SSA Image Quality Modeling

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ABSTRACT

This paper evaluates the ITIQUE image quality modeling framework for SSA applications. Based on Bovik and Sheik's VIF metric, ITIQUE evaluates the Shannon mutual information (MI) at multiple spatial scales between a pristine object and the image output from a detailed image formation chain simulation. Integrating the MI at each spatial scale and applying a calibration offset produces a prediction of NIIRS image quality indicating the level of interpretation tasks that could be supported. The model enables prediction of NIIRS quality obtainable as dependent on image collection conditions and image system design including both hardware and processing algorithms. The ITIQUE framework could facilitate concept evaluation and engineering design by quantitatively relating image formation performance directly in terms of end end-user mission needs. Previous work focused on overhead imagery of terrestrial scenes and linear processing only. This paper considers ground-based imaging of SSA targets and extends the previous study to include non-linear processing. A range of turbulence strengths and SNRs are included. ITIQUE predictions are shown to match well to results from a human visual assessment study in which a panel of human observers rated NIIRS quality of the same imagery.

1. INTRODUCTION

Image quality metrics can be broadly classified into subjective and objective. The former refer to ratings of image quality obtained by a human observer. In contrast, objective image quality metrics are numerically computed from the image data or a mathematical description of the relevant imaging system. Objective image quality metrics can be a useful tool in the design and evaluation of new imaging systems. Of particular interest are objective quality metrics that predict the value of imagery in terms of image analysis tasks that can be successfully accomplished.

The overhead and tactical imaging communities have successfully used several task-based image quality metrics over the past few decades. For example, the National Imagery Interpretability Rating Scale (NIIRS) and the General Image Quality Equation can be used to evaluate an image in terms of its utility for detection, classification, and identification tasks. The probability of combat ID (PCID), and the closely related Johnson criteria provide the probability of correct combat identification for targets based on the resolution elements across the target.

For Space Situational Awareness (SSA) applications, objective image quality metrics are sorely needed. There have been several attempts to develop subjective image quality metrics based to a high degree on the NIIRS approach. However, these metrics have not gained wide acceptance. In this paper, we describe an information theoretic framework to predict image quality (ITIQUE) and its extension to evaluate SSA imaging system performance in terms of end-user mission needs.

The rest of the paper is organized as follows: Section 2 presents background information on NIIRS and its predictive tool the GIQE. Also, an alternative method based on an Engineering NIIRS Ruler which allows for human subject studies without resorting to trained imagery analysts. Section 3 presents the ITIQUE framework and the results of a previous study using overhead imagery. Section 4 presents the extensions of the previous study the SSA arena. Finally Section 5 concludes the paper.

2. BACKGROUND

2.1 National Image Interpretability Rating Scale (NIIRS)

The NIIRS scale was introduced in 1974 and has had a long history of successful application in the evaluation of the informational potential of images[1]. The scale provides a full-reference rating provided by a trained image analyst and indicates the level of analysis task that can be performed with a particular image. NIIRS is a 10 level scale with ratings ranging from 0 (useless) to 9 with each level corresponds to a particular type of image analysis task. The criteria associated with each level have been adapted to provide different versions of the NIIRS scale for particular applications and sensing modalities.

Figure 1 below has some example overhead images with corresponding NIIRS. The image on the left has a NIIRS rating of 4 which allows identification of farm buildings as barns, silos or residences for example. The center image is a 5 NIIRS which allows identification of individual Christmas tree plantations. Finally, the image on the right is a NIIRS 8 which allows identification of grill detailing and/or license plates on a passenger vehicle or truck. An increase in a level of NIIRS corresponds roughly to a doubling of resolution. Application of the NIIRs metric to system evaluation is limited due to the need for formally trained imagery analysts.

Fig. 1. Sample overhead imagery and its corresponding NIIRS ratings illustrate the level of image analysis tasks that could be supported. Description of NIIRS level criteria are provided in the text above.

2.2 General Image Quality Equation (GIQE)

The NIIRS scale is very useful in describing the information utility of an image. However, it is not a practical tool for characterizing the performance of imaging systems given the need for trained imagery analysts. To overcome this, the GIQE[2] can be used to predict NIIRS values based on image system parameters. The original GIQE is given by,

$$NIIRS_{GIQE} = 11.81 + 3.32\log_{10}\left(\frac{RER_{GM}}{GSD_{GM}}\right) - 1.48 H_{GM} - \frac{G}{SNR} \quad , \qquad (1)$$

where RER_{GM} is the geometric mean of the relative edge response of the system, GSD_{GM} is the geometric mean of the ground-sample-distance, H_{GM} is the geometric mean of the edge response overshoot caused by MTF compensation, G is the gain of the MTFC kernel and SNR is the signal-to-noise ratio. The equation captures the key trade between sharpness and noise-amplification.

The coefficients for each of the terms in Eq. 1 above were obtained by regression to fit the results of an image evaluation study conducted with 10 trained imagery analysts[2]. A major limitation of the GIQE is that the range of validity of its predictions may not extend well beyond the span of system parameters considered for the underlying IA rating study and regression fit. New systems and imaging conditions require additional IA studies and statistical analysis. In its current form, the GIQE has limited applicability to the evaluation of SSA imagery.

2.3 **Engineering NIIRS Scale (ENS)**

A major limitation of the NIIRS scale to imaging system performance evaluation is the limited availability of trained imagery analysts. A viable alternative is to utilize an engineering NIIRS scale (ENS) to obtain NIIRS ratings for imagery without using trained analysts.

The images are evaluated by subjects using an image selection GUI such as the one shown in fig. 2. The subjects are asked to choose the reference image that most closely matches the image under evaluation on the basis of their ability to match or detect features. The center panel of the GUI flickers between the reference and test image to facilitate image evaluation. The pristine reference image and the test images are also provided in the left and right panel respectively. The set of reference images comprises a "NIIRS ruler" as shown in fig. 3. This NIIRS ruler consists of a set of images generated and calibrated to fixed Δ-NIIRS steps. Thus, each reference image translates directly to a NIIRS rating.

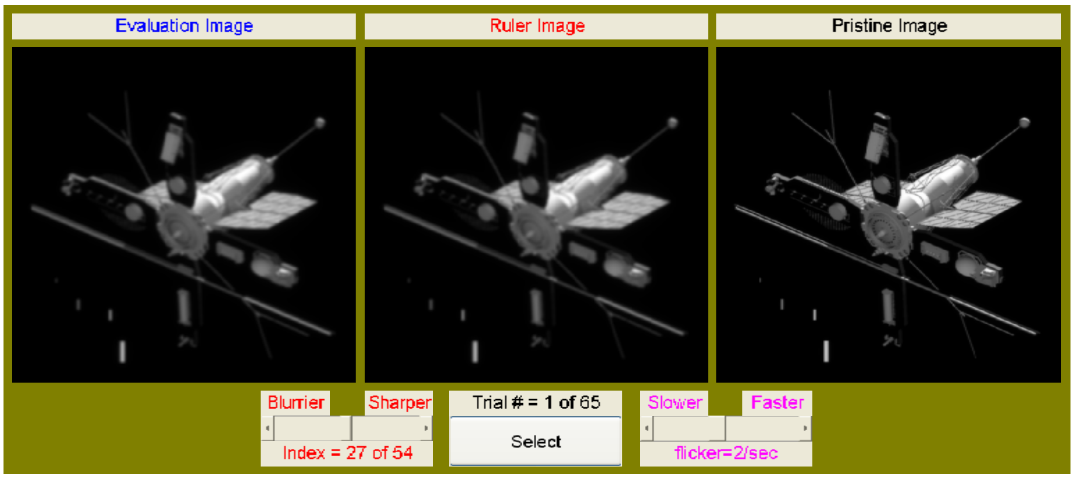


Fig. 2: Image selection GUI facilitates NIIRS assessment without the need for trained imagery analysts. The center panel flickers between the reference and test images.

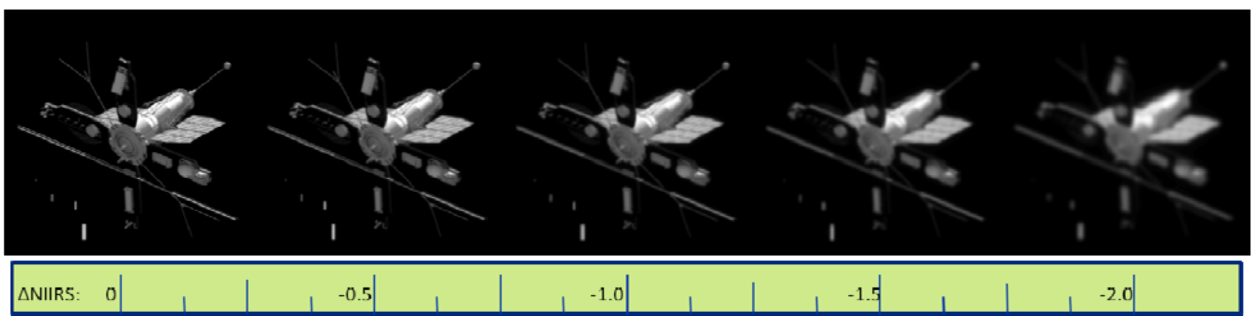


Fig. 3: Set of reference images for ENS arranged from left to right in decreasing level of NIIRS. These images together comprise a NIIRS ruler facilitating NIIRS assessment by non-trained image analysts.

3. Information Theoretic Image Quality Equation (ITIQUE)

3.1 ITIQUE Framework

Information based image quality metrics have been introduced in [3-5]. In [6] the concept of an Information Theoretic Image Quality Equation (ITIQUE) relating mutual information to NIIRS is introduced. The ITIQUE framework utilizes the Visual Information Fidelity (VIF) introduced in [3] to measure the perceptually relevant mutual information between a reference and pristine image. The framework is depicted graphically in fig. 4.

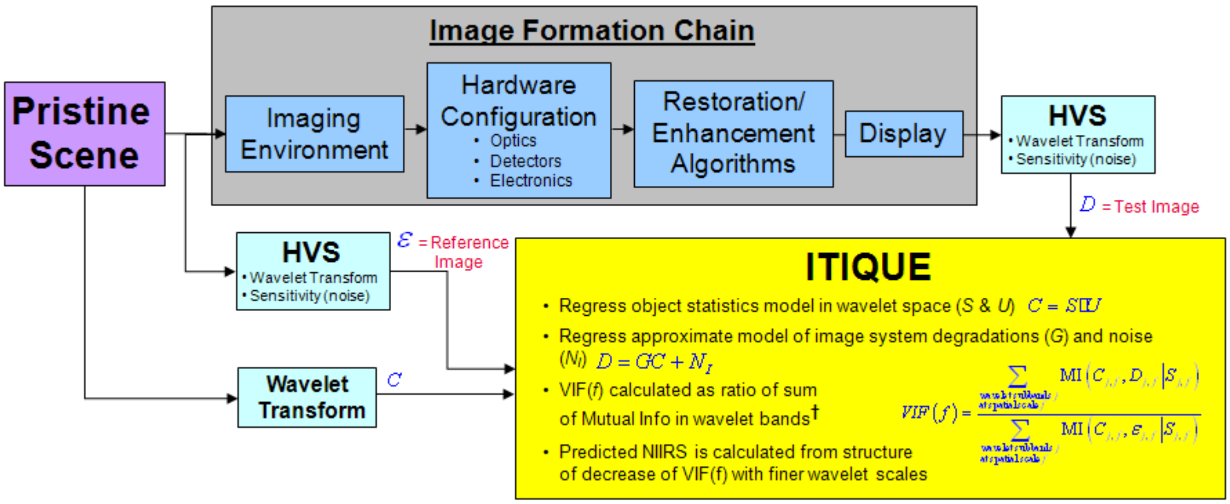


Fig. 4. ITIQUE framework uses VIF concept to measure perceptually relevant mutual information at several feature scale sizes and predict NIIRS

The reference image is the pristine input scene as seen through a model of the Human Visual System (HVS). The test image is the degraded image acquired by the imaging system, possibly post-processed by restoration or enhancement algorithms, as perceived by the HVS. The HVS model suppresses information contained in the image data that is unperceived or irrelevant from the HVS standpoint. The MI is calculated in the wavelet domain for both reference and test images.

At each wavelet sub-band, the VIF is calculated as the ratio of (a) the MI between pristine original object and perceived image after measurement and enhancement processing by the imaging system, to (b) the MI between pristine original object and perceived object as viewed *in situ*. The VIF is only influenced by object features relevant to perception by the HVS and allows for possible information gain resulting from image enhancement.

ITIQUE predicts NIIRS values by combining the VIF at multiple feature size scales according to

$$NIIRS_{ITIQUE} = C - \log_2\left(\frac{1}{\sum_f VIF(f)}\right), \qquad (2)$$

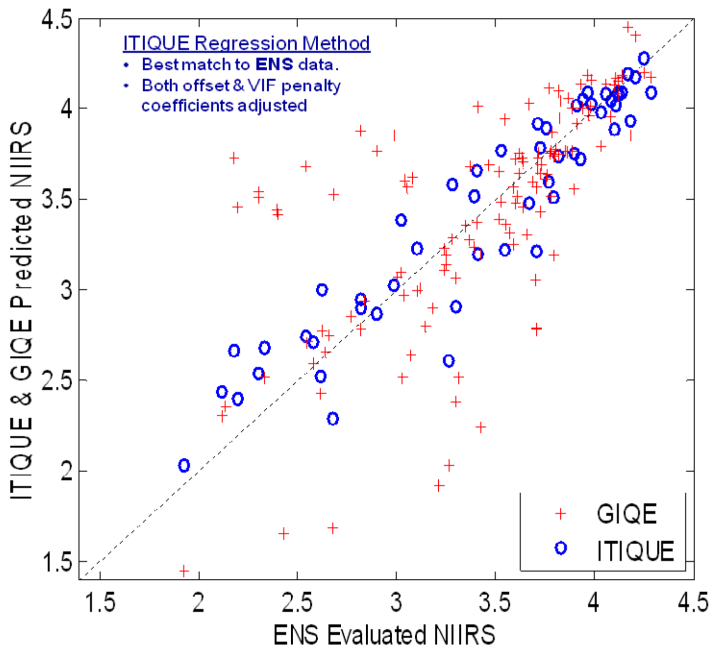
where C is a bias coefficient and the denominator inside the logarithm is the sum of the VIF computed at various relevant feature scale sizes. The value of the coefficient C in Eq. 2 can be obtained by regression against NIIRS ratings obtained by the ENS method described previously or a formal assessment using imagery analysts.

3.2 <u>ITIQUE Model Assessment</u>

An assessment of the ITIQUE framework for predicting NIIRS is presented in [6]. In that work, the authors obtained NIIRS ratings using an ENS methodology including 13 subjects and 160 images. The images were a subset of a larger dataset comprising a variety of terrain types and imaging conditions relevant for overhead imaging of terrestrial scenes. A sampling of the objects used to develop the data set is shown in fig. 5.

Fig. 5 Set of objects used to develop test and reference images for ITIQUE evaluation study

Fig. 6 below summarizes the results of the study. The ITIQUE predictions were calibrated, by adjusting the coefficient in Eq. 2, to obtain the best match the ENS ratings obtained from the panel of human observers. Fig. 6 shows the ITIQUE and GIQE results plotted against the ENS NIIRS ratings. The NIIRs predictions obtained with ITIQUE show higher correlation to the ENS study than the GIQE predictions. This is apparent visually and is confirmed by the numerical results included in the figure.



	Spearman	CorrCoeff	RMS	MAE
ENS - GIQE	0.764	0.679	0.468	0.302
ENS - ITIQUE	0.94	0.94	0.23	0.182

Larger Better (Spearman, CorrCoeff) — Smaller Better (RMS, MAE)

METRICS:
Spearman = Spearman rank order correlation
CorrCoeff = correlation coefficient
RMS = root mean square error
MAE = mean absolute error

Fig. 6. Summary of results for previous study that compares NIIRS predictions obtained using ITIQUE against GIQE. The ITIQUE predictions showed better correlation to the ENS NIIRS ratings.

4. Extension of ITIQUE Framework to SSA

The PROTEA effort funded by the Air Force Office of Scientific Research (AFOSR) is conducting a study to demonstrate the applicability of the ITIQUE framework to SSA image evaluation. The goal of the study is to demonstrate the viability of information based methods to predict image quality in an SSA environment and to develop a tool to relate SSA imaging system performance directly to end-user mission utility. The study will follow a similar approach to the study described in the previous section.

First, a large database of images spanning a range of degradations, targets and processing algorithms relevant to SSA has been generated at the MHPCC. The relevant system parameter values are shown in Table 1 below and sample images are shown in fig. 7. NIIRS ratings for each of these images will be obtained using an ENS technique described previously. The results of these NIIRS ratings will then be used to calibrate ITIQUE predictions.

Based on our previous study, we expect that the ITIQUE predictions will show strong correlation to the results of the NIIRS assessment. This will be the first validation of the information theoretic based approach to obtain a quality metric relevant to SSA applications. The resulting ITIQUE calibrated for SSA will provide a useful tool and methodology for evaluating the performance of ground based SSA imaging systems. This will be of particular use for investigation of new concepts and approached to image collection methods, conditions, system designs, and image restoration and enhancement algorithms and in architectural studies for assessing system utility.

Table 1: SSA imaging system parameters for ITIQUE validation

System Parameters	Range of Values
Object	{OKEAN, ARGOS, Orbital Express, XSS-10}
FPA Array Size (pixels)	512x512
Sampling Resolution (Q)	2
Aperture Diameter (meters)	{2, 1, 0.5, 0.25}
WFE (D/r_o)	{0, 2, 4, 6, 8}
Jitter (pixels)	{0, 0.5, 1, 2, 3}
SNR	{∞,100, 30, 10, 3, 1}
Processing	{None, shift-and-add, Wiener, MFD, MFBD}

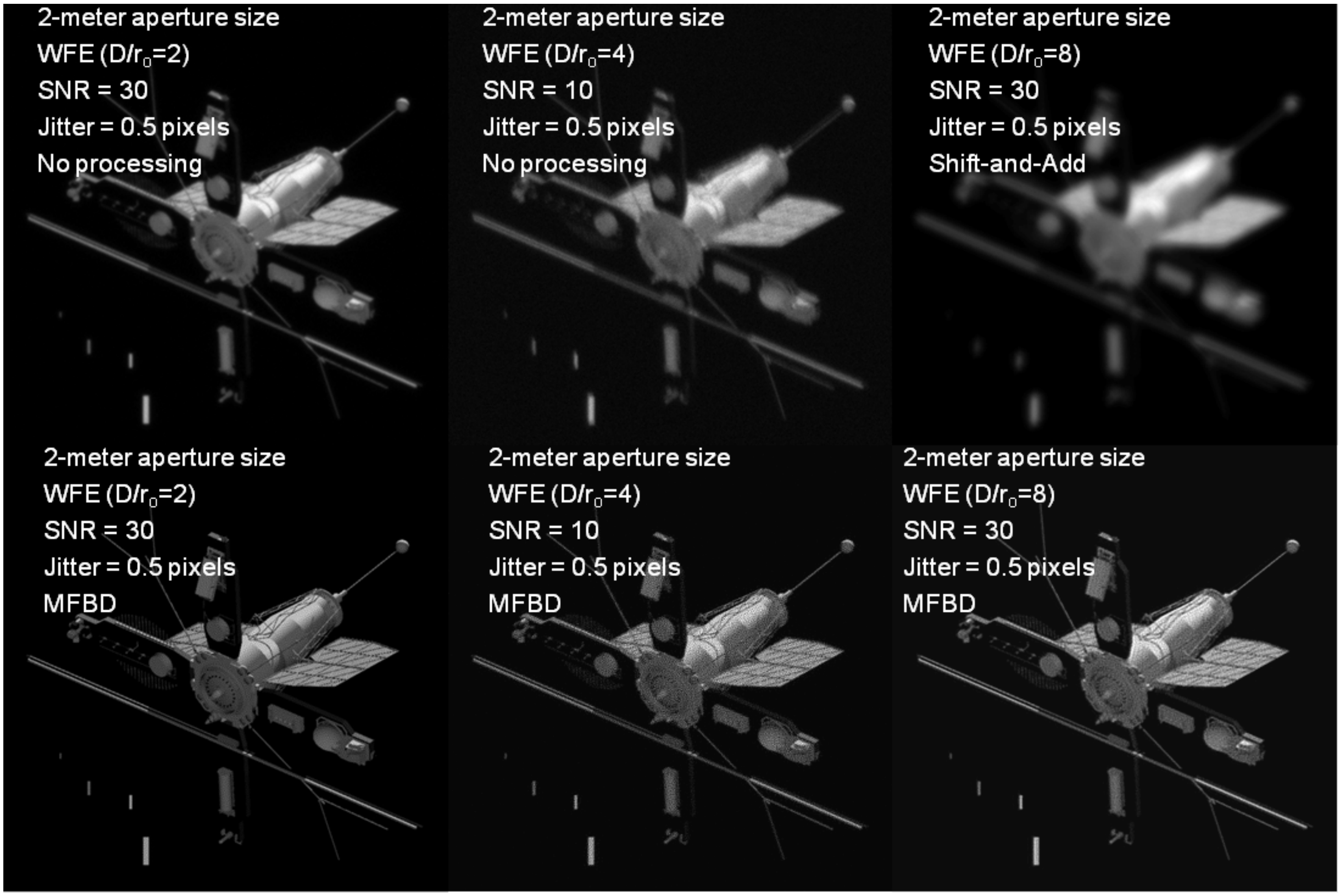


Fig. 7. Sample imagery generated in support of study to validate ITIQUE framework for SSA.

5. REFERENCES

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