Image Chain Analysis for Space Systems

Robert D. Fiete; ITT's Space Systems Division; Rochester, NY

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 on each 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, or ICA, has become an important image science tool for assessing and optimizing image quality in space imaging programs. Image chain analysis is used to understand the image formation properties of novel designs and to better understand design trades.

Introduction

In 1907 Alfred Maul patented a gyroscopically stabilized camera for rockets, thus opening the doors to an era of space imaging (Figure 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 (Figure 2). On October 7, 1959 Luna 3 captured the first image ever taken of the far side of the moon (Figure 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 GOES (Geostationary Operational Environmental Satellite) systems monitor our weather while DigitalGlobe's QuickBird satellite acquires images at just over one-half meter resolution from an altitude of 450 km (Figure 4). The Hubble Space Telescope orbits above the turbulent atmosphere to capture spectacular images of distant galaxies never seen before with ground-based telescopes (Figure 5).

Before any space imaging system is built, the image formation process must be understood to ensure that the proposed design can deliver the anticipated image quality. 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. The modeling and assessment of the end-to-end image formation process is called image chain analysis.

***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.*

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)*

Image Chain Analysis (ICA)

The image formation process of an imaging system can be broken down into fundamental links in the imaging chain. Each link and the interaction between the links plays a vital role in the final quality of the image. Image chain analysis assesses the entire imaging chain to understand and quantify the key factors that influence the quality of the final image product. Image chain analysis is necessary for defining system requirements and performing system trade studies during the concept development and design phase. When a system is operational, image chain analysis helps to further enhance the utility of the system as well as resolve any anomalies that may occur.

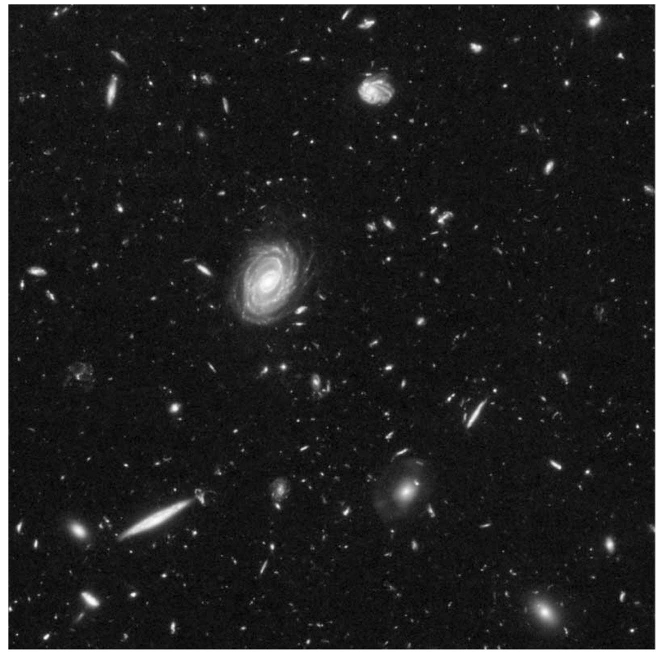

Figure 5. *Image of galaxies in the constellation Fornax, taken by the Hubble Space Telescope. (Image courtesy NASA, ESA, S. Beckwith and the HUDF Team.)*

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 image chain begins with the electromagnetic energy from the object being imaged. Imaging systems are generally categorized by the wavelength region of the electromagnetic spectrum that they record. The image collection system is typically a camera with optics and an image sensor that 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.

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, vehicle motion, optics, sensor, data compression and transmission, ground processing, and media characteristics (Figure 6). Figure 7 illustrates the simulated effects of the image chain for a line-scanning overhead imaging system as a ground scene is imaged and processed.

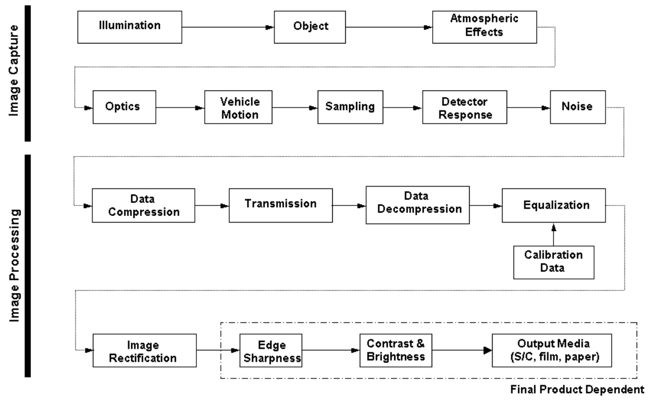

Figure 6*. Example image simulation process for an earth-looking space imaging system.*

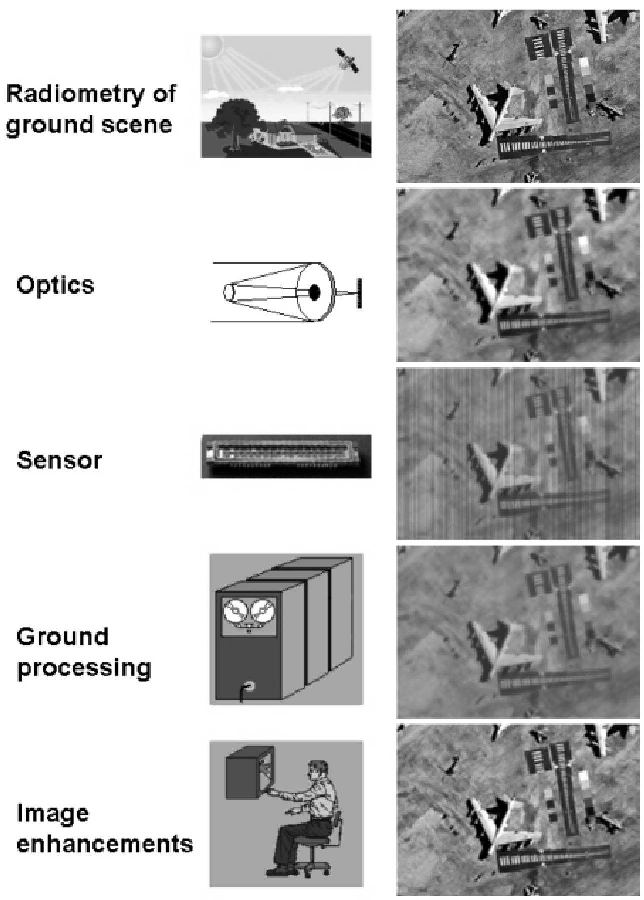

Figure 7*. Series of images illustrating the effects of the imaging chain for an earth-looking space imaging system design.*

Design Trades

Analytically it is very difficult to quantify the interactions between the various elements of the image chain without having the image data available to assess. The image simulations allow psychophysical evaluations or information extraction algorithms to be used to quantify the image quality difference between various design options.

By applying image chain analysis early in the design process, design trades can be performed and hardware decisions can be made and requirements established before the system is built. Figure 8 shows an example of two image simulations created from two very similar system designs. The systems were designed to have the same GSD (ground sampled distance), optical aperture, focal length, and dynamic range but had minor 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.

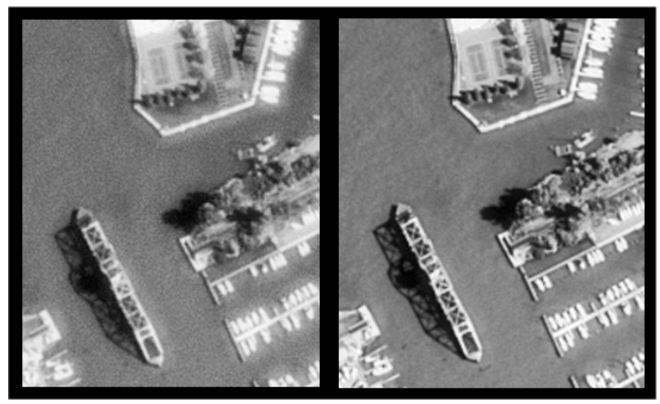

Figure 8*. Two image simulations generated from very similar system designs, but with apparent differences in image quality.*

Processing Optimization

The image simulator allows image processing algorithms to be optimized and tested before a system is operational. For example, operational data is needed to optimize the parameters of an on-board bandwidth compression algorithm before the compression hardware is integrated into the camera, but this data is not available until the system has already been launched and is operational. This catch-22 situation can be resolved by accurately optimizing the parameters using accurate simulations of operational data.

The ground processing chain can be 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.

Future Systems

As the capabilities of future space imaging system designs improve, so must the image chain models used to assess the designs. For example, higher fidelity mathematical models for optical properties, such as polarization and partial coherence, are required. Recently much interest has been placed on sparse aperture imaging systems that allow greater resolutions without increasing the weight of the optics. 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 Figure 9 demonstrate the need for longer integration times with low fill factor sparse aperture concepts in order to maintain an acceptable image quality [1].

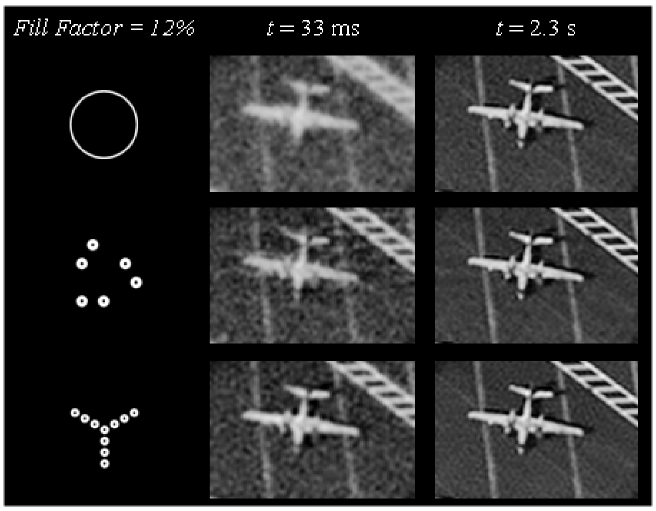

Figure 9. *Sparse aperture image simulations.*

References

[1] R. D. Fiete, T. Tantalo, J. Calus, J. A. Mooney, "Image quality of sparse-aperture designs for remote sensing," Opt. Eng., vol. 41, pp. 1957-1969 (2002).

Author Biography

Robert Fiete received his B.S. in Physics and Math from Iowa State University (1983) and his Ph.D. from the Optical Sciences Center at the University of Arizona (1987). He joined the Remote Sensing Systems operation at Eastman Kodak in 1987 where he developed image analysis algorithms and managed the Imaging Systems Technology group. In 2004 ITT acquired the Kodak's Remote Sensing Systems operation and Robert is currently the Chief Technologist at ITT's Space Systems Division. He is a member of SPIE and OSA.