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Image Chain Analysis for Space Imaging Systems

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Abstract. *Space imaging systems are designed to gather information from vantage points not accessible on Earth. Some systems are designed to look back at the Earth to help us understand our planet better while others are designed to explore the vast universe around us. The diversity of applications between the space imaging systems ensures a new set of engineering challenges with each camera design. The cameras integrated into each space system are designed to meet specific image requirements, but the measure of image quality may be very different depending on the application. For example, Earth-imaging satellites designed for monitoring weather phenomena require high radiometric fidelity whereas Earth-imaging satellites designed for monitoring world events require high spatial resolution for clear visual interpretability. Image chain analysis is used to understand the image formation properties of novel designs and to better understand design trades. Image chain analysis has become an important image science tool for assessing and optimizing image quality in space imaging programs. © 2007 Society for Imaging Science and Technology.*
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INTRODUCTION

In 1907 Alfred Maul patented a gyroscopically stabilized camera for rockets, thus opening the doors to an era of space imaging (Fig. 1). Unfortunately it would be more than 50 years before the first image was captured from space. Although the quality was poor, the first image of the Earth taken from space by Explorer VI on August 14, 1959 demonstrated the capability of imaging the Earth's cloud cover using a television camera in space (Fig. 2). On October 7, 1959 Luna 3 captured the first image ever taken of the far side of the moon (Fig. 3). Since 1959, great advances in technology have dramatically improved the capabilities of space imaging systems. Today, space imaging systems are routinely launched to image the Earth as well as the heavens. The Geostationary Operational Environmental Satellite systems monitor our weather while DigitalGlobe's QuickBird satellite acquires images at just 1/2 m resolution from an altitude of 450 km (Fig. 4). The Hubble Space Telescope orbits above the turbulent atmosphere to capture spectacular images of distant galaxies never seen before with ground-based telescopes (Fig. 5).

Before any space imaging system is built, the image formation process must be understood and system requirements defined to ensure that the proposed design, when built, will deliver the anticipated image quality. The system designs are complex and the cameras are generally not accessible once the system is launched so there is no room for error. Even after the system is launched, a complete understanding of the image formation process is essential in order to extract reliable and accurate information from the image data.

IMAGE CHAIN ANALYSIS

The image formation process of an imaging system can be broken down into fundamental links in the imaging chain.

Figure 1. Photograph from Alfred Maul's rocket.

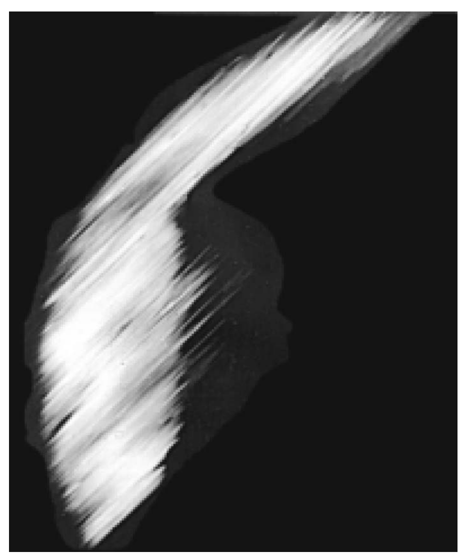

Figure 2. First image of the earth taken from space by Explorer VI on August 14, 1959.

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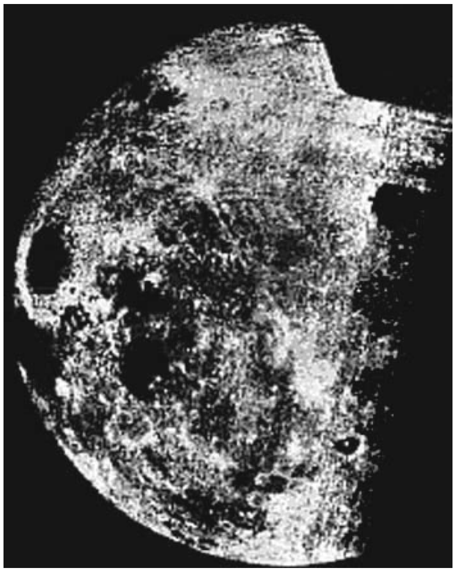

Figure 3. First image of the moon's far side, taken by Luna 3 on October 7, 1959.

Figure 4. Image of the Statue of Liberty taken from the QuickBird satellite in 2002. (Image courtesy DigitalGlobe.)

Each link in the imaging chain and the interaction between the links plays a vital role in the final quality of the image. The modeling and assessment of the end-to-end image formation process from the radiometry of the scene to the display of the image is called image chain analysis. Image chain analysis is necessary to understand and quantify the key factors that influence the quality of the final image product. Image chain analysis plays a critical role in relating the needs of the user community to the system design and the capabilities of the hardware.

The key components of the imaging chain are the radiometry, the image collection system (e.g., the camera), the processing of the image data, and the display of the data. The key components of the imaging chain for an Earth-looking space imaging system are illustrated in Fig. 6. The imaging chain begins with the source of the electromagnetic energy from the object being imaged. The electromagnetic

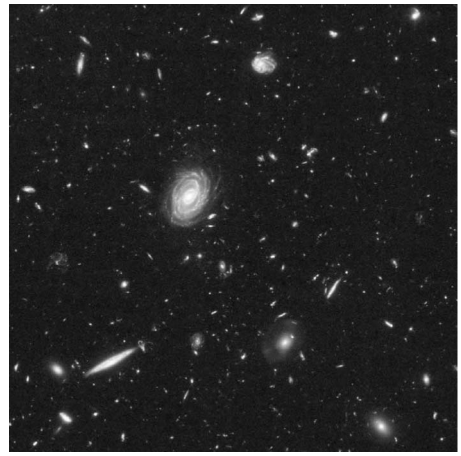

Figure 5. Image of galaxies in the constellation Fornax, taken by the Hubble Space Telescope. (Image courtesy NASA, ESA, S. Beckwith, and the HUDF Team.)

energy is captured by the image collection system, e.g., a camera with optics and an image sensor, which converts the captured electromagnetic radiation into an image data set, e.g., a digital image. This data set may require additional processing before an image is created and the image is usually processed further to enhance the interpretability and utility before being displayed or processed by algorithms to extract the desired information.

Image chain analysis plays a role through the entire development of a space imaging program (Fig. 7). During the initial concept phase, the image formation process is assessed to understand the feasibility of integrating innovative technologies into the design. An image utility evaluation is then conducted to quantify the potential image quality that system can deliver. As the system is defined, image quality trade studies are performed to understand the interactions between the various components and to define the hardware requirements. Image chain analysis helps to reduce overall risk by anticipating image quality issues before the hardware has been built and costly redesigns are necessary. After the system is launched, the image quality is measured and tracked to ensure that the system is delivering the anticipated image quality. In the unfortunate event that imaging anomalies occur in the image data, image chain analysis is used to identify the root cause and develop resolutions. As the system provides data to the user community, feedback from the users is essential to identify and prioritize improvements for the current and future systems.

IMAGE SIMULATION PROCESS

Although image chain analysis is applicable to any imaging system, the discussion here will focus on Earth-looking imaging systems and the simulation process used to assess the imaging chain. Mathematical models that describe the image formation process of the imaging chain are used to create a detailed image simulation process that produces very accurate representations of the image data from the proposed system design. For Earth-looking remote sensing systems, the image simulation process models include radiometry,

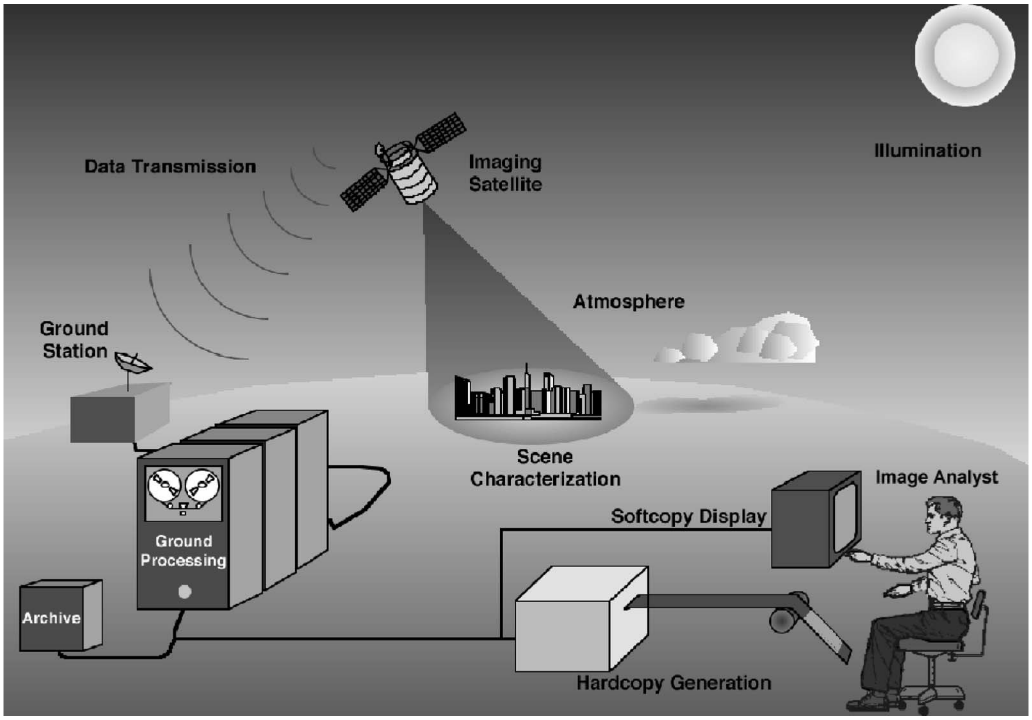

Figure 6. Imaging chain for an Earth-looking space imaging system.

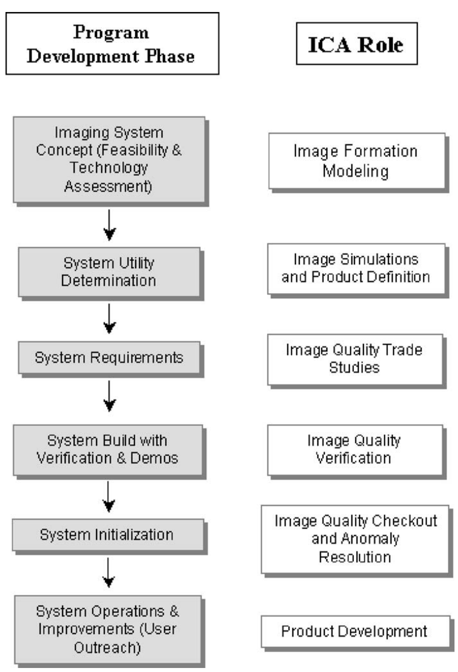

Figure 7. Image chain analysis plays a role through all phases of program development.

vehicle motion, optics, sensor, data compression and transmission, ground processing, and media characteristics (Fig. 8). The simulated effects of the image chain for a line-scanning overhead imaging system are illustrated in Fig. 9.

For a visible EO earth-looking imaging system, the image chain begins with the electromagnetic energy from a radiant source, i.e., the sun. The radiant flux within the spectral bandpass reaching the detector of the camera from the target is given by[1]

$$\Phi_{\text{detector}} = \frac{A_{\text{detector}}\pi(1-\varepsilon)}{4(f\#)^2}\int_{\lambda_{\min}}^{\lambda_{\max}} L_{\text{target}}(\lambda)\tau_{\text{optics}}(\lambda)d\lambda, \quad (1)$$

where A_{detector} is the area of the detector, ε is the fraction of the optical aperture area obscured, and $f\#$ is the system f number, L_{target} is the spectral radiance at the entrance aperture, τ_{optics} is the transmittance of the optics, and $\lambda_{\min}$ to $\lambda_{\max}$ defines the spectral bandpass. The radiometric calculations are dependent on the acquisition geometry and can be complicated; hence, radiometric models, such as MODTRAN, are generally used to calculate L_{target}.

The quality of the optics is critical to the final image quality and must be manufactured and built to very tight specifications. Light that is imaged by the optics will spread out and the point spread function (PSF) describes the spreading of the light for a point object. The optical transfer function (OTF) is the Fourier transform of the optics PSF and the magnitude of the OTF is the modulation transfer function (MTF) of the optics.[2,3] The optics MTF decreases as the spatial frequency increases, which has a blurring effect on the image. Other factors will also blur the image, e.g., vehicle motion, each with their own MTF. The actual optics MTF will be lower than the diffraction-limited optics MTF due to imperfections in the manufacturing of the optics. The optics MTF is multiplied with an optical quality MTF to achieve the actual MTF. Other MTF contributors, such as the jitter and smear caused by camera motion, can be cascaded with the optics MTF to yield a system MTF. The individual MTF curves for a notional design of a digital

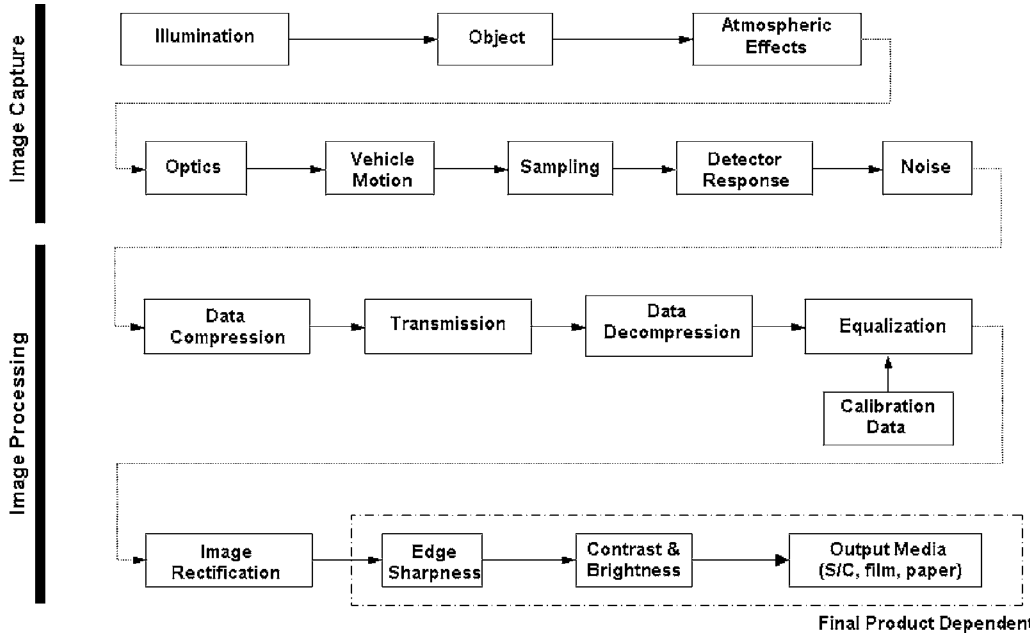

Figure 8. Image simulation process for an Earth-looking space imaging system models the image formation process.

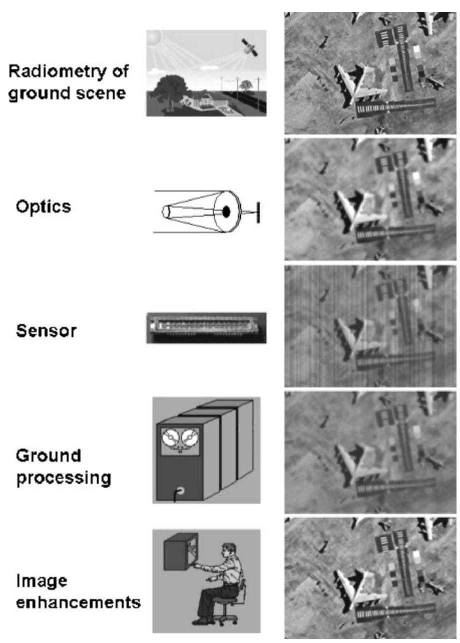

Figure 9. Series of images illustrating the effects of the imaging chain for an Earth-looking space imaging system design.

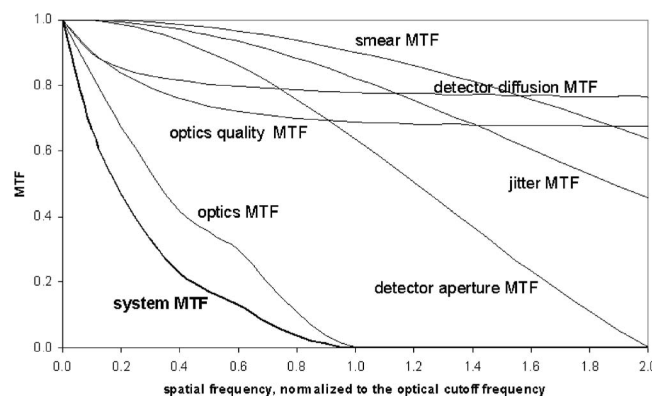

Figure 10. Individual MTF curves for a notional design and the final system MTF after the individual MTF curves have been multiplied together.

camera and the final system MTF are shown in Fig. 10. The optics MTF is usually the most significant component of the system MTF. Please note that it is necessary to use the system transfer function, not just the MTF, in the image chain models to ensure that all image quality effects, including optical aberrations, are captured.

Random noise in the signal arises from elements that add uncertainty to the signal level of the target and is quantified by the standard deviation of its statistical distribution. If the distribution of each of the different noise contributors follows a normal distribution, then the variance of the total noise is the sum of the variances of each noise contributor. For images with high signal, the primary noise contributor is the photon noise, which arises from the random fluctuations in the arrival rate of photons. The photon noise follows a Poisson distribution; therefore, the variance of the signal equals the expected signal level. Scattered radiance from the atmosphere, as well as any stray light within the camera, will produce a background signal with the target signal at the detector. When no light is incident onto the charge coupled device (CCD) detector, electrons may still be generated due to the dark noise. Finally, the analog-to-digital converter quantizes the signal when it is converted to digital counts. Combining all of these noise sources, the standard deviation for the noise can be modeled as[4]

$$\sigma_{\text{noise}} = \sqrt{s_{\text{target}} + s_{\text{background}} + \sigma^2_{\text{quantization}} + \sigma^2_{\text{dark}}}, \quad (2)$$

where s_{target} and $s_{\text{background}}$ are the average target and background signal in sensor electrons and $\sigma_{\text{quantization}}$ and σ_{dark} are the standard deviations of the quantization noise and dark noise in sensor electrons, respectively.

IMAGE QUALITY

Image quality is a broad term that encompasses many factors and has many measures. Image quality may have different meanings to different users, e.g., a user of hyperspectral data will require high spectral resolution, while a user of visible panchromatic imagery may require high spatial resolution. The utility of an image should not be equated with quality of the image. For example, geographic surveys can be performed better with overhead images that trade-off lower resolution for a larger area of coverage. The image quality is dependent on each element of the image chain. Assuming all elements of the image chain have been optimized to maximize the image quality, then the primary limitations on the image quality for most imaging systems will be the spatial resolution and the signal-to-noise ratio (SNR).

The highest spatial resolution, i.e., the resolving power, of an imaging system is the highest spatial frequency that can be resolved in the final image. Most digital Earth-looking space imaging systems use the ground sampled distance (GSD) as the measure for spatial resolution. The GSD, however, refers only to the detector sampling projected onto the ground and ignores any effects that the optical system may have on the spatial resolution. Even if the detector sampling is the limiting factor in spatial resolution, the interaction between the detector sampling and the performance of the optics plays an important role in determining the final image quality.[5]

The GSD is typically the only figure-of-merit used to communicate the image quality of an Earth-looking space imaging system. Image simulations of a scene captured at various GSD's and interpolated to the same eye scale are shown in Fig. 11. Clearly GSD is a dominant factor in image quality, but it is not the only factor to consider. Figure 12 shows image simulations for different systems all designed to capture images at the same GSD, but the simulations show clear image quality differences between the systems. If the image quality requirement was stated in GSD alone, then all of these systems would meet that same image quality requirement.

The National Imagery Interpretability Rating Scale (NIIRS) is a 0–9 scale developed by the U. S. Government's Imagery Resolution Assessment and Reporting Standards Committee to measure image quality in terms of image interpretability.[6] Separate NIIRS criteria have been developed for visible, infrared, radar, and multispectral sensor systems since the exploitation tasks for each sensor type can be very different. Although NIIRS is defined as an integer scale, ΔNIIRS (delta-NIIRS) ratings at fractional NIIRS are performed to measure small differences in image quality between two images. A ΔNIIRS that is less than 0.1 NIIRS is usually not perceptible and does not impact the interpretability of the image, whereas a ΔNIIRS above 0.2 NIIRS is easily perceptible.

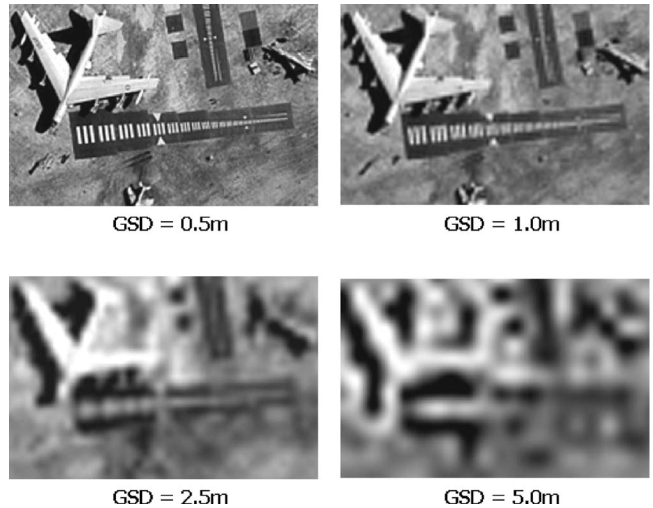

Figure 11. Image scaled to various GSD's.

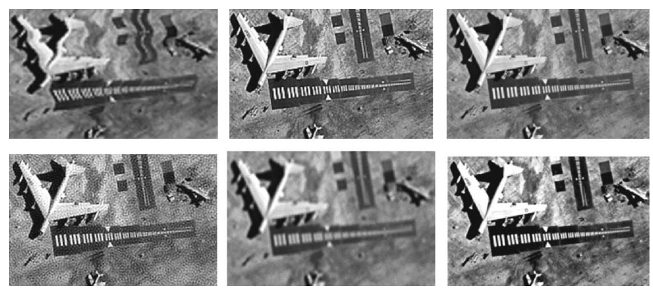

Figure 12. These images all have a GSD of 0.5 m, but have very different image quality.

The generalized image quality equation (GIQE) is a parameter-based model developed to predict the NIIRS rating of an image given an imaging system design and collection parameters. The GIQE (version 4) for visible EO systems is[7]

$$\text{NIIRS} = 10.251 - a\log_{10}\text{GSD}_{\text{GM}} + b\log_{10}\text{RER}_{\text{GM}} - 0.656H_{\text{GM}} - 0.344\frac{G}{\text{SNR}}, \quad (3)$$

where GSD_{GM} is the geometric mean GSD, RER_{GM} is the geometric mean of the normalized relative edge response (RER), H_{GM} is the geometric mean-height overshoot caused by the edge sharpening, G is the noise gain from the edge sharpening, and SNR is the signal-to-noise ratio. The coefficient a equals 3.32 and b equals 1.559, if $\text{RER}_{\text{GM}} \geqslant 0.9$; and a equals 3.16 and b equals 2.817 if $\text{RER}_{\text{GM}} < 0.9$.

The GIQE for visible EO systems is useful for general NIIRS predictions but is not accurate enough to predict small image quality differences between various designs. In general, psychophysical evaluations using high fidelity image simulations are required to discern image quality differences

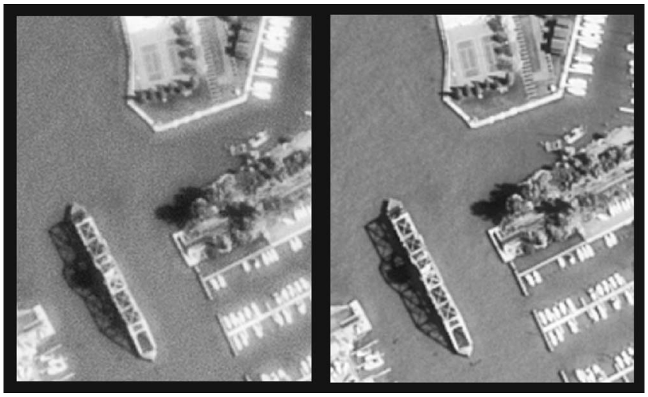

Figure 13. Two image simulations generated from very similar system designs, but with apparent differences in image quality.

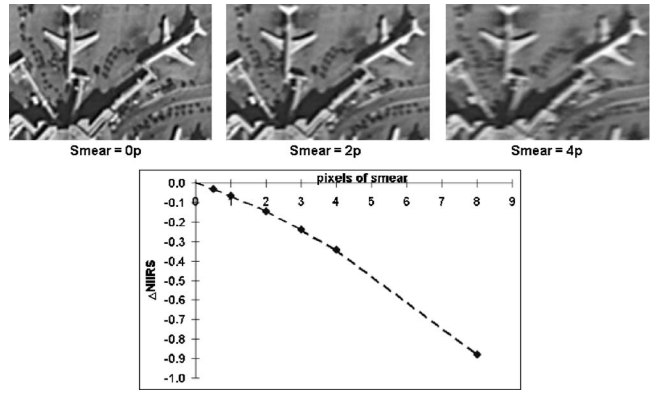

Figure 14. Image quality as a function of linear smear.

within 0.2 NIIRS. An image quality equation specific to a particular imaging system design can be modeled from the evaluation results capable of providing predictions within 0.2 NIIRS.

DESIGN TRADES

By applying image chain analysis early in the design process, design trades can be performed, hardware decisions can be made, and requirements established before the system is built. Analytically, it is very difficult to quantify the image quality in terms of the complex interactions between the various elements of the image chain without having the image data available to assess. As stated above, the GIQE is useful for general NIIRS predictions but is not accurate enough to predict small image quality differences between various design trades; therefore high fidelity image simulations are used to quantify the differences.

An example of two image simulations created from two very similar system designs is shown in Fig. 13. The systems were designed to have the same GSD, optical aperture, focal length, and dynamic range but had subtle differences in the detector design and the optical prescription. Although the system MTF and SNR calculated for the two systems are different, the actual difference in image quality could not be ascertained until high fidelity image simulations were created.

Image simulations are also useful to determine system requirements. For example, image simulations can be generated by varying one design element and then rated in a psychophysical evaluation to model the image quality change as a function of that design element. Figure 14 shows the results of an evaluation that parameterized the image quality loss in ΔNIIRS as a function of linear smear.[8] These results allow the design engineers to relate line of site control requirements to the image quality requirements.

The image simulations generated from the image chain model are also used to optimize and test processing algorithms before a system is operational. For example, operational data is needed to optimize the parameters of an onboard bandwidth compression algorithm before the compression hardware is integrated into the camera, but these data are not available until the system has already been launched and is operational. This conundrum can be resolved by accurately optimizing the parameters using accurate simulations of operational data. The ground processing chain is also optimized using the image simulations to assure that the processing center is ready to receive and process the data properly when the imaging system becomes operational. Image chain analysis will assess the interactions between different processing elements on the quality of the final image and determine the best order of the processing chain elements. The simulator also allows the performance of different algorithms to be tested and optimized within the processing chain.

SUMMARY

As the capabilities of future space imaging system improve with novel designs, so must the image chain models used to assess them. Recently much interest has been placed on sparse aperture imaging systems that allow greater resolutions without increasing the weight of the optics. These systems require the light from each individual aperture to be phased properly and combined into a single image. Complex image chain models have been developed in order to properly ascertain the system requirements necessary to produce the required imager quality. The image simulations in Fig. 15 demonstrate the need for longer integration times with low fill factor sparse aperture concepts in order to maintain an acceptable image quality.[9]

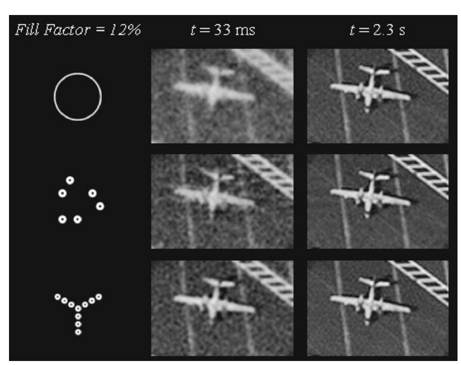

Figure 15. Sparse aperture image simulations, showing advantage of longer integration time, *t*.

Image chain analysis is necessary to understand the image quality of any digital camera design before it is built. High fidelity image simulators are developed by modeling the imaging chain to provide accurate images that represent the actual images that would be acquired if the system was actually built and operational. The image simulations are critical for understanding the image quality trades for space imaging systems. Design modifications during and after the hardware has been built will be very costly and very unlikely after the system is launched and operational.

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