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Manned Observations Technology Development FY '92 Report

Space and Life Sciences Directorate
Solar System Exploration Division
Flight Science Branch

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1.0 Introduction

The activities performed under this project were coordinated with NASA/JSC/JL (Image Sciences Division), which performs film and video processing at the JSC, and NASA/JSC/SP (Flight Crew Support Division), which developed the current ESC in cooperation with the U. S. Navy.

1.1 Background

Space Station Freedom (SSF) could provide an excellent shirt-sleeve, orbiting laboratory for developing the technology to image environmental features and processes. Technology tested in orbit then can be incorporated into future unmanned spacecraft systems to aid monitoring of oil fires, oil spills, forest fires, forest conversion, crop and rangeland changes, flooding, and structure of severe storms. Information gained by human observers about such features and processes can be incorporated immediately into NASA's Earth Observing System as a part of Mission to Planet Earth.

A promising new technology is the rapidly growing field of digital imaging, including electronic still cameras, which have several advantages compared to the storage of image data on film: Electronic images can be viewed immediately onboard the spacecraft, and on the ground as soon as they can be transmitted; no chemical processing is required. Film storage on SSF will require storage space for the mass and volume, film return necessarily must await crew exchanges, and processing is a carefully controlled chemical procedure.

Electronic imaging takes advantage of SSF images through immediate downlink via broadband transmission and reception scheduled as part Freedom's hardware. Many Earth science applications require high spatial resolution, multispectral data of dynamic events that cover large areas. Multispectral scanners, such as those used by Landsat and SPOT, fill only part of this need. It is unlikely that electronic still cameras will replace film during the next two decades for crew-directed images that require high-density data representing broad scenes.

This project evaluated the suitability of the NASA/JSC-developed electronic still camera (ESC) digital image data for Earth observations from the Space Shuttle, as a first step to aid planning for SSF. Specifically, image resolution achieved from the Space Shuttle, using the current ESC system, which is configured Loral 15mm x 15mm (1024 x1024 pixel array) CCD chip on the focal plane of a Nikon F4 was compared to that of current hand-held 70mm Hasselblad 500 EL/M film cameras.

1.2 Objectives

1.) Evaluate ESC digital data using Space Shuttle as a test bed for Space Station Freedom.

2.) Determine the relative information content (using achieved resolution as a metric) of the ESC versus current Space Shuttle film cameras.

3.) Determine if a digital photographic system will have sufficient information content for operational use in studying dynamic events from Space Station Freedom.

4.) Where possible, make projections as to the effects of expected future upgrades of the electronic imaging systems.

2.0 Methods

2.1 Experimental Design

The experimental data were acquired by Shuttle crew members during STS-48 (September 1991) and STS-45 (March 1992).[1] Simultaneous photographs were taken using a 70mm Hasselblad camera and the ESC developed by the Flight Crew Support Division, Flight Systems Branch, Flight Equipment Research and Development Section (SP43) at the Johnson Space Center (JSC). Image analysis of ESC and film camera imagery was performed to determine resolutions. The analysis was performed using PCI and Adobe Photoshop software on a Stardent workstation and a Macintosh IIfx. The same measures of goodness were performed for both the photographic and digital image pairs. The measures of goodness include relative spatial, spectral and radiometric resolution of the imaging systems. These measures are standard procedures for determining the relative merits of imaging systems (Colwell, 1983).[2]

A supporting experiment also was performed over Galveston Bay. Duplicate camera systems were onboard a helicopter and the Space Shuttle during an orbital pass over Houston to evaluate the two imaging systems using large-scale imagery. The U.S. Coast Guard Air Station Ellington Field and the Maritime Engineering Department, Texas A&M University at Galveston cooperated in logistical support as part of their regular training programs. Unfortunately, the weather conditions (a low, thick, cloud deck) during this flight were unfavorable. Furthermore, there were few differences in reflectance of the water between highly sedimented fresh water and fairly unsedimented salt water, because of a large sediment loading of the Bay water by the Trinity River during a flood event. Therefore, no significant results or conclusions could be made from this experiment. The airborne experiment is documented in Appendix B.

2.2 Data Acquisition Techniques

The goal of the Space Shuttle experiment was to acquire simultaneous image pairs from the Hasselblad and the ESC cameras. The acquisition was performed one of two ways: either two astronauts would photograph a site simultaneously, one with the Hasselblad and the other with the ESC, or a single astronaut would photograph the same site, having both cameras available for rapid tradeoff. The selected areas of interest were photographed near nadir, because the apparent difference in the Earth's surface reflectance is negligible over a few seconds of Shuttle flight when

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[1] The ESC will fly on future missions, and the system has been upgraded by increasing the effective ASA significantly, but the figures quoted here are based upon the system parameters at the time of STS-45.

[2] The bibliography contains references both cited and not cited so that an interested reader can gain further insight into the procedures used to characterize these systems.

sun elevation is high. Several hundred photographic and digital image pairs were acquired during STS-48 and STS-45 over a wide variety of terrestrial features.[3]

2.3 Acquisition Systems[4]

2.3.1 Electronic Still Camera (ESC)

2.3.1.1 Hardware Specifications

The configuration of the ESC developed at JSC and employed for this experiment uses a Nikon F4 body. The 300mm f2.8 lens resolves approximately 62 line pairs per millimeter. The camera is fully digital with 8 bit accuracy. The imaging system has a dynamic range of 60 dB and the sensor CCD has a dynamic range of 80 dB.[5] The sensor is a Loral CCD 1024x1024 pixel array with an active area of 15mm x 15mm which calculates to an idealize system resolution of 34 line pairs per millimeter. This calculates to 2.9 degree angular field-of-view. This CCD has a good modulation transfer function (MTF) (Dereniak and Crowe, 1984) because of a relatively large pixel size. The CCD array is capable of responding to wide or narrow spectral range between 400 and 1,100 nanometers; Shuttle in-cabin photography is limited to the 400 to 800 nanometer range by protective coatings on the windows (Figure 1). The current configuration for the ESC has a principal response in the red band.[6] The acquisition chip can be replaced on the ground before flight to take advantage of expected target and lighting parameters, without requiring a redesign of the camera.

The CCD array was set up to operate similarly to a photographic camera equipped with ASA-200 film (same apertures and shutter speeds). The array's effective response optimizes contrast, anti-blooming, and signal-to-noise ratio. Future versions of the ESC will operate at significantly higher ASA numbers to compensate for low-light-level conditions. Digital images are stored on removable hard drives. The current capacity is 40 images per hard disk; future capacity will be 100 images on a physically smaller hard drive. No hard disk storage errors have been observed with the ESC in this configuration; however, two analog-to-digital conversion errors have occurred. Missing pixels (areas which pixel values are incorrectly set to zero) have been observed on consecutive imagery.

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3 A catalog that lists all photographs catalog is in production as of 15 Novermber 92 and is prepared by Lockheed Engineering and Sciences Company, for the Flight Sciences Branch of the Solar System Exploration Division at NASA/JSC. The catalog contains ancillary information about each 70 mm frame taken from space, including geodetic position and geographic name of the major feature within the scene. The ESC images were then correlated to the 70 mm photographs by time and visual inspection.

4 The physical characteristics of other cameras suitable for Earth Observations which are manifested on typical Space Shuttle missions, are described in Appendix A.

5 The actual quantum efficiency of standard CCDs is about 80 to 90 percent; the quantum efficiency of film is less than 5 percent.

6 It is unknown whether the CCD detector on the ESC has an inherent polarization.

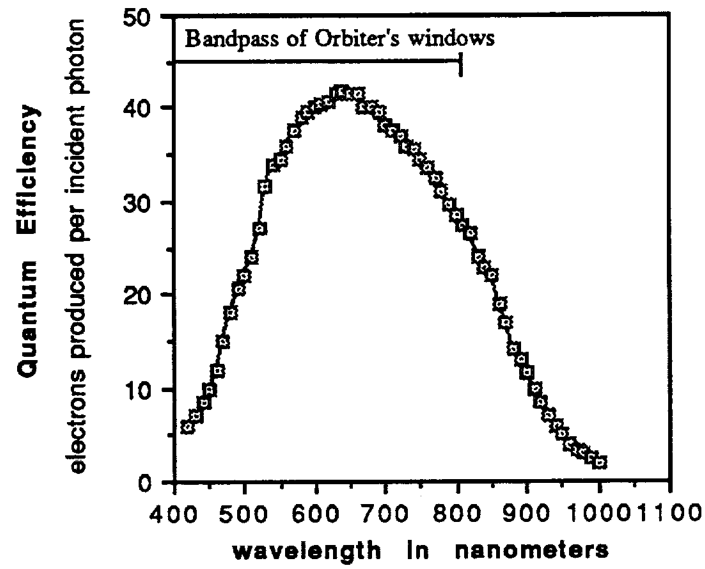


Figure 1: Response Curve for ESC camera

2.3.1.2 Current ESC Transmission Capability

Current image transmissions to the ground use the Orbiter's Ku band antenna system. Date (Greenwich Mean Time [GMT] to the nearest 2 seconds) is recorded with each image at acquisition. Ku Band Channel 2 of the Orbiter transmits at approximately 1.908 Mbits/second. Ku Band Channel 3 nominally transmits at 48 Mbits/second; the actual transmission of an image through the system is approximately 10 Mbits/second. Future capability will include S band transmission at 5 Mbits/second, but current ground stations can only receive at 120 Kbits/second.

2.3.1.3 Current Power Requirements

The system currently runs from a battery, but can be operated from the Orbiter's power supply. In the idle mode, it operates at 5 watts. During acquisition, it operates at 14 watts for approximately 14 seconds. The goal is to reduce the time for maximum power consumption to 1 second.

2.3.1.4 Operation

The ESC can operate in 4 modes, which are programmable and can be set prior to launch. Future ESC systems will enable the photographer to tune the imaging system to take advantage of specific user requirements. The current modes of operation are:

Take a picture - Store image
Take a picture - Store and downlink image
Downlink all images stored on disk.
Self timer mode

2.3.2 70mm Film Camera (Hasselblad 500 EL/M)

The 70mm Hasselblad, as well as the Nikon F4, is a single lens reflex (SLR) camera. The camera bodies flown aboard the Space Shuttle have been modified to accept a data module and film magazine containing about 100 exposures (Amsbury and Bremer, 1989). The majority of Earth observation photographs are taken with the Hasselblad camera. The 250mm lens has a resolving power of 57 line pairs per millimeter, and a 12.6° field-of-view (FOV) or approximately 4.3 times larger than the ESC's FOV with the 300mm lens. All camera power is self contained; batteries operate film advance and ancillary data encoding. Unlike current digital camera technology, film cameras are capable of acquiring visible and infrared photography without any hardware modification (Figures 2, 3). The ESC camera's spectral bandwidth is modified in the laboratory preflight and is not as adaptable inflight as film cameras.[7]

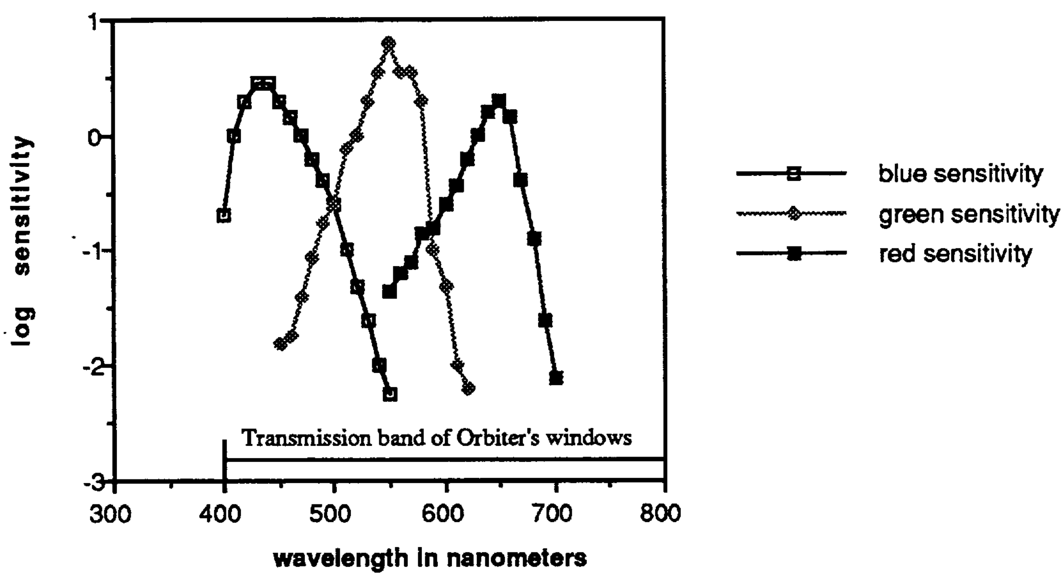


Figure 2: Response Curve for Ektachrome ASA-64 Film

[7] Typically, color visible and color infrared film are manifested for Space Flight. To acquire color infrared film, the photographer needs only to change the film in the camera and add a blue blocking filter. The blue blocking filter keeps the infrared sensitive film from exposure by light having wavelengths shorter than about 480 nannometers.

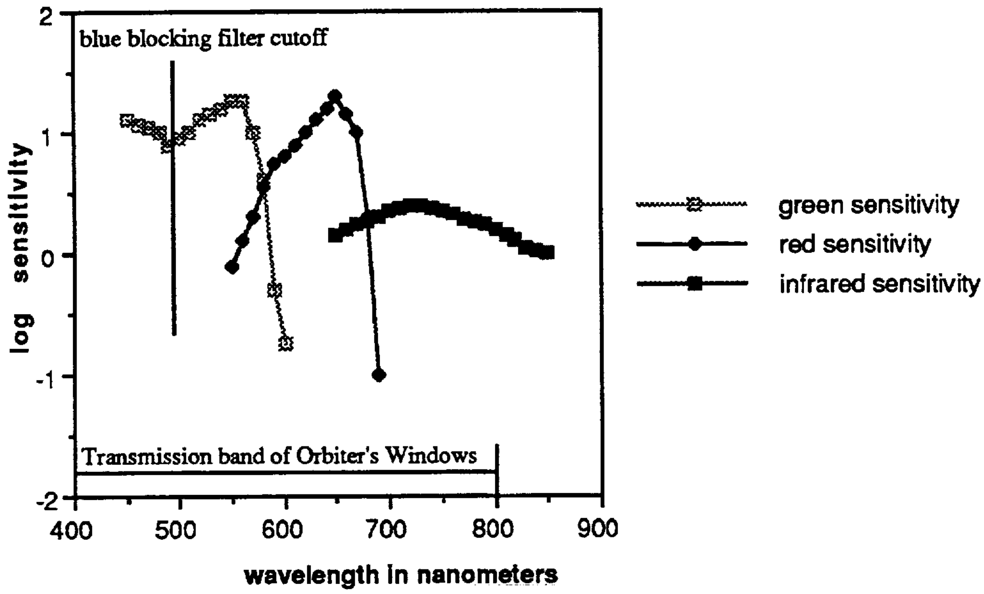
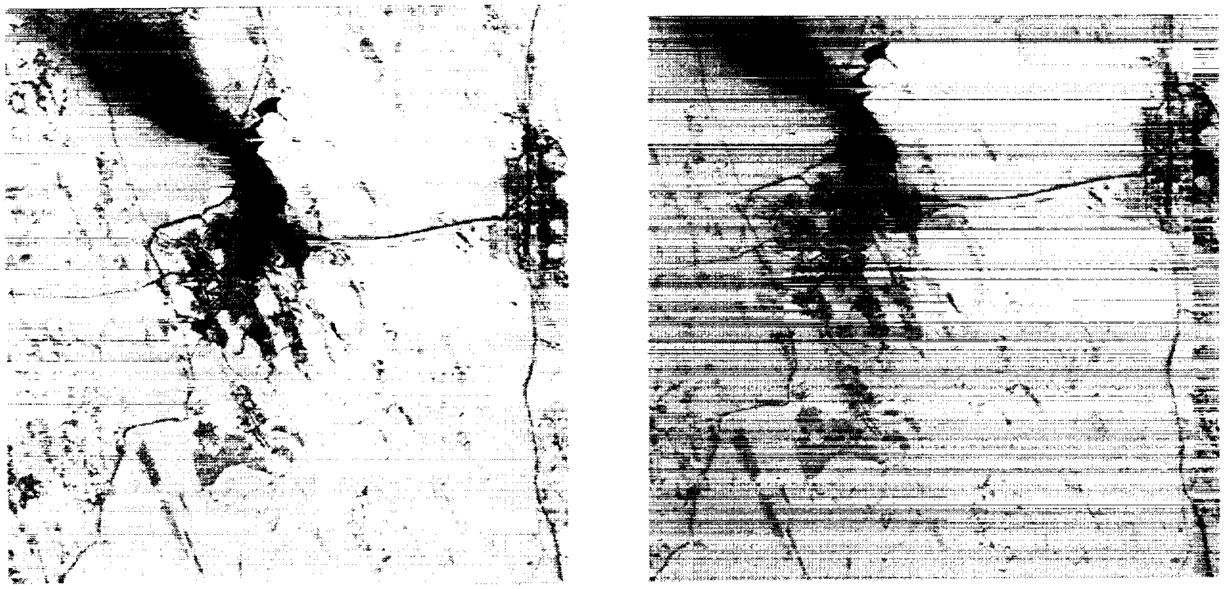


Figure 3: Response Curve for Infrared Film (Ektachrome 2443)

2.4 Study Sites

Two pairs of images were chosen for analysis. The images contain areas having high and low spatial frequency as well as a wide range of reflectance values. The first pair was acquired of Guerrero Negro on the Baja Peninsula of Mexico, and the other was taken over Keubyshev and Barabinsk in central Siberia. The Guerrero Negro scene was chosen because of the wide radiometric dynamic range and variety of targets. The coastal area would show how well the two camera systems would distinguish targets containing low-contrast edges. The Keubyshev scene was chosen to look at spatial frequency. The dark linear features and the bright snow background (large dynamic range) idealize a sensor's ability to resolve targets. The film for the Baja scene was Ektachrome 2443 color infrared (CIR) and the film for the Siberian scene was Ektachrome 64.[8]

[8] Throughout the rest of this paper, the pair of images taken over Guerrero Negro will be call the Baja Scene and the images taken over Kuybyshev will be called the Siberian Scene.



ESC Image - S45-ESC03022 *Digitized 70mm Image - S45-93-037*

Figure 4 Keubyshev. Siberia. The ESC image (4a) contains 1024x1024 and the digitized 70mm image section (4b) contains 2048x2048 pixels.

The optimum spatial resolution was calculated for the Hasselblad photographs at Space Shuttle altitude. The photographs were then digitized to appropriate pixel size. Both digitized 70mm images were sectioned or cropped to approximately the same ground-surface area as the ESC; the following analyses thus, are based upon near-identical areas. Because the current ESC uses a panchromatic sensor (black-and-white), the film response characteristics were analyzed monochromatically (for one band) in the spectral band that most closely matches the ESC. This limitation on the analysis ensures that the sensors were analyzed on an equal basis. Photographic film contains a greater radiometric resolution than the ESC and was quantized to 256 gray levels in only one spectral band for this analysis. Film is continuous in radiometry and maintains three independent spectral bands.

2.5 Analysis Equipment

The two image processing laboratories for this experiment are located at JSC in the Flight Science Branch (FSB) of the Solar System Exploration Division. The laboratories are the Environment Remote Sensing Analysis Facility (ERSAF) (Chambers, *et al.*, 1992) and Video Digital Analysis System (VDAS) (Dailey, *et al.*, 1992). These two laboratories contain two image processing workstations: a UNIX-software-based system that supports PCI image processing software, and a hardware-based Digital Equipment Corporation Virtual Memory System (DEC VMS) system that supports Library of Image Processing Software (LIPS). The two image-processing workstations are part of a local area network (LAN) connected by an Ethernet. The Ethernet also supports a large variety of personal computers and a Micro VAX computer that contains a database of all the manned Earth observation photographs from space. The database includes a sample of ESC and digitized photographs including the ESC images used in this experiment. The advantage of the Ethernet is that image data, which are fairly large data files,[9] can be easily transmitted between processing machines. The combination of the Ethernet and the image processing workstations provide an excellent facility for conducting image-analysis experiments.

NASA currently provides support to several investigators to exploit the information content of the Space Shuttle photography for Earth resources investigations (Duggin, M.J. et. al., 1989; Egan, W.G., et. al., 1992). Scientists supporting the ERSAF laboratory have provided real-time support to: IMAX, NOAA, Hercules, USDA, Smithsonian, Mesoscale Lightning Experiment, DoD, and the Space Radar Laboratory, as well as supporting other NASA projects over the long term.

2.6 Data Analysis Techniques

Information content was defined in terms of spatial, spectral and radiometric resolution. The comparison of electronic images to standard photographs was both quantitative and qualitative.

5a. ESC Image - S45-ESC02024

5b. digitized 70mm Image - S45-99-069

Picture 5 Guerrero Negro (Baja), Mexico. The ESC image contains 1024x1024 pixels and the digitized 70mm image section contains 2048x2048 pixels.

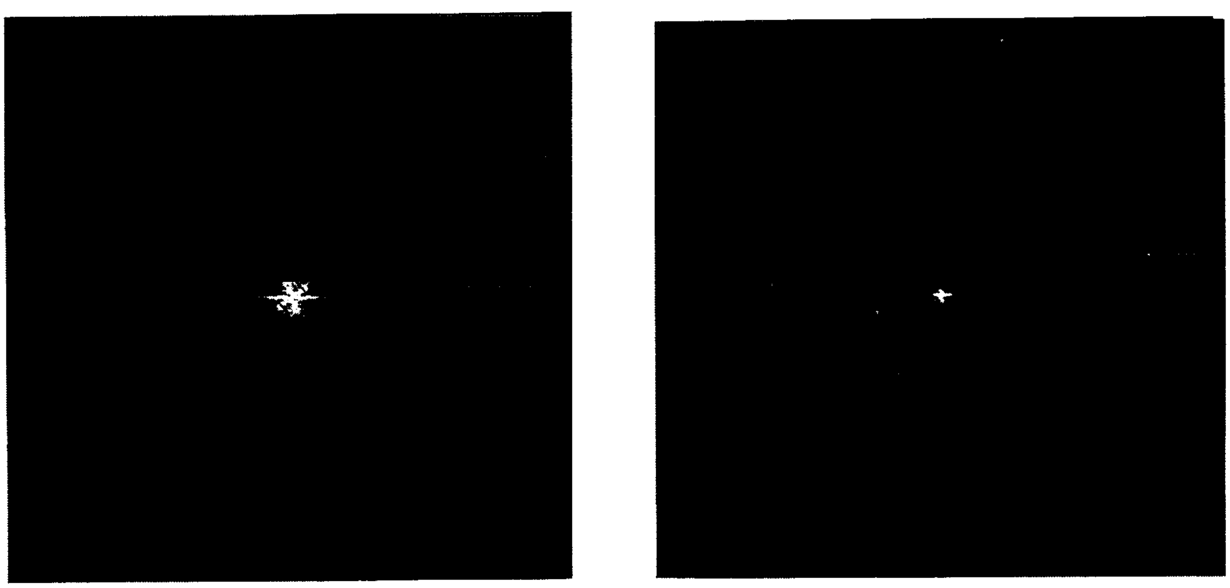
[9] The digitized Hasselblad images are approximately 23 Mbytes.

2.6.1 Digital Image Evaluation Techniques

The analog (film) photographs were digitized to the limits of resolution using a flat-bed scanner. The digitization was performed by the Dallas Photo Laboratory, Dallas, Texas, using a Kodak Premiere hardware/software system. The autofocus scanner minimized the error in the analog-to-digital conversion.[10] The ESC data are contained in a digital file consisting of 1024x1024 pixels. The digitized film products are approximately 4,000 pixels on a side. Once the two image products were in the same format, identical digital image processing techniques were performed, applied to both images covering near-identical geographic areas. The digitized red band was used for the film and the panchromatic signal for the ESC.

2.6:1.1 Frequency Analysis for Information Content

Spatial frequency (Fourier) analysis is a mathematical technique that defines information content as the system's ability to recognize edges within an image. High-frequency components generate sharp edges in an image, whereas lower-frequency components describe the general image characteristics. Information content in Fourier space is generally interpreted as the ability to discriminate linear features within a scene. To properly conduct a direct comparison of the ESC and Hasselblad images, certain parameters need to be identified: modulation transfer functions (MTFs) of lenses and systems, and film characteristics.



6a. ESC Image *6b. digitized 70mm Image*

Figure 6 Spatial Frequency (Fourier) magnitude image of the ESC image of the Siberian Scene. The area of interest contained high spatial frequencies (many regularly spaced linear features).

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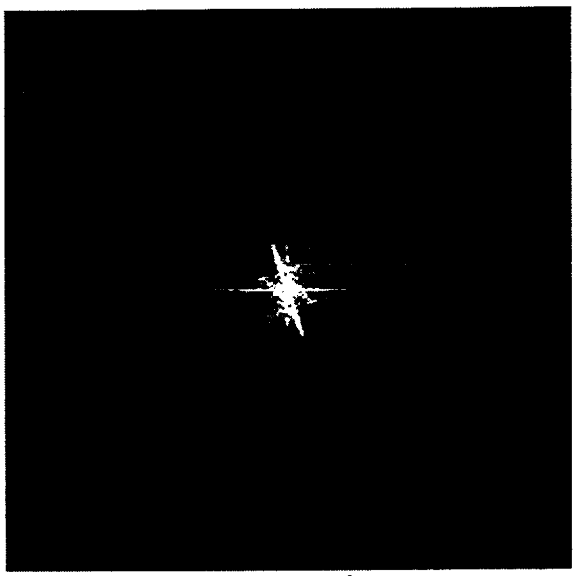
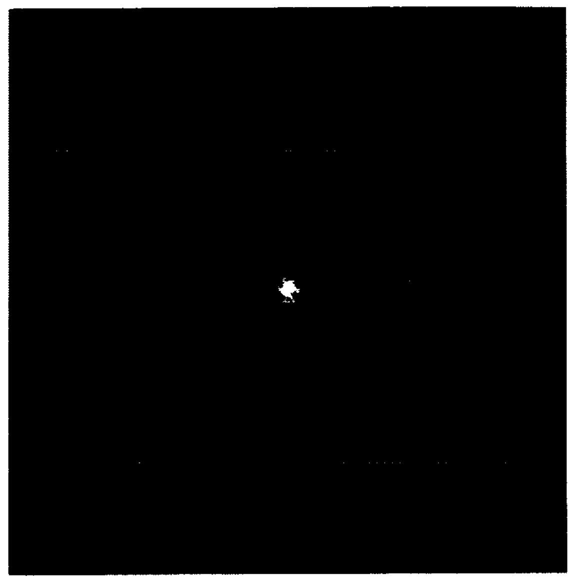
[10] A slight reduction of resolution is expected in the analog to digital conversion of a photograph, but the amount of degradation is expected to be small with this conversion system.

Each image was transformed into frequency space by way of a Fast Fourier Transform (FFT) software routine. The FFT algorithm converts the spatial information into magnitude and phase data. The log of the magnitude data was then calculated and generated as an image. This representation showed both the relative strengths and directionality of different frequency components on the original scene. The hard edges that define urban areas or land/water boundaries are easier to identify on the ESC magnitude image than on the digitized Hasselblad image. These hard edges are represented on the magnitude image as lines normal to those edges.



7a. ESC Image



7b. Digitized 70mm Image

Picture 7 Spatial Frequency (Fourier) image of the ESC image of the Baja Scene. The area of interest contained high spatial frequencies (many linear features).

To cover approximately the same region, the Hasselblad scene consisted of 512 x 512 pixels while the ESC image was 256 x 256 pixels in size. The analysis was performed on images acquired from two completely different systems. Therefore, no conclusive statements can be made about the cameras themselves. Rather, this serves as a comparison of system characteristics. The digitized Hasselblad scene appeared to have much poorer resolution than the ESC image. Frequency magnitudes were calculated to show how this degradation corresponds to resolution.

The magnitude image contains directional information as well as the relative amounts of the spatial frequency. The brighter and longer linear features indicate well-defined edges. The direction of the linear features in the Fourier image is normal to the same edges contained within the original image. The original ESC image appears to contain more edge information than the 70mm film image. This was unexpected because the digitized 70mm image has approximately four times as many pixels as the ESC. The greater number of pixels within an area, the larger the number of frequencies that are capable of being detected. Therefore, the ESC image has a higher spatial frequency than the 70mm image.

2.6.1.2 Radiometric Dynamic Range Variation

Another method of determining information content of a sensor is to analyze the radiometric dynamic range. Both the ESC and 70mm images can be quantified into at least 256 gray levels. If the quantization of the sensor response is not optimized, the separation between dark and light scene elements may not yield the subtle information about the target or separation between targets.

Several image kernels (continuous matrix of pixels) were extracted from the Siberian and Baja image pairs. The mean and standard deviation for individual kernels were calculated. The results, though qualitative, showed that the two camera systems had similar response characteristics.

Methodology

The red band of the 70mm photographs was digitized to the limits of the film spatially, and to 8 bits radiometrically. Identical areas of interest were chosen from both the digitized 70mm and the ESC images. Image kernels from the bright and dark areas were chosen within the scenes. The mean and standard deviation of the individual kernels were calculated.

Baja Scene

Mean ESC	Std. Dev. ESC	Mean Hass.	Std.Dev. Hass.
126.878	2.781	158.951	1.580
146.980	3.152	170.086	1.407
130.714	3.422	136.160	1.436
76.143	5.458	115.407	6.109
185.000	3.714	183.691	2.035
232.898	4.989	210.469	1.013
175.667	6.308	182.901	2.961
66.633	2.421	107.062	3.806
101.306	3.670	149.358	1.886
80.531	4.297	108.160	1.308
78.878	5.235	114.432	3.118

Siberian Scene

Mean ESC	Std. Dev. ESC	Mean Hass.	Std.Dev. Hass.
101.878	1.285	158.494	1.343
169.347	2.735	223.642	1.345
102.653	1.422	158.827	1.498
102.898	1.623	162.222	1.288
108.612	1.706	175.815	1.817
103.653	1.362	162.469	1.246

118.694	1.228	182.901	2.567
106.265	2.644	163.296	1.840
102.245	0.969	148.370	1.504
111.633	2.028	174.988	1.346

2.6.2 System MTF Evaluation

The resolution of Space Shuttle photography depends upon two factors; blur associated with data acquisition, and the Modulation Transfer Function (MTF) of the optical path.

2.6.2.1 Platform Blur

The two major causes of blur in Space Shuttle photography are platform motion and jitter in the operator.[11] Platform motion is easily modeled by applying Newton's second law to orbital mechanics:

$$v = \sqrt{\frac{G^{*}M_{Earth}}{r}} \approx 7.659 \frac{\text{kilometers}}{\text{second}} \text{ at 225 nautical miles (Space Station Altitude)} \quad \textbf{(1)}$$

$$\Delta x = v * \Delta t \quad \textbf{(2)}$$

r = the sum of the radius of the Earth and orbital altitude
G = gravitational constant
v = velocity tangential to the orbit (assuming a circular path)
Δx = ground blur
Δt = exposure time

The normal shutter speed for Space Shuttle photography using ASA-64 film is 1/250 second. Equation 2 shows that the Space Shuttle travels 30.8 meters during the exposure of the film. An exposure time of 1/500 second reduces the motion-induced blur by one half. If this effect was the limiting factor to photographic resolution, a directional (linear) blur should be observed on the photography. No linear blur was observed upon reviewing photographs from several Space Shuttle missions.

2.6.2.2 Operator Induced Blur

Along with platform motion, there is also blur that is associated with camera operator motion. The camera and operator may have a wider range of motion about the cabin of the Orbiter than on Earth, so the possibility exists that a blurring effect will be caused by unsteady movement during the exposure. This type of blur is most likely to be random and not directional. Operator-induced blur resembles blur due to poor focus and is not easily characterized.

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[11] Photographs from several Space Shuttle missions have been examined to determine if a directional blur exists. As of yet, no regular axial blur has been seen. This indicates that the major cause of blur in the image is due to operator jitter or focus rather than the platform motion during exposure.

Both platform and operator-induced blurs are directly proportional to exposure time. In the case of platform motion, the amount of blur may be calculated using equation 2. With a constant Orbiter velocity, a smaller value for Δx (shutter speed) indicates that the platform (Space Shuttle)will travel a shorter distance during the exposure. A similar situation arises for operator motion. As the exposure time is reduced, the operator has less time to move the camera, thus reducing the overall blurring effect. Because no directional blur has been observed in either analog photography or digital imagery, the limit of resolution must be either operator motion, or system MTF.

2.6.2.3 System MTF

The system MTF is typically described by lens resolving power in line pairs per millimeter.[12] The following equation may be used to describe the minimum ground resolved distance by a particular lens as a function of focal length, resolving power, and distance to target.[13]

$$GRD = \frac{D}{f * R} \qquad (3)$$

GRD = Ground Resolved Distance	f = focal length
D = Distance to target	R = Resolving Power

The limits of resolution for space-based optics are either 1) blur associated with image acquisition or 2) system resolving power. A typical camera configuration flown aboard the Space Station would have a minimum ground resolved distance of about 30 meters according to equations 2 and 3, not including blurring effects and atmospheric attenuation. Table 1 shows the limits of resolution for the Hasselblad and ESC cameras at different shutter speeds. The significance of Table 1 is that the limiting factor for resolution varies with camera configuration. For example, by increasing the shutter speed of the current Hasselblad photography from 1/250 second to 1/500 second or 1/1000 second, the ground resolved distance will reduce from 30.64 meters where it was limited by motion blur to 29.26 meters where theoretically calculated resolution is limited by the resolving power of the camera system; this is not a significant difference. An advantage would be possible for an ESC equipped with an upgraded 2048 x 2048 chip, because of significantly increased system resolution. The ground resolved distance will improve from 30.64 meters to 22.42 meters and change the limitation of resolution from motion blur to system MTF. The system resolution of the ESC in the Space Shuttle experiment is better

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12 The size of an individual grain of film is generally much smaller than the resolving power of the lens in most photographic systems.

13 The 250 mm Hasselblad lens has a resolving power of 57 line-pairs per mm, which is larger than the grain size of the film. The 300 mm Nikon lens resolves 62 line pairs per mm, but the current CCD array resolves 512 line pairs per 15 mm or 34 line pairs per mm. Therefore, the system MTF is limited by CCD resolution rather than by the lens resolution. Future CCD arrays will have a better resolving power than the lens.

than the Hasselblad (at 161 nautical miles [nm]) because the lens used with the ESC has a higher quality and a longer focal length.

System Resolving Power - Space Station Altitude 225 nm

Shutter Speed	Hasselblad with 250 mm lens		Current ESC with 300 mm lens		Upgrade ESC with 2048 chip	
	System MTF	Blur	System MTF	Blur	System MTF	Blur
1/250	29.26 m	30.64 m	40.72 m	30.64 m	22.42 m	30.64 m
1/500	29.26 m	15.32 m	40.72 m	15.32 m	22.42 m	15.32 m
1/1000	29.26 m	7.65 m	40.72 m	7.65 m	22.42 m	7.65 m

Table 1: Resolving Power Considerations at Space Station Altitudes[14]

Figure 8 shows how exposure time and system MTF affect resolution. At 1/250 second exposure time, all cameras are limited by motion blur except the current ESC at 225nm. That is to say that no camera may have a better resolution than approximately 30.64m. At 225nm, the current ESC is limited to a resolution of 40.72m. When exposure time is decreased, all camera resolutions become limited by system MTF (lens resolving power). With a standard film speed of ASA-64, however, the Hasselblad cameras are not capable of exposure times of less than 1/250s over a wide range of reflectance. Thus the practical resolution of the Hasselblad remains fixed at 30.5m while the current ESC may attain a 29m resolution by exploiting a faster shutter speed.

[14] Note: These measures are computational and idealistic; the actual system resolutions will be less than those quoted here. Actual resolution is determined by using an elaborate Fourier analysis with known targets within the field-of-view; the values given here are describing the systems based upon their relative merits.

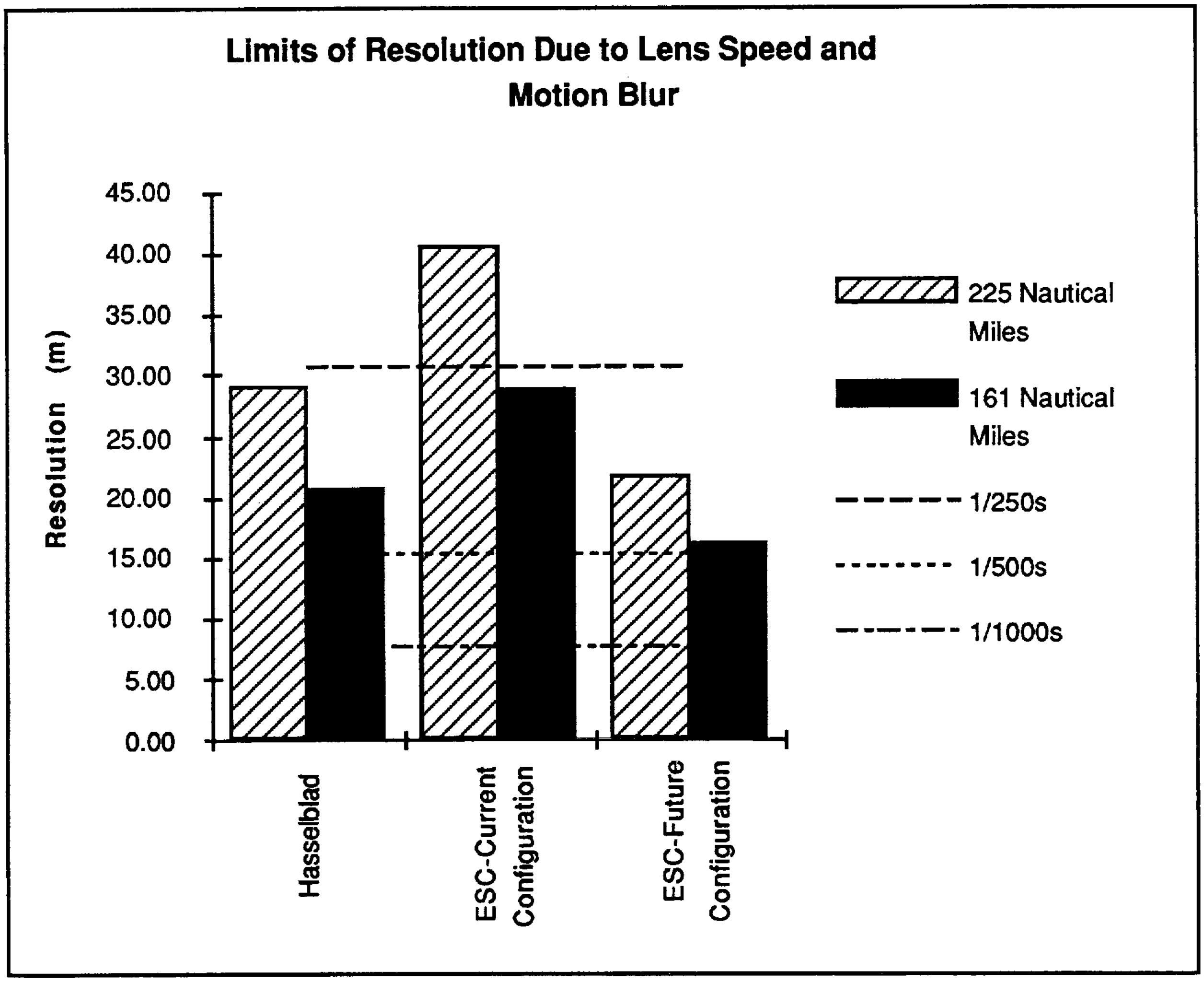


Figure 8. Limits of Resolution

2.6.2.4 Other Aberrations

A third type of blurring effect may result from poor focus. There is no infinity focus stop for the 250mm-focal-length, 70mm-format, flight lenses. Astronauts must consciously focus each frame. Also, the windows of Space Shuttle are reported to cause an astigmatism that is aperture dependent (Scott, 1991) but no preferential axis of focus has been detected during study of any of the space-based photography. Finally, no vignetting effects have been seen on any of the photographs acquired in the visible spectrum, but intensity fall-off is noticeable with CIR film radially from the center. No vignetting effects have been observed from the ESC images.

2.6.2.5 Targets Versus Background

The previously-quoted resolutions are idealized calculations given 100% contrast between a target and its background.[15] Atmospheric particulates and aerosols will reduce resolution through scattering and absorption. The primary mechanism for atmospheric attenuation is Rayleigh scattering that occurs when atmospheric particles are much larger than the wavelength of light. Because the peak response for the ESC is in the red band, scattering is expected to be greater for color visible film than for either CIR film or the ESC in its current configuration.

2.6.2.6 Film Speed/Aperture

The final variables to consider with photography are film speed and aperture. Faster films (those with higher ASA values) demand less light to sensitize the individual grains. Different light levels require that a specific range of exposure times and film speeds be employed for specific applications. Aperture is simply the size of the opening that exposes the film to light. Generally, as the aperture size increases, the required exposure for a given film decreases. The ESC configuration is set up to use higher ASA values, but its pixel size does not change. The Nikon F4 also has higher available shutter speeds than the Hasselblad (1/2000 second for the Nikon and 1/500 second for the Hasselblad). This allows the ESC images to be exposed at higher shutter speed and limit the amount of blur within a scene.

2.7 Qualitative Analysis of ESC Operational Environment

Several Earth scientists at JSC were asked to answer a questionnaire about the usefulness of near real-time digital imagery as applied to their discipline. The questionnaire also included Earth views acquired simultaneously from both the current ESC and the 70mm Hasselblad cameras. The scientists were asked about the useability of the electronic and photographic data and the relative amounts of information provided these sensors. This qualitative analysis will allow NASA to better distribute Space Station imagery in a suitable format to support the largest number of users. The comments are summarized in the results (Section 3) section of this paper.

2.8 Photographic and Digital Data Storage and Distribution for Space Station

2.8.1 Data Storage

After the ESC acquires a scene, the images are temporarily stored on computer disks until the astronauts are able to transmit them to Earth. After transmission, the computer disks may be reused. Film, in contrast, must be stored aboard the spacecraft until the crew returns to Earth. For Space Station Freedom, the exposed

[15] There are three major factors that reduce contrast between a target and its background: 1. The contrast between the signatures in the observed wavebands may be small; 2. The exposure time or effective aperture may be incorrect for the scene radiance; and 3. The atmospheric attenuation may reduce signal quality. The first two parameters can be corrected by careful planning. The last parameter may be modeled.

film may be stored as long as 3 months. During this period, exposure to the Earth's radiation belts will cause the exposed film to degrade or fog unless it is protected. Negative and CIR films are more sensitive to fogging than color positive film (Holly, 1992). The amount of degradation caused by prolonged exposure to radiation is not covered by this survey. A film storage vault was used successfully (no significant increase in base fog) to protect standard color, CIR, and black-and-white films during Skylab missions as long as 85 days (Kenney, 1975).

Storage requirements for the Space Shuttle are approximately 4 lockers that incorporate 5 storage bags at 1/2 locker each and 1 and 1/2 lockers for film and accessories. A typical Space Shuttle mission will carry approximately 20 magazines of color positive ASA-64 film at 100 frames apiece and 6 magazines of CIR film at 115 frames apiece for the Hasselblad cameras. The crews will have about 10 to 15 magazines of 70mm color positive film for the Rolleiflex camera (if flown) at roughly 65 frames apiece, 2 magazines of Linhof film color positive film at 275 frames apiece (if flown), twelve 2-hour 8 mm video tapes, nineteen half-hour 3/4 inch video tapes, and six reels of ASA-500 and six reels of ASA-100 16 mm motion picture film at 11 minutes each. The amount of film varies for the 35 mm (SLR) cameras. Space Shuttle missions vary from approximately 5 to 13 days. This is significantly shorter than the typical Space Station mission of 3 months. To satisfy film demand based on current Shuttle usage, the Space Station will need to manifest 6 times the amount of film manifested on the Shuttle.

2.8.2 Distribution of Data

One likely method for photographic data distribution of Space Station imagery is depicted in Figure 9. First, downlink video and ESC images will enter the Consolidated Control Center Network Interface and then be fed through to the JSC video control center. The raw data will be stored and cataloged. Requests for duplication of the downlinked data will be made to the Image Sciences Division. Selected data will be made available to the general public through computer network and modem transfers. This system will also allow for archived digital imagery and photographic data to be accessible to the public through the current distribution centers such as EROS Data Center.

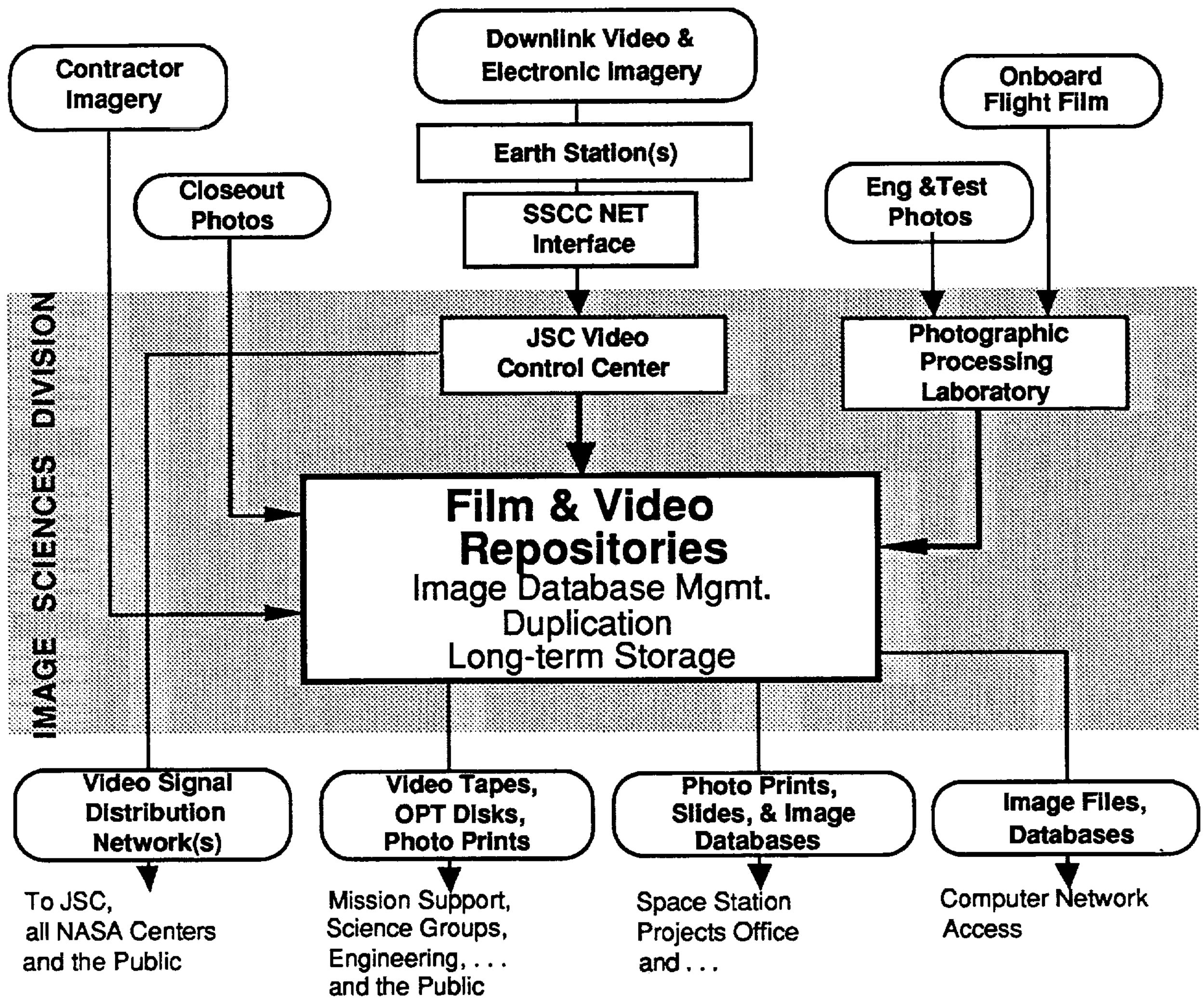


Figure 9. Possible Flow of Photographic and Digital Data

3.0 Results

The results and recommendations from the experiments are limited to current flight hardware and data-processing software; where possible the results of baselined upgrades to current systems are supplied.

3.1 Information Content

3.1.1 Frequency Domain Comparison

The results from the two current imaging systems were compared. The qualitative results showed that the ESC contained higher spatial frequencies than the film. This is significant because the 70mm image contained four times as many pixels to describe the scene. Therefore, at nominal Space Shuttle altitudes and camera configurations, the ESC has a higher frequency response (effective resolution) than the current 70mm film cameras. At Space Station altitudes, the linear information resolved by the current CCD array is expected to reduce significantly.

3.1.2 Radiometric Comparison

Limiting the analysis to the red waveband of the spectrum provided inconclusive results. The digitized 70mm image kernels generally contained a lower standard deviation than the ESC image kernels. A lower standard deviation indicates a lower separation between pixels within the kernel. The ESC contained a wider radiometric spread between kernels for the Baja Scene, while the 70mm film was better able to separate kernels within the Siberian Scene.

3.1.3 System MTF Comparison

At Space Shuttle altitudes (161nm), the current ESC spatial resolution (30 meters) is comparable to 70mm film. At Space Station altitudes (225 nm), however, the current ESC configuration resolution will reduce to 40 meters. When the CCD array doubles the number of pixels in each axis over the same sensor area, the ESC camera will have the same resolution as the current Hasselblad configuration.

3.2 Qualitative Results/System Analysis

The Earth scientists agreed upon several points following their evaluations of the image data sets. The major advantages to manned observations of the Earth over unmanned satellites are 1) quick response by an intelligent, trained observer to unexpected events and viewing conditions; and 2) the capability to communicate between the ground and the space-based observer. Phenomenological occurrences[16] identified on the ground from inspection of geostationary satellite imagery (1-4km GRD) can be communicated to the manned platform. The space-based observer can document the structure and influence of this event on the surrounding

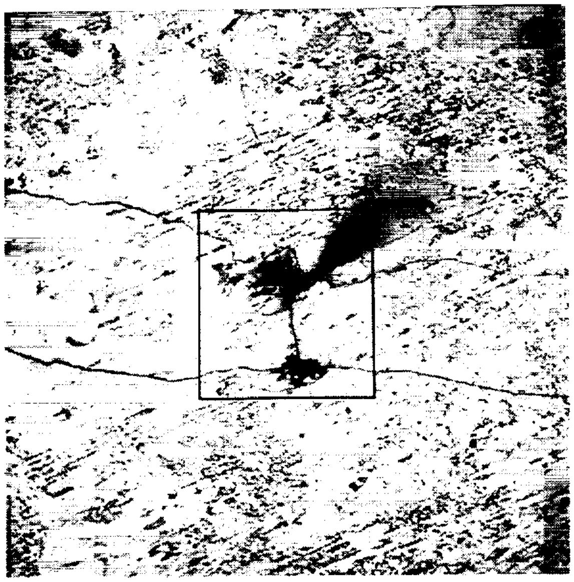
[16] Such as hurricanes, tornadoes, vocanic eruptions, oil spills, smoke and sand palls.

environment at significantly higher resolution (30-50m GRD) than geosynchronous weather satellites (1-4km GRD).

The scientists also agreed that near-real-time image data are not required for most applications. Even images of phenomenological events, once captured, can be transmitted to Earth at any regular interval. For many time-critical applications, the scientists wish to cover a large area, such as on a continental scale for weather, or in the case of an oil spill a very small area, such as part of a harbor. In either case, the required resolution would be significantly higher or lower than is expected to be available for Space Station. Also, for oil spill response the data rate would have to be continuous over the course of several days. With orbital progressions across the globe, Space Station observations would only view a particular area for about 3 revolutions (4.5 hours).

Digital data were better than analog data for some applications because it is easier to manipulate electronically. Space Station data would be used in conjunction with other satellite and ancillary data that were already in digital form. Digital images may be enhanced, transmitted, extracted and manipulated easily, and in near-real time. Finally, the cost of digitizers or the process of digitizing photographs is significant, and small research groups may not be able to afford the cost.

An important factor in the use of space-based imagery was not addressed in this resolution study. Recognition of spatial patterns plays a major role in human interpretation of images; recognition by an experienced observer may depend on discrimination of subtle differences in color, tone, and texture, that are not easily quantified. The large area FOV of medium-format film cameras is important for many applications; for this reason alone, electronic still cameras will be complementary to, but will not replace, film cameras in the near future.



10a. Siberian Scene

10b. Baja Scene

Picture 10 Relative Fields of View. The borders surround the ESC image within the Hasselblad frame.

4.0 Conclusions

The following conclusions are based upon the analysis of all viable photographic systems considered for Space Station Freedom and show that an ESC will work very well for real-time applications.

1. The ESC's ability to acquire and transmit data in near real-time will reduce storage requirements aboard SSF during Permanently Manned Configuration (PMC), expedite archival and distribution, and provide a useful product for the remote sensing of Earth and the environment.

2. In its current configuration, the resolution of the ESC at SSF altitudes will be somewhat less than that of the Hasselblad. At Space Station altitudes, the current ESC is expected to have better than 50 meters resolution which is sufficient to support a large user base and suitable for many important environmental monitoring applications. Upgrading pixel density within the CCD array will improve the resolution considerably, and expand the potential user base significantly.

3. The contrast between scene elements for an ESC image is suitable for detection and identification of large-scale physical conditions within an image.

4. The ESC's FOV is not currently adequate for many remote sensing requirements. Larger chips are commercially available to accommodate larger FOVs; but computer CPUs will have to accommodate the geometrically increased data rate.

5. The use of a filtered three CCD array will allow researchers to customize the spectral response of the ESC to meet the specific needs of their experiment. This capability is now only practicable with the use of multiple camera systems and other specially designed imaging devices.

6. The Naval Research Laboratory "Latitude-Longitude-Locator" device (Soyka and Melvin, 1991) will facilitate the ground location of image products acquired by the ESC and further expedite the cataloging and distribution process.

7. Digital ESC data will help ensure the integrity of distributed imagery, whereas analog images suffer a noticeable degradation in second or third generation products. Digital ESC data will also appeal to a wider range and greater number of users in the remote sensing community, in contrast to the general viewing and mapping community, than film does currently.

Appendix A - Other Analog Still Cameras Used During Shuttle Flights

Analog cameras are defined as those which acquire scenes and store them on a film (i.e., plastic or transparent medium). This survey will not analyze long term storage requirements of film in space (i.e., protecting the film for long duration from radiation contamination, such as a film vault like that flown aboard Skylab).

4x5" Linhof

The Linhof is the largest-format film camera that routinely is flown aboard the Space Shuttle. The format is 4x5 inches (101mm x 127mm). The Linhof magazine contains 200 to 260 exposures, depending on the thickness of the film base. The camera uses a 90mm and the 250mm lens for Earth observations. The 250mm lens has a FOV of approximately 14.25° along the 5 inch axis. The Linhof 250mm lens has a resolving power of just over 50 line pairs per millimeter, and the camera has a vacuum platen for film flatness, so the limiting factor of resolution is movement of the Space Shuttle or jitter during exposure. The one major drawback to using the Linhof for Earth observations is that the camera and film magazines require a relatively large storage area.

Nikon F4

The Nikon F4 is the same camera body as the ESC. The 300mm lens has a resolving power of 62 line pairs/mm for high contrast targets. The other advantage of the Nikon is that it is capable of a 1/2000 second shutter speed that reduces the image smear to approximately 4 meters. Likewise, the combination of the 300mm focal length with the 62 line pair per millimeter resolvability, calculates to an idealized spatial resolution of 12 meters (at 160 nautical miles). The image size is 24 X 36mm, so that the angular FOV is approximately 3.3°.

Appendix B - Trinity Bay

The objective of this portion of the ESC *versus* film experiment was to evaluate the performance of electronic and film camera in an actual application. In cooperation with Texas A&M University and the U.S. Coast Guard, remotely sensed data were acquired in conjunction with in situ measurements of suspended sediment loading in the lower portions of Galveston Bay. The response of both the ESC and Hasselblad cameras (showing turbidity interpreted from water-surface reflectance) was to be compared to measurements of suspended sediment.

Site Selection

Originally the site for the ESC experiment had been the upper part of the Trinity Bay. A review of Space Shuttle Photography spanning a period of twenty years indicated that this portion of Galveston Bay could, at times, exhibit a wide variation in water color due to the admixture of turbid, fresh water from the Trinity River with the brackish estuarine waters of Galveston Bay. Figure 1 shows the conditions that were hoped for during the experiment. The darker waters in this image, taken by astronauts aboard STS-61A, are less turbid waters or waters that, due to a higher salinity, contain a lower concentration of suspended sediment. Lighter patches of water in Trinity bay originated in the fresh, turbid plume from the Trinity River. Also, the chromatic properties of the sediment in this region appeared to be more homogeneous than in lower portions of the bay.

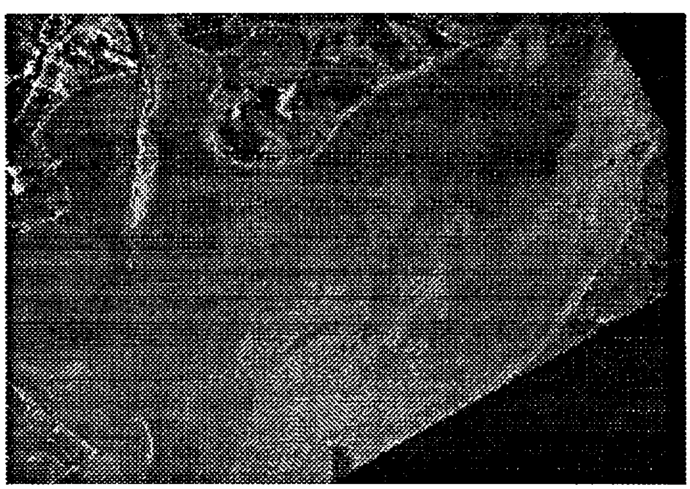


Figure 1: STS-61A-048-073

Consultation with Dr. Eric Powell and Dr. Ernie Estes of Texas A&M University prompted the relocation of the experiment site. Their concurrent opinion was that since high amounts of rainfall had significantly lowered the salinity of Trinity Bay waters, little variation in water color throughout the Trinity Bay region was expected. It was estimated by Dr. Powell that the 1ppt line might be as far south as Smith Point. Dr. Estes had flown from Houston to Beaumont the week before the experiment, and reported that the only variation in water color he was able to discern was a region just south of Smith Point. Based on Dr. Powell's information and Dr. Estes' observations it was decided that the experiment would be conducted in a region of Galveston Bay that ranged from Redfish Island to Bolivar Roads along the Houston ship channel. It was expected that the strongest gradient of salinity (hence the gradient of water color) would be in a direction parallel to the ship channel because of the tidal flow through the Galveston jetties. It was decided that at least one ground truth station would be positioned in that region south of Smith's point where Dr. Estes reported the water color variation, while another was at Redfish Island. The other stations would be positioned in a roughly linear fashion between Redfish Island and Bolivar Roads.

Equipment

Secchi Disks

The secchi disks were fabricated about one week before the experiment. They were approximately 12 inches in diameter and made from 1/4 inch flat board painted flat white. Standard disks are about 30cm across but it has been shown that Secchi depth is not largely influenced by minor variations in disk diameter. The disks were weighted with 6 inch channel iron fastened on by 6 inch eyebolts. A rope marked at regular intervals was used to measure the depth of the disk. In addition underwater viewers were made to increase the accuracy of the Secchi disk measurements by reducing refractive effects. The viewers were constructed of 6 inch PVC pipe painted black and 1/8 inch clear Plexiglas. Each of the viewers was 3 feet long.

Vessels

Three small craft and two 32 foot vessels were provided by Texas A&M University at Galveston, which allowed for the acquisition of five separate ground truth stations. The small craft were 18-foot skiffs equipped with 75hp outboards, manned by three individuals each. The 32-foot vessels were converted Coast Guard fireboat trainers and carried as many as seven individuals each. The 32-foot vessel at Redfish Island, hereafter referred to as A&M1, was instrumented with a Sea-Bird CTDI[17] to profile salinity at the Redfish station in addition to the Secchi disk instruments. Measurements were taken at regular intervals along the ship channel. The other 32-foot vessel, A&M5, was also carrying a turbidometer along with the Secchi instruments. All boats collected water samples.

Cameras

Two camera types were flown in a dual mount aboard a USCG helicopter. The first was a Hasselblad 70mm camera used with a 100mm lens and Kodak ASA-64 color film. The second camera was the Electronic Still Camera (ESC) which was equipped with a 50mm lens.

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[17] Conductivity, Temperature, Depth meter

Data Collection

It was planned that all the vessels would depart TAMUG at around 11:30 A.M. on March 27 and be at their sites by 2:00 P.M. The Coast Guard Helicopter was scheduled to leave Ellington Field at approximately 2:30 P.M. The weather on the 27th was overcast with a 30% chance of rain. Although a backup date of the 28th was considered, the forecast for that day was less inspiring than the planned date of the 27th. Originally it was intended that A&M1 would help position the three small craft by finding, by inspection, regions of varied water color. There was however some concern that in doing this A&M1 might not reach Redfish Island in time. Therefore it was decided that A&M5 would instead position two of the small craft while the remaining one was dispatched to the region south of Smith Point where the less turbid water had been sighted previously. A&M5 was unable to locate any extreme variations in water color and the two small craft were positioned at buoy numbers 36 and 46 along the Houston Ship channel. A&M1 arrived at Redfish Island at approximately 1:00 P.M., and received from A&M5 the positions of the small craft from A&M5. Figure 2 shows how the ground truth stations were arranged in that portion of the bay. Note that this image was not taken at the time of the experiment, and the sediment patterns were consequently not as highly structured as they are shown in Figure 2.

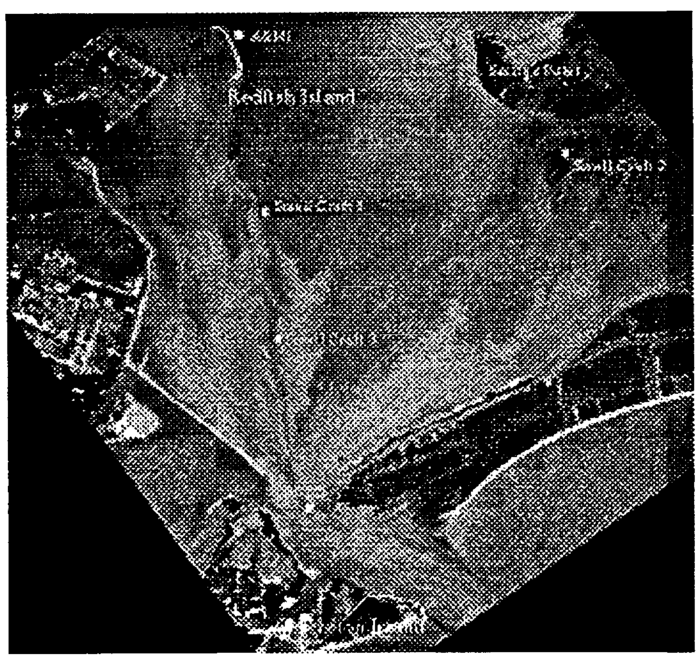

Figure 2: STS61A-048-072

Because A&M1 arrived early on station it was decided that it would proceed to a point two buoy markers north of Redfish Island to acquire CTD measurements and be back at Redfish at the appropriate time. Anticipating the deterioration of weather conditions, the USCG helicopter left Ellington field early and arrived at Redfish Island at approximately 1:30 P.M. A&M1 was off station at the time but made it back to Redfish slightly after the helicopter arrived on the scene. VHF channel 16 was selected as the hailing frequency for the helicopter and the boats. Upon initial contact with A&M1, the communication frequency was changed to VHF channel 2, and the positions of the stations were relayed to the helicopter. The other boats, unfortunately, did not receive the call for a change of frequency and were not in communication with the helicopter. It was originally planned that the helicopter would make two passes over the boats at altitudes of 1000ft and 2000ft. As the helicopter passed over each ground truth station would make a Secchi disk reading. There was some difficulty in locating the boat at Smith Point and it was consequently skipped on the first overpass. As the weather conditions were deteriorating rapidly, the second pass was conducted at 1000ft instead of 2000ft. Upon completion of the second overpass A&M1 switched communication back to channel 16 and dismissed the remaining boats back to TAMUG. On route back A&M1 collected several CTD measurements along the ship channel. These data will help characterize the state of the bay at the time the other measurements were acquired. Water samples were taken back to TAMUG for drying and weighing and those measurements are forthcoming. It is expected that these data will be of more use that the actual Secchi disk readings themselves.

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16. Abstract

This project evaluated the suitability of the NASA/JSC developed electronic still camera (ESC) digital image data for Earth observations from the Space Shuttle, as a first step to aid planning for Space Station Freedom. Specifically, image resolution achieved from the Space Shuttle using the current ESC system, which is configured with a Loral 15 mm x 15 mm (1024x1024 pixel array) CCD chip on the focal plane of a Nikon F4 camera, was compared to that of current handheld 70 mm Hasselblad 500 EL/M film cameras.

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