Digital image processing for speckle images
by Rodney D Huffman

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer Science
Montana State University
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Abstract:
The turbulent atmosphere makes it virtually impossible to image objects using conventional stellar photography. Various digital techniques have been developed to reconstruct the actual object from a series of short exposures. A. Labeyrie discovered a way to resolve angular distances for simple star patterns by computing the average autocorrelation from the snapshots. Because all phase information is lost from computing the autocorrelation, distances may be resolved but the object cannot be imaged. Imaging techniques have been developed for both the spatial and frequency domains. The Knox-Thompson and Input-Output algorithms estimate the phase for a given modulus. Other methods, such as shift-and-add, process the speckle images in the spatial domain. The shift-and-add method has been used to obtain diffraction limited images for objects containing a point that is much brighter than the other points. The shift-and-add process sometimes fails to properly align the images, resulting in "ghost" stars and other false images. This thesis reviews various techniques and describes the process by which they may be implemented. A software package was developed and instructions are given concerning its use in implementing those techniques.

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of

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ABSTRACT

The turbulent atmosphere makes it virtually impossible to image objects using conventional stellar photography. Various digital techniques have been developed to reconstruct the actual object from a series of short exposures. A. Labeyrie discovered a way to resolve angular distances for simple star patterns by computing the average autocorrelation from the snapshots. Because all phase information is lost from computing the autocorrelation, distances may be resolved but the object cannot be imaged. Imaging techniques have been developed for both the spatial and frequency domains. The Knox-Thompson and Input-Output algorithms estimate the phase for a given modulus. Other methods, such as shift-and-add, process the speckle images in the spatial domain. The shift-and-add method has been used to obtain diffraction limited images for objects containing a point that is much brighter than the other points. The shift-and-add process sometimes fails to properly align the images, resulting in "ghost" stars and other false images. This thesis reviews various techniques and describes the process by which they may be implemented. A software package was developed and instructions are given concerning its use in implementing those techniques.

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CHAPTER 1

WHAT IS DIGITAL IMAGE PROCESSING?

A Historical View

Image processing has been performed on digital computers for over 20 years. NASA first used digital image processing techniques to analyze images of the lunar surface. The Surveyor missions in the 1960s produced thousands of lunar images to evaluate landing sites for later manned missions. Later, NASA applied digital imagery to view other planets. The Voyager spacecrafts were launched in 1977 and provided the first color close-up images of Saturn and Jupiter.

Digital image processing proved to be a success in space exploration, so NASA extended its use in imaging the earth's surface with the LANDSAT series, which started with the launching of LANDSAT 1 on July 23, 1972. These satellites were equipped with digital multispectral imaging systems and were originally intended for agricultural applications. Four spectral bands (green, red, and 2 near infrared) were selected based on agricultural needs, where they were found to be useful in monitoring crops and soil moisture content. Another earth-orbiting series of satellites is the GOES series that provides images used in weather forecasting and weather pattern analysis.

Digital image processing has not been limited to astronomic and atmospheric applications. Its use has been very important in medical applications as well. Digital imagery has been combined with pattern recognition techniques to classify chromosomes [15]. It has also been useful in Radiography, where X-ray images are enhanced and averaged to accentuate relevant portions in the images.

Digital Image Processing Components

A typical digital image processing system consists of a vision component, a processing component, and a display component.

Vision Component

This component involves the conversion of a real scene into a form that can be interpreted by a computer. For a digital computer, continuous images must be converted into discrete samples. There have been a number of digital camera systems developed over the years.

The two Viking spacecraft were equiped with Vidicon tube systems [15]. With this system, an electron beam scans a charged surface that is charged as a result of its sensitivity to light. The electric charge produced at a particular point is proportional to the amount of light detected at that point. Unfortunately, this system introduces a certain amount of distortion in its images. Geometric distortion is introduced as a result of the electron beam's non-linearity. "Leaking" also occurs with this system where charges deteriorate before they are scanned.

Charge Coupled Devices (CCDs) have become popular image devices. A CCD is a solid-state device comprised of a fixed array of potential

wells. A potential well accumulates charge proportional to the amount of light it detects. The wells are then read sequentially through an analog-to-digital converter. CCDs have many advantages over Vidicon systems. Their spectral response is broader and they are very sensitive to small changes in light. They are also smaller and require no electron beam.

Video digitizers are used to acquire data from conventional television signals. The signal is transmitted at a high rate where one frame (typically a 512 by 525 matrix of pixels) is sent in one-thirtieth of one second. It is the task of the video digitizer to grab a frame from the analog signal, digitize it, and make the digitized form available to a host computer for processing.

Display Component

This component involves the display or presentation of an image after it has been acquired, digitized, and processed. A common visual display unit is the video monitor. A video monitor reads data directly from memory. Images are stored in memory in the form of an array composed of many digital elements called pixels. A pixel is the smallest conceptual information unit and designates a single point on the video screen. Each point on the screen maps to a unique location in memory. A video monitor reads the contents of memory and converts its digital readings to an analog signal which causes an electron beam to excite a photosensitive substance that coats the display screen. Video monitors typically refresh a full screen every thirtieth of a second. An image is usually transfered from memory in a host computer to private

memory for the video monitor. The video memory can also be manipulated through commands from the host computer. What is transferred and when it is transferred is controlled by a user on the host computer.

There are several devices that can be added to a video display system to aid in input and or output. Character and vector generators make it easier for a host computer to create sophisticated graphics. Trackballs, joysticks, and tablets are typical input devices to complement the usually standard keyboard.

Hard-copy devices have been developed to acquire relatively quick results compared to film processing. However, their quality of imagery is poor. On the other hand, images can be photo-processed and printed to produce higher quality images but processing time is much longer.

Processing Component

This component processes the data acquired by the vision component. The continuous image is digitized by the vision component yielding a form that can be processed by a computer. Among the three components, this component more directly involves the topic of this paper.

A typical image as seen by a computer consists of a two dimensional array of discrete quantities. Each point in the array (called a pixel) represents a unique point in the image and their binary values denote degrees of grayness. The human eye can only resolve approximately 40 shades of gray, but a computer, with a pixel size of 8 bits, can represent 256 shades of gray. The micro-based image processing system (MIPS) in the Electrical Engineering Department at Montana State University has a gray level accuracy of 6 bits (0 to 255 in steps of 4).

Any distortion caused by the vision element can be corrected in the processing element. An example of this is where lunar images acquired by the Mariner spacecraft were corrected to compensate for the geometric distortion produced by the camera systems. In this case, a program was executed to perform a simple geometric transformation.

Images can also be enhanced to accentuate desired portions. Supervised and automatic contrasting techniques have been developed to bring out detail that is barely resolvable to the naked eye prior to processing. Most enhancing procedures involve the image histogram which is simply a distribution function of the number of pixels with respect to gray level. Contrasting techniques broadens the gray range for images that have little range, resulting in more discernable detail.

Digital image processing is not limited to image enhancement. It is a useful restoration tool as well, which is the topic of this paper. Where enhancing techniques produce distorted versions of the actual object, restoration techniques perform the contrary operation of producing a true image from one or more degraded images. If enough a priori information is known about an object, images of that object can be analyzed and processed to produce images that more closely resemble the actual object. For example, if the instantaneous point spread function were known, a severely blurred image can be deconvolved to produce a truer image of the actual object. This paper discusses restoration techniques using multiple images of the same object.

Besides processing images, this element must also contain resources for storing the images to be processed. Random accessed memory (RAM) may be adequate for processing techniques that require only a single

image, but techniques that process multiple images require more storage. A more practical storage medium is disk storage (hard and or floppy). Both images and programs can be stored on disk and the disks can be interchanged to provide virtually an unlimited amount of storage. A storage medium that is both inexpensive and ideal for archiving images is magnetic tape. A good digital image system should have sufficient computing and storage facilities.

Software

So far much has been discussed concerning the hardware architecture of such a system but nothing has been mentioned about the software. A typical system should include programs for enhancing images, where supervised and automatic contrasting programs can be used. Geometric transformation programs can also be included to compensate for distortion inherent in images of curved surfaces. Geometric transformations were performed on many of the space images to compensate for the distortion induced by the camera systems.

Support programs should also be a part of the software package. In many cases it is desirable to zoom in on certain portions of an image or to shift portions around on the visual display. Overlay capabilities are desirable where a user may want to superimpose images to measure the amount of correlation, or may want to superimpose a grid pattern over an image to measure distances.

Fast-Fourier-transform programs provide an excellent imaging tool for both restoration and enhancing techniques. If the system does not contain floating point hardware, efficient software routines should be

written to support these programs.

Access to the various software programs should be simple, and the programs should be "user friendly". There should be as little redundancy as possible. Thus, input and output should be standardized so that related programs may be executed in sequence.

A Specific Image Processing System

The Electrical Engineering Department at Montana State University has a micro-based image processing system. The main computer system consists of an Intel 8080 microprocessor and 64K bytes of RAM memory. For I/O, the system contains a keyboard, a black-and-white video monitor, and a dual floppy disk unit. The system contains a video camera for input and a video recorder for input or output. The display element consists of a black-and-white television monitor. The system also contains a video digitizer to convert an analog signal to digital form and a digital-to-analog converter to convert a digital image to an analog signal to be transmitted to the television monitor.

To aid in processing and storing, the micro system is linked with a VAX 780 system thru a serial port. All the programs for this paper were written for the VAX system and the language used was FORTRAN 77. A diagram of the whole system is shown in figure 2.

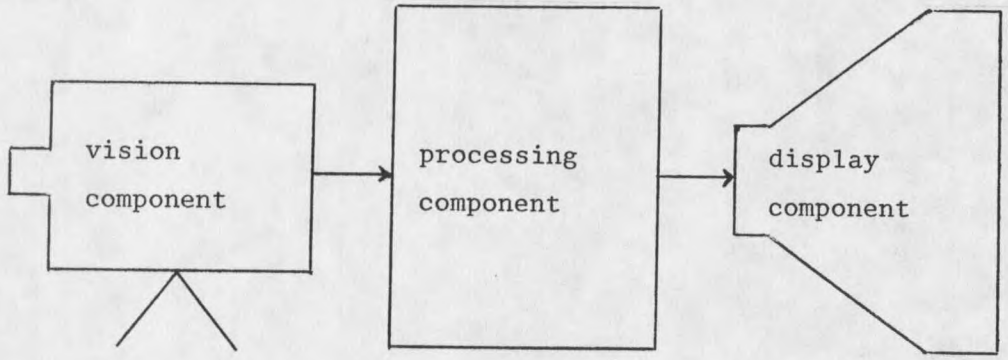

Figure 1. Conceptual diagram of an image system.

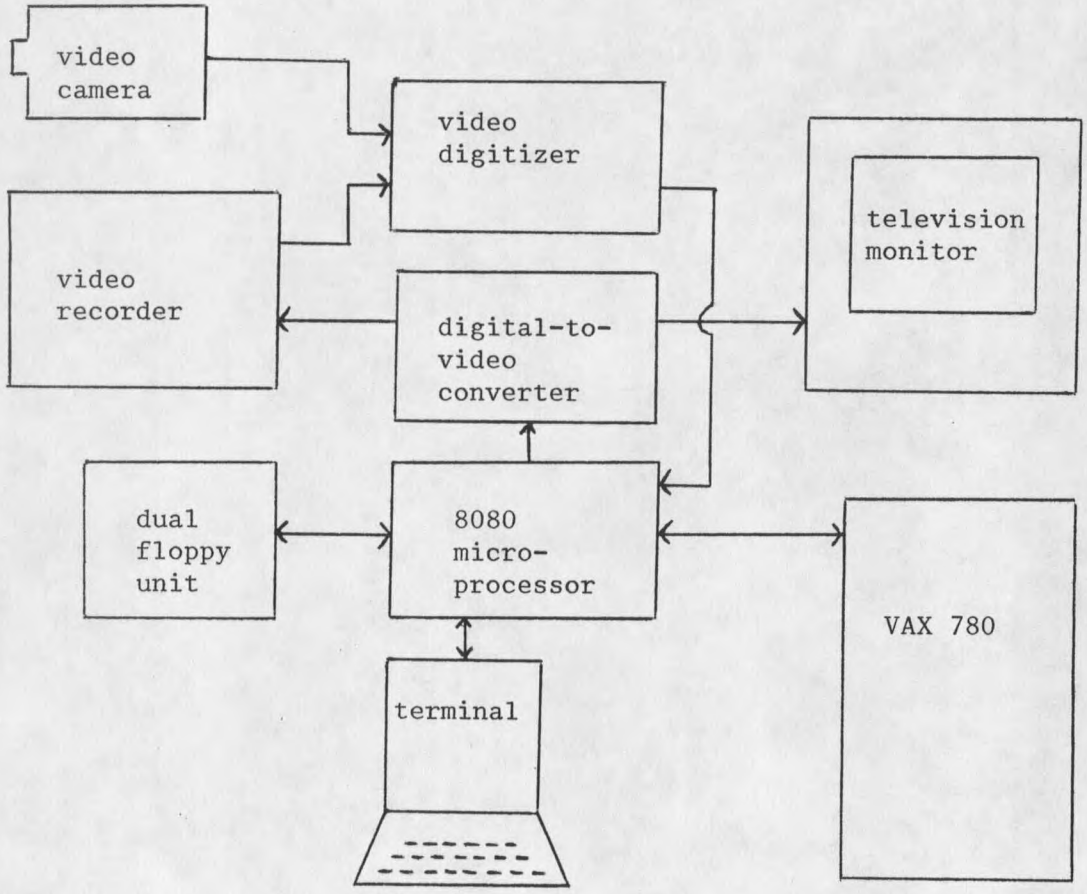

Figure 2. Diagram of the image system at Montana State University.

CHAPTER 2

IMAGING THROUGH THE ATMOSPHERE

Conventional stellar photography requires long exposure times to gather as much light as possible. A long exposure of a point star produces a severely blurred image that is much larger than the actual point star. The blurred region is often referred to as the seeing disk and is the result of the turbulent atmosphere. Images of multiple stars are so severely distorted that the actual stars cannot be resolved. However, it was discovered that short exposure photography (a few milliseconds) contains detail out to the diffraction limit of the telescope. So images that were once only resolvable through interferometry are now resolvable by taking a series of snapshots through a telescope with its aperture fully dialated. This chapter presents and discusses the major sources of distortion, namely the atmosphere and the telescope.

Fraunhofer Diffraction

Fraunhofer diffraction is a significant phenomenon in the field of astronomy. It describes the interfering effects of radiation waves as they penetrate an aperture, where the wave fronts are parallel to the plane of the aperture. Light radiation emitted from a point source, infinitely far from a circular aperture, penetrates the aperture and strikes a plate positioned at the focal point of the lens with an

intensity distribution spread out in concentric rings with a bright central disk. The intensity of the diffraction pattern decreases as the distance from the center of the disk increases. The dotted line in figure 3 shows the nature of a typical diffraction pattern in one dimension.

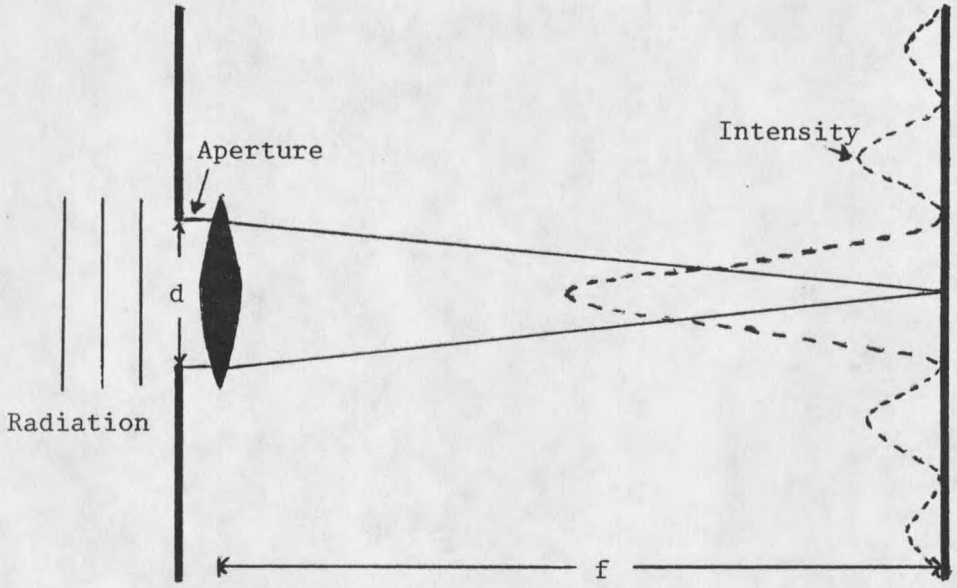

Figure 3. Fraunhofer diffraction.

More precisely, the intensity distribution is given by the formula,

$$I(\phi) = I(0)\left[\frac{2J_1(\pi d\phi/\lambda)}{\pi d\phi/\lambda}\right]^2 \qquad (1)$$

where ϕ is the angle between the intensity line and the axis, d is the diameter of the aperture, λ is the radiation wavelength, and J_1 is the first order Bessel function given as

$$J_1(\pi d\phi/\lambda) = (1/2\pi)\int_0^{2\pi} \cos(\phi - (\pi d\phi/\lambda)\sin\phi)d\phi \qquad (2)$$

The first dark ring is located at $\emptyset=1.22\lambda/d$, as shown in figure 4. The central disk, commonly referred to as the Airy disk, was first derived by Sir George Biddell Airy [18].

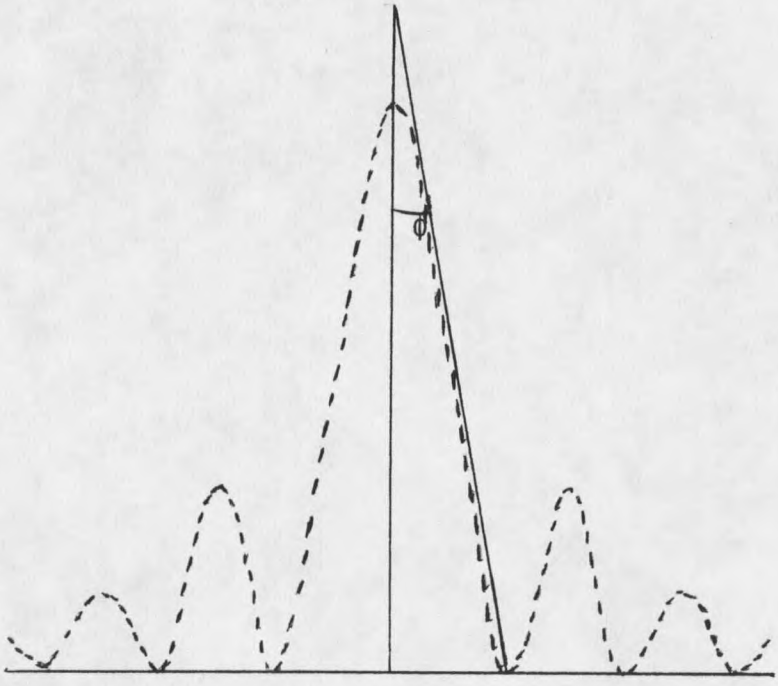

Figure 4. Airy disk.

Resolution

Now consider two point sources, a and b, that are emitting coherent radiation (in phase with each other). What would be displayed on the plate, in this case, is the overlay of one diffraction pattern on top of the other as shown in figure 5. As the points are drawn closer together, more overlap is observed in their diffraction patterns, making it harder to resolve the two points. Thus, two points are more easily resolved as the angular distance between them increases.

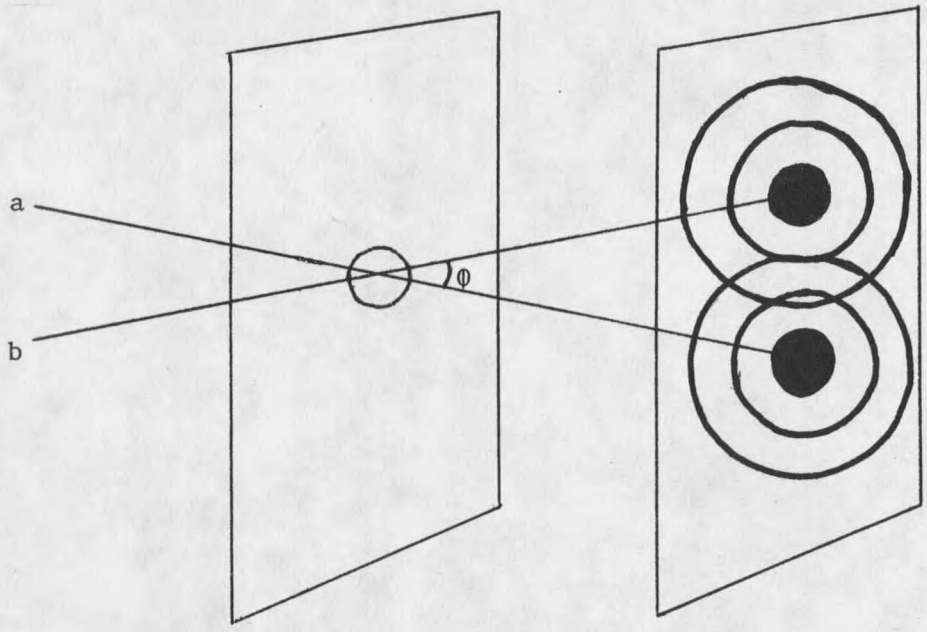

Figure 5. Two-point diffraction pattern.

If the center of one pattern is superimposed on the first dark ring of the other, as shown in figure 6, the angle between the two points, known to be equal to $1.22\lambda/d$, is called the Raleigh two-point resolution limit and is used as one way of measuring the resolution capability of lenses. The Raleigh limit is also important in the intuitive sense, stating that resolution can be increased by either increasing the aperture or by passing radiation of a higher wavelength. This is important in astronomical imaging, because not only does a large aperture gather more light (photons), it also increases the resolution, making it possible to observe finer details.