Satellite Digital Photography: Preserving the Image in the Digital-to-Analog Conversion

Jerome R. Noss
Autometric, Incorporated
Springfield, Virginia, USA

Abstract

The preparation of full-color photographic hardcopy from digital data acquired by civilian imaging satellites has been a standard practice since the launch of the first Landsat in 1972.[1] Satellite digital imaging provides broad area coverage of terrain features by composites of data from visible and non-visible spectral bands. Analyses and interpretations of the displayed features are blends of inference, measurement, and the assessment of terrestrial change over time. Largely overlooked in the production of satellite photographs is the significant loss of original imaging data that occurs in its conversion to a photographic end product. This paper presents an overview of the digital-to-analog conversion process and traces the loss and degradation of digital imaging data during the production of color photography. Emphasis is placed on the reciprocity of film to its exposure by film recorders, the methodology of photographic production, and the inadequacies of conventional photographic processing to the requirements of satellite digital imaging. A solution to the problem is offered by a review of the inherent capabilities of silver halide technology to respond to the dimensions of a satellite digital imaging database, the production requirements essential to the retention of the radiometric and spatial resolution of remote sensing systems, and the potential benefits to image analysts and photo interpreters provided by the validation of satellite digital photographs.

Introduction

The purpose of satellite-based digital imaging systems is to gather information about the earth's atmosphere, oceans, and terrestrial features. When that information is displayed as a full-color photograph, it is the culmination of a series of events that enable the viewer to study phenomena beyond the range of human vision and photographic film. That series begins when sensors on the satellite detect bands of electromagnetic radiation recorded as digital data. Radiometric resolution refers to the range of discrete values assigned to the radiant energy detected by the sensors. The radiometric resolution of the Landsat Thematic Mapper and the SPOT imaging satellite is 256 levels (0-255). The spatial resolution of satellite imaging systems is the area covered by one detecting picture element (pixel) of the sensor array. The spatial resolution of Landsat Thematic Mapper data is 30 x 30 meters for each of six visual and infrared (IR) bands and 120 meters for one thermal IR band. SPOT delivers 10 meter spatial resolution from one panchromatic band and 20 meter data from three multispectral bands.[2-3]

Raw imaging data transmitted by the satellite typically undergoes a series of preprocessing routines to correct for geometric and radiometric corrections.[4-5] Variations in the position of the satellite during data acquisition influence the geometric accuracy of the image structure. Algorithms based on tracking data from the ground station are written to mathematically adjust for such distortions before the image is released as a working database. Corrections to the response curves of the satellite's sensors likewise restore radiometric accuracy to the raw digital data.

Corrected data for any one spectral band received from the satellite rarely fill all 256 cells that define the radiometric resolution potential. The composited full-color image is built from the contributing data of three bands selected for a particular application of image interpretation. The compositing formula dictates which one of the additive primary colors – red, green, or blue – is assigned to each of the bands. Regardless of the medium selected for display of the full-color image, it is essential that the monochromatic or gray scale accommodate 256 discrete steps from 0 through 255 if the palette of 16,777,216 colors is to be achieved. Any reduction of that palette will indiscriminately eliminate original data acquired by the satellite and devalue the information content of the image. The challenge, therefore, is to ensure that the display medium retains the full range of data delivered by the satellite and that validation of the color signatures generated by that data be made available to photo interpreters.

When the end product is to be a color photograph, an electro-optical film recorder is used to convert the digital image database into a latent analog image in a photographic emulsion. The digital value of each pixel represented in each of the contributing bands regulates the intensity of the light source in the film recorder to expose the emulsion pixel by pixel. The composite of three values generates a single color signature for each pixel in the photograph.

When the recorder writes the data from each band onto a separate sheet of black-and-white film, the opacities of each pixel function as neutral density filters to control the exposure of a color emulsion. The process of writing separate black-and-white film records for each band of data requires the precise registration of the three separations to produce an image that retains the spatial resolution delivered by the satellite. If the recorder writes directly to a color emulsion, data for each pixel from the three selected bands controls the intensity of each additive primary color light source. In either case, it is the blend of primary colors across a range of 0 through 255 levels from three sets of data that establishes the *potential* palette of 16,777,216 colors. How many of those signatures are used in the makeup of an image is driven by the reflected and emitted energy detected by the satellite's sensors. How many survive the digital-to-analog conversion remain to be seen.

Table 1 shows a sample of 12 signatures whose single-band values and additive primary color assignments are composited to create the color in a single pixel. In the color composition of a satellite image, "0" is a significant digit that regulates the absence of exposure by a primary color to isolate red, green, and blue along with cyan, magenta, yellow, black and tens of thousands of other colors unrecognized by the dictionary of color names.[6]

Table 1. Derivation of Color Signatures

Pixel #	Band A Red	Band B Green	Band C Blue	Composited Color Signature
1.	255	0	0	Red
2.	0	255	0	Green
3.	0	0	255	Blue
4.	0	255	255	Cyan
5.	255	0	255	Magenta
6.	255	255	0	Yellow
7.	0	0	0	Black
8.	255	255	255	White
9.	64	64	64	Dark Gray
10.	128	128	128	Med. Gray
11.	224	224	224	Light Gray
12.	128	96	96	Puce ???

Dimensions of the Problem

Photographic emulsions are analog sensors capable of recording electromagnetic wavelengths from ultraviolet through near infrared. Sensitometry is the science of measuring the response of photographic emulsions to those wavelengths.[7-8] The predictable limits of the response lie within exposure ranges defined by the intensity of radiation and the duration of the exposure, i.e., the common formula: *exposure = intensity x time*. This formula, known as the *reciprocity law*, governs the exposure of film within the limits of its spectral sensitivity. With any change in the intensity of the light source that exposes the film there must be a reciprocal adjustment to the duration of the exposure to regulate the quantity of light that reaches the film. In a popular camera, correct exposures are provided through combinations of f/stops and shutter speeds. When time or intensity of the exposure exceeds the predictable response of the film there is a failure of the reciprocity law that governs that exposure. Although reciprocity law failure is driven more by extremely short or extremely long exposure times than by intensity of the light source, the reciprocal limits of any one film require experimental verification.[9-10]

Practical sensitometry is not reflected in the commercial practice of satellite digital photography. In spite of the magnificent displays of imagery provided by SPOT and Landsat, the preparation of those images does not reflect an agreement of the writing time of film recorders with the reciprocity limits of film. A representative exposure delivered by a film recorder for each pixel is 4/10,000,000^{ths} of a second. The commercial films available to those recorders encounter reciprocity law failure far removed from the writing time which the recorder provides.[10] Continuous-tone black-and-white films have reciprocity thresholds in the vicinity of 1/100,000th second. Color films reach their thresholds around 1/10,000th of a second. That represents a 400x exposure shortfall for B/W film and a menacing 4000x digression for color emulsions![11]

The emulsion characteristics of continuous-tone black-and-white films do not agree with the requirements for a successful digital-to-analog conversion of the satellite's database. The combined film speed, grain, contrast, resolution, and exposure latitude of any single emulsion run counter to the optimum characteristics of an emulsion that would satisfy the conversion requirement. Generally speaking, the slower high resolution films that would hold the definition of single microscopic pixels have finer grain, higher intrinsic contrast, and less forgiving exposure latitudes. Conversely, those films offering greater speed and latitude that would help to alleviate departures from reciprocity law, pay the price with coarser grain, lower resolution, and reduced contrast.

The commercial films available for general photography are designed around a range of 32 densities because that spread of values looks best to the collective eye. Longer ranges flatten the contrast of the image and weaken the emotional response to the picture. Shorter ranges steal from the shadows and highlights that define the detail and textures which make a photograph visually exciting. When Ansel Adams and Fred Archer codified the principles of sensitometry at the Art Center School in Los Angeles in 1940, they developed a practical application of exposure and processing that would position a range of 32 values within a scale of zones extending from pure black to pure white. That Zone System is based on the capability of continuous-tone black-and-white films to record light values 256 times as great as the value recorded at the effective threshold of the emulsion.[12]

Practitioners of the Zone System learn to expand or contract the reflected light range of a scene by selective processing of their film. Preferential treatment of shadow or highlight textures across a range of five zones is the product of an established response to controlled chemical processing. The commercial processing routines to which the output of film recorders are characteristically subjected do nothing to moderate the original photographic sin of severely inadequate exposures. Commercial processing was not intended for satellite digital photography. Because time is money in the competitive world of commercial photography, modern processing procedures are designed to move film "from dry-to-dry" as quickly as possible. The one-hour labs that serve the world of amateur photography are the ubiquitous testimony to that fact.

There are no digital films, although Tani suggests the possibility of silver halide and color emulsions designed to meet the demands of digital photography.[13] Color or black-and-white photographic emulsions can display digital imagery only as a response to exposures regulated by a database that governs the intensity of a light source in a film recorder. The survival rate of the database and the quality of the color image depends on the emulsion characteristics of the film in the recorder, chemistry matched to those characteristics, and processing procedures that control a family of influential variables. The intensity and frequency of the film's agitation in those baths, the duration of the film's immersion in each bath, and the film drying process are critically significant steps in a sequence that enables the effective production of a satellite digital photograph.

Commercial laboratories that once produced Landsat and SPOT photography by the registration and color compositing of black-and-white film separations have, in recent years, opted for the convenience and reduced production time provided by film recorders that write directly to a color emulsion. The time consuming and tedious exercise of punch registering three transparencies is eliminated and the spatial resolution of the color image almost meets the design specifications of the satellite that delivered the data. The downside of that production convenience is the considerable loss of data by film, chemistry, and processing routines never intended to accommodate the tidal wave of digital data transmitted by an imaging satellite.

In the late 1980's, Eastman Kodak sponsored a venture company that was to be a showplace and standard for the best of commercial laboratory practice. KRS Remote Sensing was created to serve the rapidly expanding market for satellite imagery. With that market as the objective and with, arguably, the finest example of commercial processing anyone had yet developed, the measured output of their color film recorders and highly controlled processing was 107 discrete densities from a digital input of 256 values. That compression of input values for the data from each of three bands recorded by the satellite amounts to a loss of 92% of the imaging capability of the system! Table 2 presents a sampling of single-band film densities and their mathematical relationship to the dimensions of a 3-band color palette. The third column in Table 2 indicates the percentage loss of color signatures driven by the reduction of film densities.

Clearly, any attempt to backfit the requirements of satellite digital photography into the processing routines of commercial laboratories, however sophisticated and well controlled, is an exercise in futility. The purpose of launching imaging satellites is to gather information from an imaging system that exceeds the limitations of human vision and photographic film. The capability of that system to display that information most effectively relies on the proper application of good photographic principles and practices. The problem lies with the radiometric resolution of commercial imaging satellites that exceeds the data retention limits of commercial processing for the production of color photography. Writing directly to color sacrifices radiometric resolution. Writing to black-and-white film separations using conventional photographic processing sacrifices radiometric resolution and challenges the talents of laboratory technicians to achieve acceptable registration that will not seriously degrade spatial resolution. The hybrid technology of satellite digital photography requires a custom designed laboratory ritual that holds the full dimension of a 24-bit color palette and provides to the image analyst and photo interpreter some assurance that the radiometric and spatial resolution of the imaging system has been retained in the end product.

Table 2. Loss of Color Signatures

Film	Densities	Color Palette	% Color Signature Loss
1.	256	16,777,216	0.0
2.	247	15,069,223	10.2
3.	237	13,312,053	20.7
4.	227	11,697,083	30.3
5.	217	10,218,313	39.1
6.	207	8,869,743	47.1
7.	197	7,645,373	54.4
8.	187	6,539,203	61.0
9.	177	5,545,233	66.9
10.	167	4,657,463	72.2
11.	157	3,869,893	76.9
12.	147	3,176,523	81.1
13.	137	2,571,353	84.7
14.	127	2,048,383	87.8
15.	117	1,601,613	90.5
16.	107	1,225,043	92.7
17.	97	912,673	94.6
18.	87	658,503	96.1
19.	77	456,533	97.3
20.	67	300,763	98.2
21.	57	185,193	98.9
22.	47	103,823	99.4
23.	37	50,653	99.7
24.	32	32,768	99.8

Elements of a Solution

All continuous-tone black-and-white film will hold 256 discrete densities, but not all film is appropriate to the practice of satellite imaging. A seemingly infinite number of film and chemistry combinations provide a comparable number of response characteristics. Those combinations best suited to the task will have a low level of chemical fog, extremely fine grain, very high resolution, and an extended straight line portion of the sensitometric response curve. Latent image stability may be a factor if exposed film cannot be processed promptly. Exposure latitude will not be critical because the design specifications governing the laboratory practice will be calibrated to the light output of the film recorder. The degree of reciprocity law failure established by the variance of film speed and the writing time of the film recorder will be factored into the processing equation.

The processing times, temperatures, and associated film speeds supplied for commercially available black-and-white films by their manufacturers will be little more that a point of departure for the custom processing that is required. Against the optimum range of 32 values delivered by standard processing, the satellite's range of 256 values will respond predictably to the extended range processing tactics that will characterize the customized laboratory practice. The choice of water and the mixing of chemistry will introduce control over the standard procedures that cope with the variable pH factors of municipal water and the evaporation of critical developing agents. Replensishers will give way to single-use formulations and the filtering out of gelatinous debris will cease to be an option. The design of processing for satellite digital photography will be more than the mere refinement of standard laboratory practice; it will—by necessity—establish control over every variable in the selection and processing of silver halide emulsions.

Wet film is an unstable medium. The grains of black metallic silver that are the densities in a processed image are suspended in a layer of saturated gelatin whose dimensions will change considerably as it dries. The subtle shift in the position of silver grains that can occur within the emulsion when drying is accelerated by rapid processing are of no consequence for standard commercial photography. Most of the curl in the emulsion caused by shrinkage is countered by the anticurl backing of the film, the only difference being the positioning of silver grains in the emulsion that influence the rate of drying and the degree of shrinkage. When film separations require critically accurate registration, however, that shrinkage becomes a significant factor. The quantity and distribution of silver within each film separation is unique to the band data that it records to the extent that shrinkage can produce variance in the exact size of the image from separation to separation. Precise registration becomes a near impossibility unless film drying is rigidly controlled.

Conventional film punches used for industrial graphics production are not acceptable for the registration of satellite image film separations. The size and placement of punch pins, the force characteristics applied to the punching, and the potential for slippage between separations when being punched are factors which must be controlled if the spatial and radiometric resolution of the image is to be retained. Film recorders with internal film punches are only a partial solution because their punch activity precedes the processing of the film that can influence precision.

The registration of one film record with another requires the positioning of crosshairs in each corner of the film outside the area of the image. The intersection of each crosshair should be a single pixel which dictates that registration be accomplished under fairly high magnification depending on the selected spot size of the film recorder. As the spatial resolution of imaging satellites continues to improve, spot sizes will diminish in order to accomodate the increased number of pixels contributing to the image.[14] Improved spatial resolution promises more reliable color signatures because a smaller area reduces the averaging of reflected energy within the instantaneous field-of-view (IFOV) for each of the sensors in the detecting array.[15] In order to retain that improved spatial and radiometric resolution it is imperative that any cumulative registration error not exceed 49% of the area of one pixel. A legitimate color signature requires the overlap of all three primary colors according to their digital values. If the percent of overlap is 51% or greater, the dominant perceived color will establish the graded acceptability of the color signature.

Color fidelity in the end product obligates the use of narrow-band additive color light sources during the compositing exercise. Care must be taken, however, that the selection of the light source does not extend exposure times beyond the top end of the reciprocity window. If the band width of the light source is too great, saturation of the additive primaries will be lost to adjacent wavelengths and the color balance of the entire palette will suffer accordingly. A major advantage of building a color negative (or positive) from single-band film separations is the opportunity to work around the excessively brief exposure times of film recorders. Reciprocity failure in color film is particularly critical because each of the three color layers in the emulsion will respond differently to produce an uncontrolled shift in color balance.[16] Unless care is taken in the selection of primary color light sources, much of the advantage which should be enjoyed by working with exposure times within the reciprocity limits of the color film will be given up to reciprocity failure caused by overly long exposures.

Figure 1 shows a composited white pixel (#8 in Table 1) whose registration error results in a signature factor (SF) of .64 and an effective spatial resolution (ER) that is 120% of the design specifications of the imaging satellite. SF.64 indicates that the composited pixel area is 64% of the area of a single-band pixel whose dimension may be taken from the intersection of any crosshair on a film separation. The primary and secondary color banding that surrounds the pixel is theoretical to the extent that isolated pixels do not occur in the database of the image and what color banding might occur is determined by the color signatures of adjacent pixels. The key lies with one's perception of the final image and the color dominance of the individual pixel.

With the 79 meter resolution of early Landsat multispectral images and the 50 micron spots of contemporary film recorders, the registration of film separations required only a bit of practice and a reasonably steady hand. Nevertheless, the availability of acceptable satellite imagery was limited to only a very few laboratories. Within the next two years, commercial satellites will provide data to challenge the most precise of registration procedures. The registration of film separations written with spot sizes as small as 10 microns will require a whole new level of control over the entire sequence of image production. Even very high resolution films with extremely fine grain structure produce a line that under 100x magnification resembles a statistician's scattergram. The comparative measurement of a composited color pixel with its black-and-white counterpart requires film with the apparent contradiction of high resolution and a long tonal range to accomplish the task.

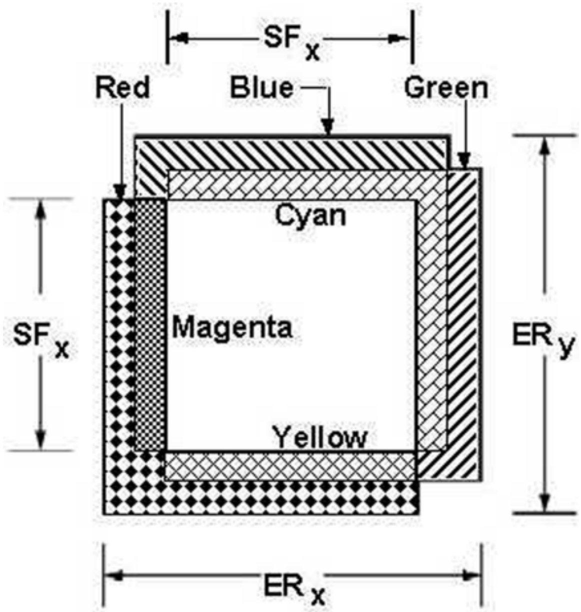

Figure 1. A composited white pixel with SF.64 / ER 120%

The validation of a satellite digital photograph means that the *measured* survival of the color palette, the *measured* significance of the color signatures, and the true spatial resolution of the image based on the comparative *measurements* of single band and composited pixels be reported faithfully to the image analyst and photo interpreter. The accuracy and interpretative value of a satellite photograph generally requires some form of a ground-truth program where in situ measurements are obtained with surface and airborne instruments operating over the area of the satellite image.[17] It follows, therefore, that the reliability of ground-truthing depends on the reliability of the image under study. Fraudulent satellite photography does more than threaten the legitimacy of ground-truthing, it introduces the probability of spurious interpretations based on the distorted remnants of the original imaging database.

Conclusion

When satellite digital photography became a commercial reality with the launch of Landsat 1 in 1972, quality control was left to the few laboratories who ventured into the production of the 79 meter 6-bit multispectral images. Any similarity of satellite photographs from different labs working with the same data was purely coincidental. Satellite photography was a new ball game without a rule book. The assumption of standard commercial photographic procedures extended to the NASA lab at the Goddard Space Flight Center and the source of Landsat data at the Government's Eros Data Center in Sioux Falls. Private labs, such as those belonging to oil and gas exploration companies, acquired data and produced their photographs without reference to an operational standard that would confirm the accuracy of their effort. Image enhancement algorithms were developed to improve a database whose content was never fully displayed. Data was manipulated, truncated, and generally abused without anyone seeing the original image transmitted by the satellite. In the rush to computer enhancements and electronic color displays, little attention was paid to extended range processing and registration procedures that, even then, were essential to authentic and reliable full-color satellite digital photography.

Twenty-seven years later the photogrammetric and remote sensing communities are anticipating the launch of advanced digital imaging satellites that will provide 1-meter panchromatic, 4-meter multispectral, and 8-meter hyperspectral data.[18] The evolution of virtually every aspect of the hybrid technology of satellite digital photography will have occurred *except* the practice of photographic hardcopy production that will stand the test of validation. In the absence of that capability, objective measurement will yield to inference, ground-truth expeditions will be suspect, and individual photographic laboratories will continue to produce their rendition of popular satellite images. That condition is not acceptable.

Concern for the perceptual capabilities of human vision to detect differences in a palette of nearly 17 million colors or a gray scale of 256 steps ignores the arrangement of pixels in a satellite photograph that establishes its spatial and radiometric resolution. Pixel values in an image are not distributed with the ordered ascendancy of a step wedge. Higher and higher resolution images are worth the effort to acquire them because the adjacency of one pixel value with another throughout the image is the basis for the discrimination of terrestrial features. McCann's discussion of color theory and the psychology of color sensation makes the point that vision does not depend on the responses to a single pixel but depends, instead, to relative responses all across the field of view.[19] At the common map scale of 1:250,000, single pixels in a Landsat or SPOT image cannot be seen without selective focusing and large spot sizes in the film recorder. But the perceived comparative resolution of two versions of the same image will favor the one whose discrete pixel resolution exceeds the other.

Much time, effort, and resources have gone into the acquisition of satellite digital imaging data. A corresponding effort to elevate the practice of satellite digital photography is long overdue. The technology to meet the challenge of preserving the image in the digital-to-analog conversion is available now.

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