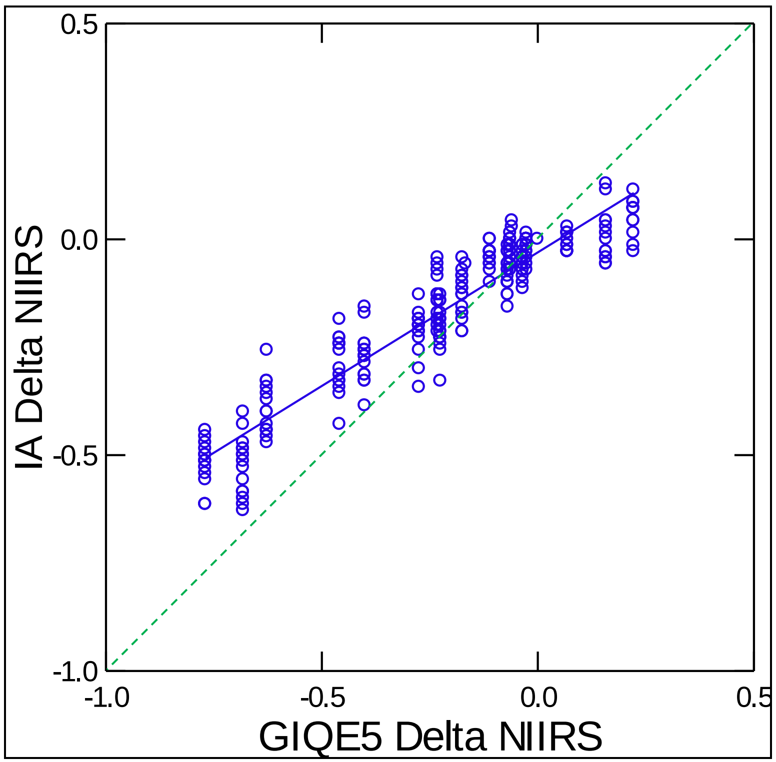
Evaluation Design

- From an archive of previous evaluations, NIQU identified 251 images where SNR, smear and unenhanced RERs were systematically varied.

- These images were then Delta NIIRS rated comparing them to a base case image.
  - 8 IAs participated in the evaluation

Provisional GIQE5 Derived From GIQE3

$$\mathbf{NIIRS = c0 \;+ c1*log_{10}(GSD) + c2*(1 - \;e^{c3/SNR})*log_{10}(RER_0) \;+ c4*log_{10}(RER_0)^4 + \;c5/SNR + c6*smear}$$



- Where the coefficients are the same as reported earlier except for the addition of a smear term c6 = -0.0713.
- $R^2 = 0.94$
- The IA NIIRS data is linear with the GIQE5 predicted NIIRS.
- But the GIQE5 NIIRS is biased possibly due to the use of the new NIIRS scale.
  - Data should lie on the diagonal.

Preliminary GIQE5 Estimated from IA NIIRS Ratings

$$\mathbf{NIIRS = c0 + c1*log_{10}(GSD) + c2*(1 - e^{c3/SNR})*log_{10}(RER_0) + c4*log_{10}(RER_0)^4 + c5/SNR + c6*smear}$$

Source	SS	df	an Squares
Regression	14.3335	5	2.8667
Residual	0.7406	246	0.003
Total	15.0741	251	
Mean corrected	7.9743	250	

$R^2 = 0.95$
SE = 0.055

Parameter	Estimate	ASE	Parameter/ASE	Wald 95% Confidence Interval	
				Lower	Upper
C3	-5.308	0.858	-6.185	-6.999	-3.618
C4	-0.402	0.138	-2.923	-0.673	-0.131
C5	-2.920	0.833	-3.507	-4.561	-1.280
C6	-0.069	0.005	-13.912	-0.079	-0.059

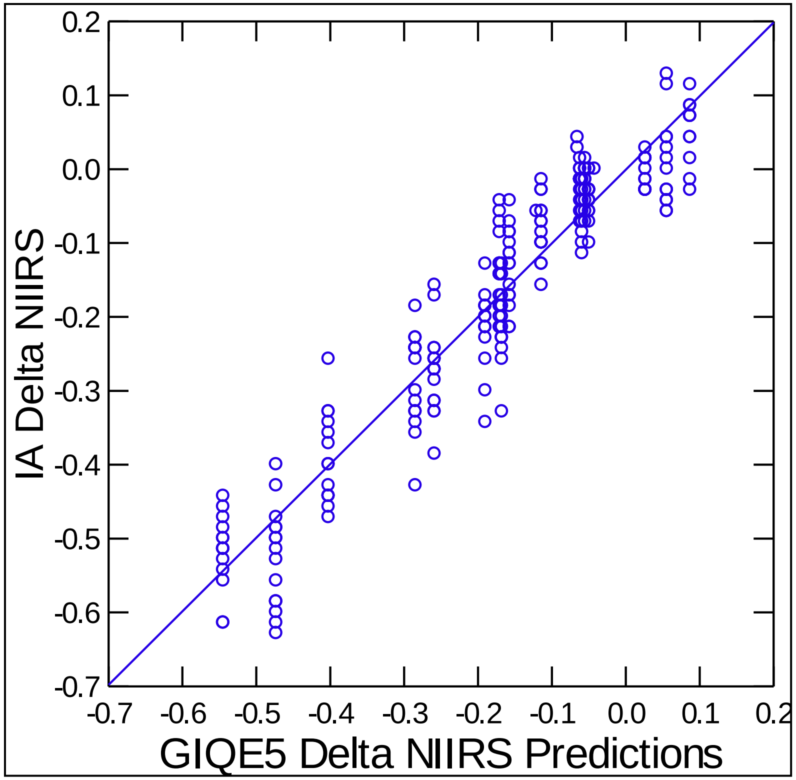
- The first three coefficients are pre-defined to be compatible with GIQE3:

  c0 = 9.7
  c1 = -3.32
  c2 = 3.32

- The four remaining coefficients are estimated as below:

  c3 = -5.308
  c4 = -0.402
  c5 = -2.920
  c6 = -0.069

Plot of IA NIIRS data and the Preliminary GIQE5



A Preliminary GIQE5

$$\mathbf{NIIRS = 9.7 - 3.32*\log_{10}(GSD) + 3.32*(1 - e^{-5.308/SNR})*\log_{10}(RER_0) - 0.402*\log_{10}(RER_0)^4 - 2.92/SNR - 0.069*smear}$$

- This equation is subject to further revisions as more images are evaluated and added to the analysis to examine additional parameter ranges including:

  RER_0: (0.2, 0.5)

  SNR: (10, 200)

  Smear: (0, 3 pixels)

Validation & Additional Research

We plan to do additional in-house validation

We welcome additional data

We hope to investigation the merits of different means of computing GSD

- Ground Plane
- Slant Plane
- Other

Backup Slides

NIIRS

- The National Imagery Interpretability Rating Scale, or NIIRS, is a spatial utility scale applicable for all sensor modalities.

- The current NIIRS is divided into ten integer rating levels (0, 9).

- The NIIRS provides a standardized indicator of imagery's usefulness for planning missions, system tasking, evaluating system performance

- NIIRS, along with the specific sensor phenomenology (refresh rate, spectral bands, etc.) supports determination of the full utility of a given sensor with respect to a mission need.

Some Literature References to GIQE

1. Samuel T. Thurman and James R. Fienup, "Application of the General Image Quality Equation to Aberrated Imagery", Applied Optics, Vol. 49, No. 11, 10 April 2010, pp2132-2142
   - Reports the results of an experiment where a softcopy test target was degraded by various amounts of aberration and compared the NIIRS loss to that was predicted by the GIQE3 and GIQE4. Degraded images were optimized using a Wiener filter. Image simulations used WorldView/GeoEye type sensor parameters (Q= 1.18, mirror diameter = .6 m, etc.) as the base case. Both GIQEs underestimated the NIIRS loss for low SNR cases, with the GIQE3 better than GIQE4. Re-estimating the G/SNR coefficient for the GIQE3 case (and dropping the H term), their modified GIQE agreed "quite well with experimental results, yielding coefficients of determination R^2 =0.945 and 0.933 for the defocus and mid-frequency aberration cases, respectively"
   - Thurman and Fienup's adjusted GIQE, (R^2 = 0.945 and 0.933)
     - » Delta NIIRS = $0.291 + \log_2(RER_{enhanced}) - 2.229G / SNR$ (Defocus)
     - » Delta NIIRS = $0.283 + \log_2(RER_{enhanced}) - 2.574\, G / SNR$ (Mid-Spatial-Frequency)
     - » where the RER and G are calculated after optimization

Some Literature References to GIQE (continued)

2. Samuel T. Thurman and James R. Fienup, "An Analysis of the General Image Quality Equation", Visual Information Processing XVII, ed. Zia-ur Rahman, et al, Proc. SPIE Vol. 6978, 2008, 69780F, pp1-13
   – This paper reports the results of an experiment that altered image quality by changing GSD, RER (via changes in Q) and SNR. Wiener filtering was used to sharpen the degraded test images. Their results "indicate the GIQE 3.0 image quality predictions are more accurate than those from GIQE 4.0". A major limitation of the study was that in all cases, Q was equal to or greater than 2 with a maximum value of 8. Most remote sensing systems have Qs less than 2.0, with Q ≈1 fairly typical.

3. Robert D. Fiete and Theodore Tantalo, "Comparison of SNR Image Quality Metrics for Remote Sensing Systems", Optical Engineers, April 2001, Vol. 40(4) pp574-585.
   – This paper discusses various SNR metrics and reports the results of an NIIRS ratings of an image simulation experiment. Parent image of the simulation were photographs that were subsequently digitized. The digitized images were then modified modeling the noise characteristics of the Kodak Space Remote Sensing Camera Model 1000.

Some Literature References to GIQE (continued)

They determine the following relationship between delta NIIRS and delta SNR from an image evaluation:

- delta NIIRS = (-1.36 +- 0.16)/SNR,
- where SNR = 1/(12.5* NE$\Delta\rho$). This coefficient should be compared to the GIQE3 SNR coefficient of 1.0

4. Robert D. Fiete and Theodore Tantalo, "Image Quality of Increased Along-Scan Sampling for Remote Sensing Systems", Optical Engineers, May 1999, Vol. 38 (5), pp815-820
   - This paper examines the consequences of increasing the along scan sampling rate of a linear image array sensor, essentially creating an image with a better GSD in the along scan direction compared to the GSD in the cross scan direction. They create simulated imagery and determine the NIIRS improvement from an image evaluation. They show NIIRS increases linearly with along scan sampling rate (or equivalently linear with Q) up to a factor of 1.5x in the along scan direction and then levels off reaching a maximum of 0.35 NIIRS at 2x. Elliptical shaped GSDs complicate this experiment and any conclusions are specific and cannot be generalized. However the authors did note the GIQE4 does not predict the data at all well, and this is relevant to this effort

Some Literature References to GIQE (continued)

5. Steven Smith, James Mooney, Theodore Tantalo, Robert Fiete, "Understanding Image Quality Losses Due to Smear in High-Resolution Remote Sensing Imaging Systems", Optical Engineers, May 1999, Vol. 38 (5), pp821-826
   - This paper examines the effects of image smear on image quality. Images were simulated to have 0, 1, 2, 3, 4, and 8 pixels of smear in the along scan direction. Parameters were Q=1, WFE RMSE= 0.1, SNR = 50, a fill factor of 70%, and 1 meter GSD. A NIIRS evaluation produced the following equation:

$$\text{NIIRS Loss} = 0.0031 - 0.063\text{*smear} - 0.0059\text{*smear}^2$$

   - The authors caution that this result may be specific to the modeled imaging system and may not generalize.

Wiener Filtering

- Typically, Wiener filtering is defined in the Fourier domain as:

$$\frac{S(u,v)^*}{\left((|S(u,v)|)^2 + c\,\frac{stdN^2}{scene(u,v)}\right)}$$

where S(u,v) is the system MTF, stdN is standard deviation of the noise (assumed to be white), scene(u,v) is the scene MTF, and $c > 0$ is a fudge factor that can be used to adjusts the amount of gain applied.

- The definition above requires further specification and the one below is similar to one proposed in (1).

$$\frac{S(u,v)^*}{\left((|S(u,v)|)^2 + c\,\frac{5252 * (N+\sigma^2) * \rho^{3.14}}{N^2}\right)}$$

where N the average number of photoelectrons per pixel, $c = 0.2$, $\rho = (u^2 + v^2)^{0.5}$, u and v vary between 0.0 and 1.0 (Nyquist = 0.5) and detector read noise, σ.

Calculation of RER

The normalized edge response (ER) is calculated as:

$$ER_X(\xi) = 0.5 + \frac{1}{\pi}\int_0^{(nOptcutx)}\left(\frac{SystemX(v)}{v} \bullet \sin(2\pi v\xi)\right)dv \qquad X\text{-axis}$$

$$ER_Y(\xi) = 0.5 + \frac{1}{\pi}\int_0^{(nOptcuty)}\left(\frac{SystemY(v)}{v} \bullet \sin(2\pi v\xi)\right)dv \qquad Y\text{-axis}$$

where:

nOptcutx, nOptcuty = normalized (to the effective sample spacing) optics cut-offs in the x and y directions

System X, System Y= system MTF in the x and y directions

x = response position from the center of a horizontal pixel edge

v = spatial frequency in cycles per sample spacing

The system MTF is normalized to the effective pixel spacing after aggregation or decimation.

Given the calculated responses, RER is defined as the response difference between points -0.5 and +0.5 pixels from the edge center.

$$RER_X = ER_X(0.5) - ER_X(-0.5)$$

$$RER_Y = ER_Y(0.5) - ER_Y(-0.5)$$

The geometric mean RER is then computed

SNR, N and NEΔρ

- In ref(1), noise is modeled in terms of average electrons
  - Detector read noise σ = 50 photoelectrons (standard deviation)
  - Average Number of photoelectrons per pixel= N (various)
  - $SNR = N / (2*(N+\sigma^2)^{0.5})$

  It is assumed a 16% reflectance target has N photoelectrons on average. Signal is defined as the difference between a 16% reflectance and 8% reflectance targets

- Assuming SNR = 1/(12.5*NEΔρ), where NEΔρ is the Noise Equivelent Delta Reflectance and solving for N in the above equation

$$N = \frac{0.0256 + \left(0.00065536 + (256NE\Delta\rho)^2\right)^{0.5}}{(2NE\Delta\rho)^2}$$

- In particular, as found in reference (1)
  - When NEΔρ = 0.0004, SNR = 200 and N = 162,462
  - When NEΔρ = 0.0016, SNR = 50 and N = 12,071
  - When NEΔρ = 0.0080, SNR = 10 and N = 1220

$Q = \lambda FP/p$

- Q measures how finely the detector samples the diffraction-limited optics Point Spread Function (PSF)
  - λ is the mean wavelength
  - FN is the *f*-number and is equal to the focal length (*f*) divided by the mirror diameter (D)
  - p is the detector sampling pitch
- Baseline imaging system will have the following parameters representative of commercial panchromatic remote sensing systems
  - $\lambda = 0.644\ \mu m$
  - D = 0.6 m
  - $f = 8.8$ m
  - $p = 8.16\ \mu m$
  - Q = 1.16
- Other parameters of interest and their assumed baseline values are:
  - fill factor – the percent of the mirror non-obscured (85%)
  - Waveform Error RMSE (= 0.0)
  - smear (= 0.0 pixels)

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