A Digital Imaging System
For Auroral Processes

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by

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Saskatoon, Saskatchewan
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ABSTRACT

The All-Sky Camera (ASC) system produces images which are used to study auroral processes. The video-cassette recorder-based ASC used by the Institute of Space and Atmospheric Studies at the Rabbit Lake, Saskatchewan field site from 1991 to 1993 produces analog images which did not utilize the full video resolution capabilities of the system. As well, the analog images degraded with repeated playback of the videotape and the images could not be readily sent to scientists at remote locations.

As an alternative solution, this thesis describes the development, implementation and results of a digital imaging ASC system for auroral processes. The system is a combination of hardware and software which corrects the problems inherent in the VCR-based system and has the capability to acquire, process and store digital images directly at the field site. The digital images utilize the full video resolution capabilities of the ASC, feature improved signal-to-noise ratio over VCR images and facilitate subsequent ease of post-acquisition image processing by scientists.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>COPYRIGHT</td>
<td>i</td>
</tr>
<tr>
<td>PERMISSION TO USE</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>x</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Analog ASC Imaging Systems</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Rabbit Lake ASC 1991 - 1993</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Technological Advances</td>
<td>5</td>
</tr>
<tr>
<td>1.4 Thesis Objectives</td>
<td>5</td>
</tr>
<tr>
<td>2. Digital Imaging System Equipment</td>
<td>9</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>9</td>
</tr>
<tr>
<td>2.2 Optical Assembly</td>
<td>10</td>
</tr>
<tr>
<td>2.2.1 General Description</td>
<td>10</td>
</tr>
<tr>
<td>2.2.2 ISIT Video Cameras</td>
<td>11</td>
</tr>
<tr>
<td>2.2.3 AGC Voltage</td>
<td>13</td>
</tr>
<tr>
<td>2.3 Data Acquisition Assembly</td>
<td>15</td>
</tr>
<tr>
<td>2.3.1 Computer Assembly</td>
<td>16</td>
</tr>
<tr>
<td>2.3.1.1 Video Frame Grabber</td>
<td>17</td>
</tr>
<tr>
<td>2.3.1.2 A/D and I/O Card</td>
<td>19</td>
</tr>
<tr>
<td>2.3.1.3 Timing</td>
<td>21</td>
</tr>
<tr>
<td>2.3.1.4 RAM Drive</td>
<td>23</td>
</tr>
<tr>
<td>2.3.1.5 SCSI Bus and Storage Devices</td>
<td>23</td>
</tr>
<tr>
<td>2.3.2 Time-Lapse VCR</td>
<td>24</td>
</tr>
<tr>
<td>3.0 System Software</td>
<td>26</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>26</td>
</tr>
</tbody>
</table>
3.2 Control Software ................................................................. 26
3.3 Data Compression ................................................................. 31
3.4 Archival of Data to 8 mm Digital Tape .................................. 34
  3.4.1 Archival Software ............................................................. 34
  3.4.2 Archival of Data to Tape and System Power Failures ........... 36
4. Results and Analysis .............................................................. 41
  4.1 Introduction ...................................................................... 41
  4.2 Digital versus Analog Image Quality .................................... 41
  4.3 Sampling .......................................................................... 59
5. Image Intensified CCD Cameras ............................................ 60
  5.1 Intensified CCD Video Cameras ......................................... 60
  5.2 Electrophysics Corporation Intensified CCD Camera System .... 63
6. Conclusions and Future Work ............................................... 69
  6.1 Conclusions ................................................................. 69
  6.2 Future Work ................................................................. 71
7. References ............................................................................. 73
8. Appendix ................................................................................. 78
   A. Software ............................................................................ 78
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4.1</td>
<td>Summary of Effect of Averaging Frames on SNR</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>SNR Improvement Using Different Rxx(k) for Signal Power</td>
<td>56</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>Electrophysics Camera Response to Green (557.7 nm) Light</td>
<td>65</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>ISIT Camera Response to Green (557.7 nm) Light</td>
<td>65</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>Electrophysics Camera Response to Broadband Light</td>
<td>66</td>
</tr>
<tr>
<td>Table 5.4</td>
<td>ISIT Camera Response to Broadband Light</td>
<td>66</td>
</tr>
<tr>
<td>Table 5.5</td>
<td>Electrophysics Camera Response to Red (630.0 nm) Light</td>
<td>67</td>
</tr>
<tr>
<td>Table 5.6</td>
<td>ISIT Camera Response to Red (630.0 nm) Light</td>
<td>67</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Block Diagram of Rabbit Lake All-Sky Camera System 1991 - 1993</td>
<td>4</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Block Diagram of Digital Imaging ASC System</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Block Diagram of ISIT Camera</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>ISIT Camera AGC Voltage Response to Broadband Input Light</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>ISIT Camera AGC Voltage Response to Green (557.7 nm) Input Light</td>
<td>14</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>ISIT Camera AGC Voltage Response to Red (630.0 nm) Input Light</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Digital Imaging Computer Assembly</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Video Frame Grabber Block Diagram</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Spectrum NTSC+ Frame Grabber Pixel Map (One Horizontal Row)</td>
<td>19</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>Buffer/Attenuation Circuit for Camera AGC</td>
<td>20</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Basic Format of Data Storage on 8 mm Tape</td>
<td>24</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>Basic Control Software Flow Chart for ASC</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Data Collection Flow Chart</td>
<td>30</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>Normal Method of Data Archival to 8 mm Data Cartridge</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Filemark Erased After Power Failure</td>
<td>37</td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Tape Archiving Using Spare Sets and Filemarks</td>
<td>38</td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>Fourth Filemark Erased After Power Failure</td>
<td>38</td>
</tr>
<tr>
<td>Figure 3.7</td>
<td>New Third Filemark Written Followed by Blank Tape</td>
<td>39</td>
</tr>
<tr>
<td>Figure 3.8</td>
<td>Power Failure Interrupts Writing of Data Volume Set</td>
<td>39</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>VCR ASC Image (No Filter) December 7, 1994 (4:53:45 UTC)</td>
<td>42</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Digital ASC Image (No Filter) December 7, 1994 (4:53:45 UTC)</td>
<td>43</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>VCR ASC Image (No Filter) December 7, 1994 (5:02:52 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Digital ASC Image (No Filter) December 7, 1994 (5:02:52 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>VCR ASC Image (557.7 nm Filter) December 7, 1994 (5:09:49 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td>Digital ASC Image (557.7 nm Filter) December 7, 1994 (5:09:49 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>VCR ASC Image (630.0 nm Filter) December 7, 1994 (4:58:05 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.8</td>
<td>Digital ASC Image (630.0 nm Filter) December 7, 1994 (4:58:05 UTC)</td>
<td></td>
</tr>
<tr>
<td>4.9</td>
<td>Digital Image of LBS #2 Screen (Single Frame with No Averaging)</td>
<td></td>
</tr>
<tr>
<td>4.10</td>
<td>Image of LBS #2 Screen with 8 Frames Averaged</td>
<td></td>
</tr>
<tr>
<td>4.11</td>
<td>Image of LBS #2 Screen with 64 Frames Averaged</td>
<td></td>
</tr>
<tr>
<td>4.12</td>
<td>Probability Distribution of Quantization Error</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Basic CCD Image Array Schematic</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Generation III Image Intensifier Schematic</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Block Diagram of Electrophysics Camera System</td>
<td></td>
</tr>
</tbody>
</table>
**LIST OF ABBREVIATIONS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Sky Camera</td>
<td>ASC</td>
</tr>
<tr>
<td>Automatic Gain Control</td>
<td>AGC</td>
</tr>
<tr>
<td>Canadian Network for Space Research</td>
<td>CNSR</td>
</tr>
<tr>
<td>Charge Coupled Device</td>
<td>CCD</td>
</tr>
<tr>
<td>Coordinated Universal Time</td>
<td>UTC</td>
</tr>
<tr>
<td>Gallium Arsenide</td>
<td>GaAs</td>
</tr>
<tr>
<td>Industry Standard Architecture</td>
<td>ISA</td>
</tr>
<tr>
<td>Institute of Space and Atmospheric Studies</td>
<td>ISAS</td>
</tr>
<tr>
<td>Intensifier-Silicon-Intensifier Target</td>
<td>ISIT</td>
</tr>
<tr>
<td>International Standards Organization</td>
<td>ISO</td>
</tr>
<tr>
<td>Joint Photographic Experts Group</td>
<td>JPEG</td>
</tr>
<tr>
<td>Low Brightness Source</td>
<td>LBS</td>
</tr>
<tr>
<td>Metal Oxide Semiconductor</td>
<td>MOS</td>
</tr>
<tr>
<td>Microchannel Plate</td>
<td>MCP</td>
</tr>
<tr>
<td>Moving Pictures Experts Group</td>
<td>MPEG</td>
</tr>
<tr>
<td>National Institute of Standards and Technology</td>
<td>NIST</td>
</tr>
<tr>
<td>National Television Standards Committee</td>
<td>NTSC</td>
</tr>
<tr>
<td>Portable Gray Map</td>
<td>PGM</td>
</tr>
<tr>
<td>Signal-to-Noise Ratio</td>
<td>SNR</td>
</tr>
<tr>
<td>Small Computer System Interface</td>
<td>SCSI</td>
</tr>
<tr>
<td>Scandanavian Twin Auroral Radar Experiment</td>
<td>STARE</td>
</tr>
<tr>
<td>Super Dual Auroral Radar Network</td>
<td>SuperDARN</td>
</tr>
<tr>
<td>Universal Coordinated Time</td>
<td>UTC</td>
</tr>
<tr>
<td>Video-Cassette Recorder</td>
<td>VCR</td>
</tr>
<tr>
<td>Video Graphics Adapter</td>
<td>VGA</td>
</tr>
</tbody>
</table>
1. Introduction

The All-Sky Camera, or ASC, is a scientific instrument for ground-based studies of the aurora (also known as the Northern Lights in the Northern Hemisphere). In typical use over the past four decades, the basic ASC system has consisted of a camera pointing down on a convex, parabolic mirror which images the majority of the night sky. The camera is mounted inside a weatherproof casing with electrical heating circuitry for protection against cold environments. The camera and its housing are mounted on top of a tripod or support legs. The mirror reflects light from the majority of the sky up into the camera lens and the camera records images of the sky and auroral activity on a medium such as film or video tape. By using these images of the aurora in conjunction with data from other scientific instrumentation, physicists are able to gain a better understanding of how the stream of particles emanating from the sun, known as the solar wind, affects the earth and its atmosphere.

1.1 Analog ASC Imaging Systems

In the four decades that the ASC has been used by scientists at the Institute of Space and Atmospheric Studies (ISAS) at the University of Saskatchewan, changes have been made to the ASC system to reflect advances in camera technology, computer technology, and recording media. The first ASC systems from 1955 onward were based on 16 mm or 35 mm movie cameras. ASC systems based on such cameras were used well into the 1980’s at various field sites. The cameras were used to record the images of the sky on black and white or color film at a rate of 1 to 8 frames per minute. The exposure times for each image varied from 2 to 60 seconds depending on the type of film used. These 16 and 35 mm cameras were built around
a 30 meter film magazine which could record only a few nights of data. Therefore, frequent intervention was required by a field site operator to change rolls of film [1, 2].

In 1984, an Intensifier-Silicon-Intensifier Target (ISIT) camera with monochrome television RS-170 video output was used for the first time in an ASC by the University of Saskatchewan ISAS group [3]. This camera permitted improved time resolution of the development of auroral activity as it was very sensitive to very low levels of input light. The ISIT camera enabled continuous recording of the night sky at a rate of 60 separate analog video fields per second directly to a video tape via a video-cassette recorder (VCR) [4]. However, this method of recording still had the disadvantage of requiring continuous supervision by a field site operator for maintenance operations such as changing video tapes once or twice per evening of system operation. During winter campaigns at the Rabbit Lake field site, which is located at Collins Bay (58°13' N, 103°42' W) near the west shore of Wollaston Lake in Northern Saskatchewan, the operator usually arrived at the site just after sunset and monitored the recording equipment for about a twelve hour time period. The operator turned on the ASC and the recording VCR during dark hours when the sky was not completely overcast [4, 5].

This television camera-based system was improved by the advent and use of time-lapse video-cassette recorders which extended the recording time on a normal video tape from 6 hours to 24 hours. However, this system still required a site operator to change the video tapes every two days.

1.2 Rabbit Lake ASC 1991 - 1993

In 1991, a personal computer was employed for the first time to control recording of single video fields from the ISIT video camera to a time-lapse VCR. The use of a computer and software to control the recording process permitted tremendous flexibility in achieving time-lapse imaging of the sky. Instead of recording sixty separate images of the night sky in one second in a continuous-record mode or recording the images at a rate fixed by the videocassette controls, the computer-controlled time-lapse VCR permitted recording of one image of the night
sky every three to six seconds depending on the software control settings. Through
time-lapse recording to the VCR video tape, the number of similar images recorded to
a video tape per unit time was reduced but excellent temporal resolution still was
achieved. The computer software also determined the local sunrise and sunset times
for a given geographical location and started the recording process after sunset
without intervention by a field site operator. Therefore, a maintenance visit to the
field site by ISAS personnel was required only approximately once per three weeks
for changing of the video tape.

This system also permitted computer-controlled switching of solenoids to
position green (557.7 nm) and red (630.0 nm) optical filters in front of the video
camera lens to acquire different features of the aurora in addition to the features
shown by spectral broadband images. To prevent damaging light levels from entering
the camera lens, a solenoid positioned a mechanical shutter in front of the lens during
daylight hours under software control. The solenoid also moved the mechanical
shutter in front of the camera lens when bright ambient light levels were detected by a
photocell in the base of the camera assembly. A block diagram of the system used at
the Rabbit Lake field site from late 1991 to early 1993 is shown in Figure 1.1 below.
The optical assembly was outdoors and exposed to the environment. The control
assembly was kept inside a heated trailer approximately 40 meters away.

Despite the advance in auroral imaging capability exhibited by the analog,
VCR-based ASC system, there were still several disadvantages. The first
disadvantage was that the analog video tapes did not provide the best possible spatial
resolution of the aurora. While 30 video frames at 525 lines per frame are scanned
per second in RS-170, each frame is in fact made up of interlaced odd and even fields
(either the odd or the even scan lines from the 525 line video frame). The time-lapse
VCR used in the Rabbit Lake ASC recorded only a single RS-170 video field for each
image. Thus, in reality, only half of the possible resolution existed on each video
image. This is an important consideration when attempting to spatially correlate the
optical data with data from radar-based studies of the aurora.
The second disadvantage was that if a scientific team from another research centre required some of these images, the tape would have to be copied and the new videocassette would be sent by mail or courier. This method of data transmission is inconvenient especially if only a few images are required.

Finally, the analog video signal on the video tapes degrades after repeated playbacks on a VCR due to wear on the magnetic recording tape. The quality of the
data therefore deteriorates. A new method of data storage is desirable to prevent change in image quality with repeated playback.

1.3 Technological Advances

The rapid rise in the rate of development in computer, recording media, and video technology has created new design possibilities. Faster computer hardware in personal computer-based systems was continually being developed while becoming more widely available at lower cost. Faster computer hardware permitted complex processing of large amounts of data at a field site. As well, the availability and capability of the personal computer-based video frame grabber (to digitize a television video signal) steadily increased. Developments in storage media for computer data also permitted greater amounts of data to be stored at lower costs.

As a result of this leap in computer and video technology, it is now possible to take the video signal directly from the video camera, digitize the image on a frame grabber, and store the digital image on a magnetic medium, all at the remote field site. Digital image data from an ASC would be more useful than the analog images on a video tape. It is now possible not only to digitize a full 525 line video frame into a single image for improved resolution but also to perform digital image processing (during and after data acquisition). Digital images are easier to send to other scientists over computer networks. The image quality also does not degrade with repeated playback unless damage occurs directly to the storage media.

1.4 Thesis Objectives

It was the objective of this thesis to design a digital imaging ASC system to overcome the disadvantages explained above in Section 1.2. However, the analog imaging system based on the time-lapse VCR is to be retained since it provides a back-up system for data collection. The digital imaging system is to be run in parallel
with the older analog imaging system such that for each recorded digital image, one corresponding image is recorded by the time-lapse VCR.

Several important constraints, with regards to the development of a new ASC system, were set by ISAS scientists at the beginning of the investigation of this thesis. One constraint was that the digital ASC images should be a minimum of 512 x 480 pixels in size and that the digital images should be stored on the 8 mm, 5 GB EXABYTE tape format directly at the field site since tape drives for this storage medium were widely in use at ISAS for other projects. A second constraint was that visits to the field site by ISAS personnel for changing data tapes and system maintenance should be minimized to approximately one visit per four week period to minimize personnel travel costs. Since the new ASC system should operate unmanned for four week periods, the system should be able to recover properly from power failures at the field site and continue recording images when power was restored. Also, the improvements to the previous ASC system should be minimized in terms of extra monetary expenditures.

Another constraint was that a minimum of one ASC digital image should be recorded every seven seconds during the night-time data-collection period. As well, each stored image should consist of the maximum possible number of images averaged together over as short a time span as possible (within the seven second time limit) to improve the signal-to-noise ratio of each image (where the signal was the desired image of the sky and auroral activity, and the noise was the undesired part of the image which obscured such details). The seven second limit was chosen by ISAS scientists since data obtained from other scientific instrumentation is averaged over comparable time periods. As well, it was desirable to time stamp the image data within one second of a common time reference used by other scientific equipment in order to allow correlation of data collected by different instruments such as radar and magnetometers.

The constraints required that a number of problems be resolved during the course of investigation for this thesis. The choice of 8 mm tapes as a storage medium implied that software suitable for archiving the ASC image data to tape directly at the field site had to be adapted, tested and implemented. As well, controls, used to ensure that the ASC system could continue to collect and store image data on the 8 mm tapes properly upon recovery from field-site power failures, were needed to reduce the number of maintenance visits by ISAS personnel.
The constraints on the type of storage medium, the required data collection periods between data tape changes by ISAS personnel, and the required rate of acquiring images during each night's data collection period restricts the format in which the images could be stored on the 8 mm tape. Since periods of data collection near the winter solstice are about 14 to 15 consecutive hours per day at the Rabbit Lake field site, about 7000 to 8000 images could be collected in a single night. If the field site is visited by ISAS personnel once every thirty days to change data tapes, then up to 240,000 images could be collected. This implies that each collected image must on average be no more than about 22 kB in size. If the image is in an uncompressed format and one byte is used to represent one pixel, then the 22 kB size limitation implies that each image may only be 150 x 150 pixels in size. Since the desired image resolution is 512 x 480 pixels, data compression methods must be investigated to permit storage of images within the given constraints.

Time stamping the ASC image data to a common time reference requires that a clock unit is used to synchronize on a time standard used by other scientific instrumentation. The clock unit must output the time reference on demand from the control computer in a format which can be accessed by the control computer software in order to time stamp the data.

The minimization of monetary expenditures for the improvements to the ASC system prevents the purchase of a video frame grabber board with the capability to integrate digitized video frames directly in hardware. While a video frame grabber with real-time video frame integration could integrate 30 digitized video frames per second, the prohibitive cost of about $5000 US or more in 1993 prevented the use of this type of frame grabber in this thesis project. As a result, a frame grabber of lower cost must be purchased. However, the disadvantage of using a lower cost frame grabber would be that software must be written to integrate the digitized video frames. As a result, the development time for the project would be increased. As well, the maximum number of digitized video frames that could be averaged within the 7 second time constraint would be limited since the software method of performing the integration would be less time efficient than direct integration by a hardware video frame grabber.
One very important issue concerns the life span of the ISIT camera already in use at the Rabbit Lake field site in the current ASC system. While the new ASC system is to continue using the same ISIT camera employed in the auroral studies of 1991 - 1993 at Rabbit Lake, a possible replacement camera should be investigated since ISIT cameras have been known to have limited life spans. In 1993, ISIT cameras could no longer be purchased as a complete unit and only expensive replacement parts (up to about $15000 CDN for an ISIT camera tube for example) could be purchased. One possible replacement for ISIT camera technology involves the solid state camera device known as the Charge Coupled Device (CCD).

This thesis will explore the development, implementation, and testing of a digital imaging system for auroral processes for the Rabbit Lake field site. Chapter 1 provides the introduction for this thesis project. Chapter 2 covers the optical and data collection equipment used for the Rabbit Lake ASC. Chapter 3 explains the control software and processing of the digital data performed at the field site. Chapter 4 discusses the results of the new digital imaging system in comparison to the analog recording system. The tests and results from a new Generation III Image Intensifier and CCD camera-based system are discussed in Chapter 5. Chapter 6 summarizes the thesis and gives suggestions for future work.
2. Digital Imaging System Equipment

2.1 Introduction

In this chapter, the hardware required to perform the digital imaging of the aurora and to store the digital image data is discussed. This equipment is installed at the Rabbit Lake Canadian Network for Space Research (CNSR) Observatory. The observatory building is located at Collins Bay, Saskatchewan (58°13’ N, 103°42’ W) and is next to the airport landing strip for the Cameco Mines uranium mine. The Cameco mining camp is situated about 7 km to the south. At night, airport traffic and automobile traffic (on a nearby road about 100 m east of the observatory building) is minimal. The remoteness of the site provides sky viewing conditions that minimize contamination of the images from artificial light sources.

There are two main assemblies to the digital imaging system for auroral processes. The first assembly is the optical assembly which is exposed to the outside environment. The second assembly comprises the data acquisition and control hardware which is located in the observatory building about 35 meters to the south of the optical assembly. Interconnect cables are used to send control signals from the data acquisition computer to the optical assembly and to send data from the optical assembly to the data acquisition hardware.

A block diagram of the digital imaging all-sky camera system implemented at the Rabbit Lake CNSR Observatory is shown in Figure 2.1 on the next page. The digital imaging hardware was designed as an extension to the previous system based on analog video image recording on video-cassette tapes and therefore, from this block diagram, the system does not seem much different from that shown in Figure 1.1 in Chapter 1. The only two differences at this level are that the video signal is input into both the computer and the time-lapse VCR and a voltage from the video camera, the automatic gain control (AGC) voltage, is input into the computer.
Figure 2.1: Block Diagram of Digital Imaging ASC System

2.2 Optical Assembly

2.2.1 General Description

The optical assembly comprises three main sub-assemblies. These are the mirror-base assembly, the camera housing assembly, and the tripod legs which support the camera housing above the mirror-base.
The mirror-base assembly consists of a parabolic mirror mounted on a hexagonal casing. The parabolic mirror has a nearly hemispherical field-of-view centered on the vertical and extending 85° toward the horizon. The parabolic mirror is 35.3 cm in diameter and has a focal length of 11.1 cm.

The mirror-base houses three manual switches for electrical power, fuses, a photocell, and a heating circuit. The manual switches in the base provide electrical power to the camera, to the heating circuits in the optical assembly, and to the filter and shutter solenoids. There are protection fuses for the solenoids, heaters, and camera. The photocell is a safety device which closes the camera shutter (even if the computer software determines that it should be open) if the light intensity exceeds a critical level. Three metal brackets attach the mirror-base assembly to the three tripod legs.

The mirror-base is connected to three external cables. One cable supplies 120 V AC electrical power from the observatory building. The second cable sends control signals from the data acquisition computer to drive the solenoids to move the shutter and the filters in front of the camera lens. Electrical power and the control signals are sent from the mirror-base up to the weather-proof case via a third cable that is routed through one of the tripod legs.

The weatherproof casing houses the camera, the green and red optical filters, a mechanical shutter, the solenoids to move the filters and shutter in front of the camera lens, and the camera heater circuit. The video signal is sent directly to the data acquisition hardware by a separate coaxial cable. The camera AGC voltage is sent to the mirror-base via the cable routed through the tripod leg. The AGC voltage is then sent back to the computer via the cable which carries the control signals from the computer to the optical assembly.

2.2.2 ISIT Video Cameras

The optical system uses a RCA TC1040/H Intensifier-Silicon-Intensifier Target (ISIT) camera. The ISIT is a two-stage device. A 25 mm, f/1.4 auto-iris objective lens is used to focus light from the parabolic mirror on a first-stage image intensifier tube which amplifies the light intensity. Fiber optics are used to couple the
image intensifier to the second stage which is the Silicon-Intensifier Tube (SIT). Photoelectrons from the first stage intensifier are accelerated and focused on a silicon wafer target consisting of a tightly spaced matrix of PN junction diodes. The accelerated photoelectrons impinge on the target causing multiple dissociations of electron-hole pairs giving a second stage of gain. The generated holes modulate the steady-state current when the scanning beam of electrons is swept across the target. This AC signal is read out through a capacitor [6, 7]. See Figure 2.2 for a block diagram of the ISIT camera.

![Figure 2.2: Block Diagram of ISIT Camera](image)

The gain of the ISIT tube alone is 800:1. Coupled with the f/1.4 auto-iris lens and the camera's automatic gain control circuitry, the automatic light range of this camera is $4 \times 10^9:1$. This camera is suited to extremely low-light level applications such as the detection of aurora. This type of tube provides relatively lag-free video output and minimized blooming effects caused by bright light sources against a dark background within a scene [8].

The scanned, electrical AC signal output from the silicon target forms the basis of the RS-170 monochrome video, which is the same as North American National Television Standards Committee (NTSC) video except that no color information is included. The RS-170 video output is 60 interlaced fields per second. This practice of scanning the odd numbered lines for one field followed by scanning the even numbered lines for the next field reduces image flicker. Therefore, a
complete RS-170 525 line, full-resolution frame is scanned every 1/30th of a second [9, 10]. However, of these 525 horizontal lines, only 483 are usable for image information. The reason for this is that the bottom 21 lines of each field (or bottom 42 lines of each frame) are used for synchronization signals and testing purposes [11].

Despite the excellent sensitivity of the ISIT camera, there are some disadvantages. The first is that the ISIT camera is no longer manufactured (although the ISIT tubes are still available at camera service centres.) If the ISIT tube should fail, then the only recourse is to have the tube replaced at an estimated cost of about $15000 Canadian in 1994 when the original complete camera and lens was purchased for about $15000 Canadian in 1991. The tube is also large and fragile because of the evacuated glass enclosure.

2.2.3 AGC Voltage

The camera's automatic gain control (AGC) voltage, which changes with varying input light intensity, is recorded by the data acquisition computer. For each image acquired, a corresponding AGC voltage value is saved to a computer text file.

Graphs of AGC voltage versus input light intensity were generated by calibration tests using Low Brightness Source (LBS) #2 from the ISAS Optics Lab. LBS #2 is a calibrated light source with known output levels in the broadband optical spectrum, the 557.7 nm (green) line, and the 630.0 nm (red) line. For the 557.7 nm and 630.0 nm lines, optical transmission filters with 10 nm bandwidths were used. A 100 times attenuation neutral density filter was used for broadband testing. The camera was pointed at the screen of this calibrated light source such that the light input into the camera was of uniform intensity across the field-of-view. The appropriate optical filter was placed in front of the camera lens. Sheets of black cloth were used to minimize contamination of the LBS output by external light. The intensity of the light input into the camera lens was varied in kiloRayleighs (kR) where one Rayleigh is $10^6$ photons per cm$^2$-second. The following graphs (Figures 2.3, 2.4, and 2.5) show the response of the AGC versus input broadband, green (557.7 nm), and red (630.0 nm) light intensity.
Figure 2.3: ISIT Camera AGC Voltage Response to Broadband Input Light

Figure 2.4: ISIT Camera AGC Voltage Response to Green (557.7 nm) Input Light
Using the recorded AGC value to find the particular light intensity for a given auroral arc is unsound. The calibration tests used light that was uniform in intensity across the field-of-view for the camera. In the field operation of the system, aurora occurs as bright streaks or arcs in a small portion of the image against a dark background. As a result, correlation of a recorded AGC value to the intensity of an auroral arc in an image is not recommended. However, the AGC values may be used to check for time periods where images with bright objects (such as aurora, the moon, etc.) were collected.

2.3 Data Acquisition Assembly

The data acquisition assembly is comprised of two major sub-assemblies. One of these is the computer assembly which performs the conversion of the images
to a digital form and stores the digital images on a permanent medium. The other is the time-lapse video-cassette recorder which stores the images in analog form as in the previous ASC system.

In this section, the computer hardware assembly is discussed in detail. A brief discussion on the continued use of the older analog image recording system (based on the video-cassette recorder) is included as well.

2.3.1 Computer Assembly

Figure 2.6 below shows a block diagram of the major components of the control computer assembly. The basic computer system consists of an Intel 486 DX-50 microprocessor (which runs at 50 MHz) with 8 MB of RAM, a 16 bit ISA bus, and a VGA graphics card. The additional hardware required to perform the digital imaging of the aurora are a 512 x 480 pixel 8 bit video frame grabber, an A/D and digital I/O Card, an external clock unit, and a Small Computer Signal Interface (SCSI) bus with a 420 MB Hard Drive and a 5.0 GB 8 mm digital tape drive.
2.3.1.1 Video Frame Grabber

The frame grabber, the most central item to the digital imaging hardware, performs the digitization of the analog video signal. In this system, the frame grabber used is a Redlake Spectrum NTSC+. It digitizes the incoming video signal, either in field mode (one video field per 1/60th of a second) or frame mode (one video frame of two interlaced fields every 1/30th of a second), and displays the digitized video.
image on the computer screen, all in real-time. The Redlake Spectrum NTSC+ frame grabber does not permit real-time integration of video frames under hardware control but the cost of $2000 US in 1993 (as compared to estimated $5000 US for a comparable model with hardware real-time video frame integration capability) helps minimize economic expenditure for the project. A simplified block diagram of the frame grabber is shown below in Figure 2.7.

![Video Frame Grabber Block Diagram](image)

The Spectrum NTSC+ can digitize and display color (NTSC) or monochrome (RS-170) video signals. This frame grabber uses two bytes for each pixel. See Figure 2.8 below. If the incoming video signal is NTSC, the low byte of each pixel contains green (G) information and the high byte contains alternating red (R) or blue (B) information. This scheme for the pixel map is shown below for one 512 pixel horizontal line.
If the incoming video signal to the frame grabber is RS-170, then the 8 bit gray scale information is contained in the low byte of each pixel and the high byte in each pixel contains a zero. This is the scheme of interest for the Rabbit Lake ASC.

The RS-170 monochrome video is input into an 8 bit A/D conversion block. An input lookup table (LUT) is used to modify the contrast and brightness of the image according to software set values. The digitized video images are then stored in the two frame buffers. Each frame buffer is 512 x 512 pixels in size but horizontal lines 481 to 512 consist of only the vertical synchronization signals in the video. Therefore, no actual image information is contained in those lines. Each of the frame buffers is 512 kB divided into 16 banks of 512 x 32 pixels. In each frame, the useful monochrome image information occupies only the low byte of each pixel and the first 480 horizontal lines, thereby permitting a resolution of 512 x 480 pixels as required by the resolution constraints on the image data.

Frame buffer 1 contains the latest digitized image and frame buffer 0 contains the previous image [12]. Software control of registers on the frame grabber determines which bank of the selected frame buffer is memory mapped into the computer's I/O address space. Control software may access the pixel values from this memory mapped location to provide further processing. The digitized image goes through output lookup tables for software-set zoom and pan functions. Before the image is output to the computer monitor, text and graphics may be overlaid onto the image from the VGA graphics card.

2.3.1.2 A/D and I/O Card

The A/D and I/O card is a Keithley Metrabyte DAS-4. It provides three input and four output digital bits at TTL voltage levels (0 to 5 volts). Three output digital
bits are used to control the solenoids that move the mechanical shutter and optical filters in front of the camera lens in the optical assembly. The fourth output digital bit controls the single-shot record mode of the time-lapse VCR. The digital output lines are connected directly to the solenoids and VCR since these devices operate at TTL voltage levels.

The DAS-4 also has 8 analog input A/D channels at 8 bits of resolution. The input range of the A/D is ±5 volts [13]. Only one channel of analog input is used to digitize the AGC voltage from the Camera. Since the AGC voltage ranges from about -7.0 volts to about +11.0 volts, a buffer and attenuation circuit is used to condition the AGC voltage before it is input to the A/D, as shown in Figure 2.9 below.

![Buffer/Attenuation Circuit for Camera AGC](image)

Figure 2.9: Buffer/Attenuation Circuit for Camera AGC

All of the operational amplifiers used in the buffer/attenuation circuit are National Semiconductor LM741 (or Texas Instruments uA741M which are direct replacements) [14]. IC1 and IC2 are configured as voltage followers to provide a high input impedance (of about 2 MΩ) to minimize loading of the camera electronics.
by the A/D electronics. The inverting differential amplifier (consisting of IC3 and resistors R1 to R4) then attenuates the voltage by a factor of 3.27. This attenuation factor was found experimentally. After the voltage has been attenuated and digitized, it is multiplied digitally by the above factor to correspond with the voltage measured at the camera AGC output. This corrected AGC voltage is recorded to the computer text file for each image acquired.

2.3.1.3 Timing

In attempting to relate data and events from the ASC images with data from other scientific instruments such as radar, the issue of timing becomes important. For a single event, all instruments of interest should use the same time reference. However, costs of the timing clock increase rapidly as a system requires greater accuracy. To have all of the instrumentation using clocks with an accuracy to within $10^{-6}$ seconds of the same time reference is impractical and next to impossible due to delays in signal propagation.

The time reference known as Coordinated Universal Time (UTC) as set by the National Institute of Standards and Technology (NIST) is generally used by most scientists for the study of space phenomena. For the Rabbit Lake ASC, it is desirable to have the data within plus or minus one second of UTC. Although this range of accuracy in time stamping the data is practical, this stipulation still provides difficulties in timing if the internal hardware clock of the ASC computer is to be used. The internal clocks supplied with most personal computers are not very accurate and drift by large amounts. For example, the internal computer clock in the Rabbit Lake data acquisition system drifts 17 seconds or more per day when uncorrected.

One solution of the timing problem is the use of UTC information broadcast by NIST. WWV, a 10 MHz radio signal broadcast from Fort Collins, Colorado (40°41'N, 105°02'W), is one such station which broadcasts UTC information. With WWV, not only is there a voice announcement of the time but there is also tone information which can be decoded by electronic hardware to give the UT. The beginning of each hour is signaled by a 0.8 second long, 1500 Hz tone. The beginning of each minute is signaled by a 0.8 second, 1000 Hz tone. Each second (except the 29th and 59th) of each minute has 100 Hz ticks.
The digital imaging system uses an external hardware clock unit which can decode the timing information from WWV. The external clock unit is a Heath GCW-1001 Most Accurate Clock II which cost about $500 CDN in 1993. It is capable of decoding the WWV radio signal information automatically and outputs the UTC information on LED digits on the front face of the clock. It continually adjusts itself for accuracy within ten milliseconds of UTC during good radio reception and maintains high accuracy during poor signal conditions. The clock must receive one to three uninterrupted minutes of valid time information to properly lock in and display UTC with an accuracy of ten milliseconds [15]. When radio reception is poor and no valid time information can be decoded by the external clock, it outputs a time which is accurate to within 0.25 seconds (of UTC) per day. Normally, this is not a problem as WWV can be decoded several times per day. A 9 V DC battery is used to maintain the time output of the clock unit in case of short power failures.

An RS-232 serial interface allows the data acquisition computer to access the UTC information by sending a command to the GCW-1001 clock via software control. The information from the GCW-1001 clock is used not only to time stamp the digital images but also to set the computer clock continually. Therefore, if communication with the external clock is lost temporarily, the computer clock may be used for a short period of time with reasonable accuracy. Such a situation would happen when an extended power failure occurs at the field site and the backup 9 V DC battery has been depleted. When the line power is restored, the GCW-1001 clock will not output any time until it is able to decode WWV. Until the external clock decodes WWV properly, the computer clock is used as the time reference.

Other time types of systems using the UTC reference such as the Global Positioning System (GPS) were investigated as well. However, although GPS clock hardware cards with interfaces to personal computers were available, most cards did not permit the request of current UTC information on demand which is a feature required to properly time stamp the image data. Furthermore, GPS clock cards cost a minimum of $1000 CDN in 1993 and the high cost relative to the Heath GCW-1001 unit, deterred further investigation into this technology.
2.3.1.4 RAM Drive

A 2 MB block of the total of 8 MB of RAM in the Rabbit Lake ASC computer is allocated to create a RAM drive. This 2 MB RAM drive acts like any other disk drive to the system except that no mechanical moving parts are involved and therefore, access to any files on the RAM drive is much quicker. In order to speed up the data acquisition process, this RAM drive is used in the compression of each raw digital image file. Please refer to the discussion of software operation in Chapter 3 for more information.

2.3.1.5 SCSI Bus and Storage Devices

The final storage medium for the ASC digital images at the field site is the 8 mm data cartridge tape. This medium was chosen for convenience and compatibility reasons since a number of devices which write to and read from this medium are already in use by other data acquisition systems in the ISAS group.

All 8 mm cartridge tape data drives use the Small Computer System Interface (SCSI) bus. SCSI is a parallel I/O bus which provides a host computer with device independence within a class of devices. Therefore, different tape drives, disk drives, printers, and communication devices may be added to the host computer without major modifications to the system hardware or software [16]. An adapter card must be installed in the host system to adapt the SCSI bus to the host bus. In the Rabbit Lake ASC computer, the SCSI Bus adapter is an Adaptec AHA-1540C/1542C [17]. It plugs into a regular Industry Standard Architecture (ISA) bus which handles 16 bit wide data and 24 bit addresses.

At the field site, the tape drive used for archiving the digital image data to the 8 mm cartridge tapes is an EXABYTE EXB-8500. Included in the EXB-8500 are read/write/erase electronics, a Sony tape transport mechanism, and control electronics. The EXB-8500 can write up to 5.0 GB of information on a standard 8 mm data cartridge with 112 m of magnetic tape. The data to be archived are assembled as one volume set and written out to the cartridge in 1024 byte data blocks. In the digital imaging ASC system, one volume set of data normally consists of images from a single night (sunset to sunrise). A filemark is written to tape after each
volume set of data so that a particular volume set of data can be located quickly. Data may only be appended to the end of a filemark that is followed by blank tape. Data cannot be written over tape which already contains data [18]. Figure 2.10 below shows this method of writing information to the 8 mm data cartridge.

![Figure 2.10: Basic Format of Data Storage on 8 mm Tape](image)

Also connected to the ISA to SCSI bus adapter is a 420 MB SCSI hard disk drive which stores the images as they are collected over one night. The images are deleted from the hard disk after they have been archived to the 8 mm tape. The hard disk also contains a permanent copy of the control software required to operate the ASC system.

### 2.3.2 Time-Lapse VCR

The video-cassette recorder is a Panasonic Time Lapse Recorder Model AG-6720A-P [19]. The VCR is set to slow play (SP) and runs in one-shot time lapse mode (i.e. the VCR records one video field at a time on command from the control computer). A video field (with the equivalent horizontal resolution of 300 vertical TV scan lines) is recorded to video tape when a low (0 Volt) pulse of 250 milliseconds is sent from the control computer to the VCR "one-shot" input. The VCR is also used to insert the time and date into the VCR tape pictures. A Panasonic TR-930CB video monitor is used to display the video signal from the camera.

Although the digital imaging hardware is a significant improvement upon the analog imaging system, the VCR is still maintained as a part of the ASC system and runs in parallel with the digital imaging hardware. The system is set up such that, for each digital image recorded, a corresponding VCR image is also acquired. One
reason for this mode of operation is that the VCR provides a robust method to supply a back-up of the data if the digital images cannot be archived properly. The second reason is that the videotapes provide scientists with a quick-look option which allows them to view the general auroral activity in the sky before choosing specific digital images for extraction from the 8 mm digital tapes.
3. Software and Data Processing

3.1 Introduction

In the previous chapter, the hardware of the digital imaging system was discussed. Next, the software used for the digital imaging system is described. The software determines how the acquired images from the frame grabber are processed at the field site. There are three main areas to be considered.

The first consideration is the software which controls the imaging hardware and the data acquisition process. The second consideration is the data compression of the acquired digital images. The final topic of this chapter is the software for writing the compressed data onto 8 mm data cartridges at the field site.

3.2 Control Software

The executable control software which operates the digital imaging system automatically is called RABBIT40.EXE [20, 21]. RABBIT40.EXE runs under MS-DOS (Disk Operating System for IBM PC-compatibles) in version 5.0 or higher only. It oversees all aspects of the day-to-day running of the All-Sky Camera system with minimal intervention by a site operator and collects the data in digital and analog (video-cassette) format. The software determines the data acquisition period of each day, controls the type of optical filter to be used in acquiring a particular image, the compression of each acquired image, and the storage of the images on the appropriate media.

The source code for RABBIT40.EXE was written in Pascal and 8086 Assembly language [22]. It was compiled using Borland Turbo Pascal 7.0 for MS-DOS 5.0 [23]. The source code also includes external Pascal software units which were obtained from software coded by other scientists at ISAS or from public domain
File Transmission Protocol (FTP) sites. These external units include: COMM_TP4.PAS (used for RS-232 communications with the Heath GCW-1001 external clock unit), XMS.PAS (used for expanded memory buffers), and GRUNIT2.PAS (includes some basic frame grabber initialization routines) [20, 21]. As well, three executable programs are called from inside RABBIT40.EXE. These executables are CJPEG.EXE (compresses each acquired image from the frame grabber), TMAKE3.EXE (archives the data to the 8 mm tape in the EXABYTE drive), and CTCTRL.EXE (winds the 8 mm tape to the correct position after a power failure) [24].

The executable programs, RABBIT40.EXE and CJPEG.EXE, are loaded automatically into the 2 MB RAM drive by the AUTOEXEC.BAT file upon power-up of the ASC computer. RABBIT40.EXE then reads a data file which stores information including the number of volume sets written on the 8 mm data cartridge currently in the EXABYTE drive, the number of frames to grab and average per image, and the number of images to obtain for each filter configuration. The 8 mm data cartridge, which always rewinds to the physical beginning of tape upon power-up of the system, is rewound to the proper position at the logical end of the tape using CTCTRL.EXE. Then, if any image files are stored on the hard drive of the ASC computer, they are archived to the 8 mm tape, after which they are deleted from the hard drive.

An ephemeris routine (originally coded by Nick Lloyd of ISAS) acquires the date from the ASC computer and the time (from the Heath external clock, if available, or the internal computer clock, if necessary) to determine the status of the system. If the ephemeris determines that the daylight conditions exist, the system enters an idle mode and continually checks for the sun to drop more than 100° from the zenith. This condition is considered to be sunset. When sunset occurs, the data collection mode begins. Data collection continues until sunrise (where the sun is less than 100° from the zenith). At sunrise, all of the image files are archived on the 8 mm tape and deleted from the hard drive. This control sequence then repeats itself.

The control sequence continues until an operator arrives at the field site (usually about once every 30 days) to change the 8 mm and video-cassette tapes. The site operator may exit the idle or data-collection modes by striking a special control key sequence to perform routine maintenance operations such as cleaning of the
EXABYTE tape heads and changing the 8 mm and video-cassette tapes. A basic flowchart for the ASC control software is shown in Figure 3.1.

The data collection mode of the ASC system repeats the same process for each image acquired. The appropriate filter (either 557.7 nm green, 630.0 nm red, or no filter) is moved in front of the lens of the video camera. During the first 0.15
seconds, a 480 kilobyte expanded memory buffer (which is in the computer memory and is large enough to hold a 512 x 480 x 16 bit image) is written with zeros. Then in the next 3.20 seconds, eight separate 512 x 480 x 8 bit images (totalling 8/30 seconds of optical integration data) from the frame grabber are summed to the memory buffer over the ISA bus. The images could have been integrated to the Spectrum NTSC+ frame grabber on-board memory using software control. The advantage to this method is that only a single image is transferred over the ISA bus after all of the images have been summed up. However, it was found that integrating the images under software control in the frame grabber on-board memory permitted only four separate video frames to be summed over approximately 3.00 seconds. This contrasts with the process of transferring eight separate images over the ISA bus and summing the images to the computer expanded memory buffer, which could be done in 3.20 seconds. Since four extra images could be integrated at a cost of only an extra 0.20 seconds, the latter method for integrating the digitized images was chosen.

Then, in the next 0.25 seconds, the AGC voltage is recorded from the video camera, the VCR "one-shot" input is pulsed low to record a single video field on video-cassette tape, and, if necessary, a new optical filter is moved in front of the camera lens. Universal Time information is obtained from the Heath GCW-1001 clock unit to create, for the acquired digital image, a file name which is representative of the date and time of image acquisition, the filter used, the field site, and the compression type used. In the next 0.71 seconds, the image in expanded memory is divided by 8 and written out to the RAM drive. In the next 2.29 seconds, the CJPEG.EXE program is called up to compress the gray scale image (known as Portable Gray Map or PGM format) into the Joint Photographic Experts Group, or JPEG, format. The CJPEG.EXE program creates the JPEG file on the RAM drive. The PGM file is deleted from the RAM disk and the JPEG file is moved from the RAM drive to the hard drive. The AGC voltage information, filename, date, and time are written to a text file on the hard disk. Then the image collection cycle begins again. Thus, the time to acquire and save one digital image to the hard disk is about 6.60 seconds. Figure 3.2 shows a simplified flow chart of the image acquisition process.
Figure 3.2: Data Collection Flow Chart

The mean time interval of 6.60 seconds to acquire one image is found from a long term average over several thousand images. The actual time to acquire any single image will vary. Some of the variation in this data acquisition time is caused by the use of the smart drive option from Microsoft Windows Version 3.1. The executable file, SMARTDRV.EXE, is a disk-caching program. It temporarily saves information to be written to the hard disk in an expanded memory cache. When the cache is full, all of the information in the cache is saved to the hard disk in a single access [25]. This method reduces the number of accesses to the hard disk and therefore speeds the data acquisition process. Another factor in the variation of the data acquisition time of each image is the size of the image file after it has been compressed to the JPEG format. Smaller data files require less transfer time while saving to hard disk. Other aspects of data compression are discussed in Section 3.3 below.
The averaging of digitized frames in the data collection mode is used to improve the signal-to-noise ratio (SNR) of the digital images by reducing the power of the white noise. If the SNR is defined as the signal power divided by the noise power, then averaging N images will improve the SNR over that of a single image by N in theory [26, 27, 28]. The time of about 7 seconds for acquiring a single compressed image was made as short as was judged possible for obtaining the highest possible improvement in SNR while still permitting valid temporal comparison with radar data (that is obtained at much faster rates but is averaged over time spans of the same magnitude). Within the 7 second time limit, as many images as possible were averaged while performing the other required operations in the data acquisition cycle, as described above. The limitations of the frame grabber hardware, the transfer rate of the images from the frame grabber to the expanded memory buffer, and the need for improvement in SNR resulted in eight separate digitized video frames being averaged over 3.35 seconds within this 7 second time limit. Chapter 4 includes a discussion of the actual results in the improvement of SNR by averaging images.

3.3 Data Compression

The aspect of data compression plays an important role in the digital imaging ASC system. The averaged frames from the frame grabber create a single PGM image file whose size is just over 240 kB. During long data collection periods such as those near the winter solstice, up to 8000 image files are acquired in a single night. Therefore, to keep all of these files on hard disk before archiving them to the 8 mm data cartridge, a hard disk with a capacity of about 2 GB would be required. Furthermore, a single 8 mm data cartridge with a tape length of 112 metres holds a maximum of 5 GB. As it is desirable to have the ASC system operate unmanned for up to 30 days at a time, archival storage of the digital images in PGM format would be unsound. For a single 8 mm tape to hold 30 days of image data, each image file should be on average no more than about 22 kB in size.

When large amounts of data are to be transferred and stored, data compression can be used to provide several benefits. Storage requirements are reduced and the time to store the image files to various media is lessened. Compression also can reduce the number of transmission errors for the same amount of information,
assuming a fixed probability of error. Finally, the reduced storage requirements minimize economic expenditures [29].

Several considerations should be made in choosing a particular format. One consideration is the method in which the image data is to be used by scientists. Generally, data, from other instruments, at a single point in time are to be compared with a single ASC digital image.

Another consideration is the compression ratio and image quality obtained by the format. The compression ratio is defined as the length of the original data string divided by the length of the compressed data string. The compression format should allow at least 30 days of digital images to be recorded on a single 5 GB, 8 mm tape since that is the usual period of time during which the ASC system operates without human intervention.

The final aspect taken into consideration is the time required to compress an image from the raw format. While faster compression exists in the use of hardware-based compression boards for some formats, this comes only at a higher cost of the ASC system.

Numerous compression formats for data exist. They can generally be placed into two broad groups, lossy and lossless. Lossless data compression means that the reconstructed data is exactly the same as the original data. However, lossless compression usually results in low compression ratios in the range of about 3:1. Lossy compression techniques do not precisely preserve the original data but they do have higher compression ratios such as 10:1 to 50:1 for images or about 200:1 for video [30]. The raw image size collected by the ASC is just over 240 kB and therefore, a lossless compression method would likely yield a compressed image of only about 80 kB in size. Also, there are some lossy compression methods which permit images of the same quality as that created by lossless compression methods when comparing the two types of images by the unaided human eye. Therefore, only lossy compression methods were considered for use in the ASC system.

The Joint Photographics Experts Group, or JPEG, format is used to compress still images or natural, real world scenes. The JPEG standard comprises an algorithm developed by a research team, the Independent JPEG Group, under the auspices of the
International Standards Organization (ISO). JPEG converts an image from the RGB (red, green, blue) color space into the YUV color space where Y represents luminance and U and V represent chrominance signals (Y minus Red and Y minus Blue, respectively). Spatial redundancies and known color spectral responses of the human eye are used in the algorithm to compress the data [31].

JPEG is lossy in that the decompressed or reconstructed image is not the same as the original image. While JPEG is indeed lossy, the difference between the compressed image and the original image is minimal to the human eye when using the standard or default compression settings. An original 512 x 480 x 8 bit gray scale ASC image of 240 kB in size can be compressed to about 10 to 20 kB in about 2.1 to 2.4 seconds on an Intel 486 DX-50 computer with the executable program, CJPEG.EXE. This compression software is coded by the Independent JPEG Group and is available at many FTP sites. The advantages over other compression methods are that files are compressed quickly enough within the acquisition time requirement of 7 seconds per image without requiring the extra expense of a hardware compression board while still permitting 8 separate video frames to be averaged.

The Moving Pictures Experts Group, or MPEG, format is used in compression of motion video and audio signals. There are several standards of MPEG but, for the compression of motion video signals, they use temporal redundancies in addition to exploiting the spatial and color aspects of the human visual system (as in JPEG) to reduce the size of the original data [30]. However, since the output of the MPEG encoder is a motion video file which shows the temporal development of aurora, this format is not generally suitable for correlation with data from other instrumentation because scientists typically choose only a few still images from several thousand for correlation studies.

MPEG also is extremely computationally intensive. The software implementation requires that processing be performed after a number of images have been collected. For example, raw PGM images could be collected for 10 minutes and then converted into an MPEG file but this means that no images can be collected during the compression process. Furthermore, due to the large amounts of computing power required, software based MPEG compression can only be realized for the current ASC system (with the associated temporal image acquisition design limits) by reducing the size of the image from 512 x 480 pixels to 160 x 120 pixels [32].
reduced image size does result in extremely high compression ratios. For example, 20 sample raw PGM ASC images (20 x 512 x 480 x 8 bit or about 4.8 MB total) were converted into the MPEG format to create a single file of about 21 kB. The average processing time to compress each single image was about 5.5 seconds. However, the high compression ratio for this set of 20 test images of 228:1 was offset by the reduced resolution of each image. Real-time hardware compression boards for MPEG are commercially available at a higher resolution of 350 x 240 pixels, but at a cost of $5000 US and higher in 1994.

The Fractal compression format was the final format considered for use in this project. This technology is patented by Iterated Systems Incorporated and thus, information and software for this compression format is not widely available in 1994. Currently, the only commercially available fractal compression program is the Images Incorporated program created by Iterated Systems Incorporated. It is only executable as a menu-driven program inside Microsoft Windows 3.1 and therefore is not compatible with control by an external program, as in the digital imaging ASC [33]. The time for fractal image compression is also very slow on a 486 DX-50 system; the typical time to compress a single 512 x 480 x 8 bit image into the fractal format is about 65 to 70 seconds. This is impractical for compressing the digital images from the ASC without a serious loss of temporal resolution. The compressed images are also about 80 kB in size which are about four to eight times larger than comparable ASC images compressed using the JPEG format.

3.4 Archival of Data to 8 mm Digital Tape

3.4.1 Archival Software

Several different types of software were tested and used to archive the digital images to the 8 mm data cartridges. The executable programs tested were TAR.EXE, TARCHIV.EXE, and TMAKE3.EXE [34]. The advantages and disadvantages of each are discussed below.
TAR.EXE is a tape archiver which is available as free shareware from many FTP sites. With TAR, a file or groups of files can be stored in an archive. TAR can also be used to add files to an existing archive, list the files in an archive, or extract the files from the archive. Executable programs that use the TAR format are available for IBM PC-compatible computers as a Disk Operating System (DOS) program and for UNIX systems. This is an important consideration when it is desirable to permit extraction of the data on different system platforms. However, when extracting files from a TAR archive, the user must extract files that are sequentially stored on the tape. The capability of selectively choosing, for example, the first and last files of an archive for extraction is not possible with one single execution of TAR. In such a case, the user would have to extract the first file with one execution of TAR, rewind the tape to the beginning of the volume set, and re-execute TAR to extract the last file of the volume set.

TAR was tested in the ASC system for an eight month field campaign from September, 1993 to May, 1994. As a program that was executed under the control of a human operator, who could check to see that the archival process was properly performed for a set of data, TAR worked well. However, under the control of the Rabbit Lake ASC control software without any site operator intervention for up to 30 days at a time, unexplained errors occurred at the field site during archival. The most prominent problem was that TAR would inexplicably halt archiving on its own in the middle of writing data to the 8 mm tape. No error logging could be performed with TAR.EXE to find out what problems existed and, as a result, alternatives were tested.

TARCHIV.EXE is a DOS executable program that was coded by Andreas Schiffler of ISAS and the software is available at ISAS. It had the advantage of allowing the user to selectively extract any files from a volume set no matter where they are sequentially located within the set. Thus, for example, file numbers 1, 145, and 2345 in an archive of 3500 files could be extracted with a single execution of TARCHIV. TARCHIV also allowed error logging as the writing of data to tape occurred.

However, TARCHIV had some serious disadvantages. The first was that it existed as a program only for DOS computers. As well, it had its own storage format so that tapes that were written using TARCHIV could not be used on UNIX systems without writing a new program to perform data extraction. As well, TARCHIV built
a library or list of the files to be archived in the lower 640 kB of memory of the computer. When no other programs were resident in memory and TARCHIV was executed from the DOS command line, no difficulties were encountered. However, when using TARCHIV under the control of the Rabbit Lake ASC software, which occupies approximately 250 kB of the 640 kB conventional memory, limitations in the number of files that could be archived in a single volume set were found since less memory was available to build the list of files. Up to 8000 image files can be collected in a single night with the ASC system. TARCHIV, under the control of the Rabbit Lake ASC software, could archive only about 3500 files at once, whereas it was certainly desirable to have all of the data from a single night saved under one volume set.

TMAKE3.EXE is the current archiving software used in the ASC system. It was originally a program called TAPEMAKE, coded by Nick Lloyd of ISAS, and was intended to be used to write only a single volume set of data to a SCSI tape drive with automatic rewind of the tape upon completion of the archiving process for the volume set. Since the code was available and well understood by programmers at ISAS, TAPEMAKE was chosen for use as the basis for the archiving of the ASC digital images. Modifications were made to TAPEMAKE by Dieter Andre to create TMAKE3. It permits the writing of filemarks to tape after each volume set of data and disables the automatic tape rewind function. TMAKE3 writes the data to 8 mm tape in the TAR format. Thus the data can be extracted on UNIX and MS-DOS computer systems.

TMAKE3 also writes out a text error log file to hard disk. This provides the benefit of permitting a site operator to determine immediately if any problems have occurred with the system in archiving the digital images to 8 mm tape. As well, scientists may use the log file to quickly verify that a particular set of data was properly written on a tape without attempting to extract the data first.

3.4.2 Archival of Data to Tape and System Power Failures

It should be noted that with the EXABYTE EXB-8500 tape drive, data may be appended only to the end of a filemark that is followed by blank tape. Data cannot be written over tape which already contains data. Previously, power failures at the field
site caused numerous problems in properly recording data to the 8 mm data cartridge after the system was restarted.

With the current version of control software, RABBIT40.EXE, each volume set of images from a single night of data acquisition is not sequentially written to tape as shown below in Figure 3.3.

![Figure 3.3: Normal Method of Data Archival to 8 mm Data Cartridge](image)

The reason for not storing the data as shown is due to problems which occur during line power failures at the field site. It has been found that during site power failures while the tape drive is inactive, the last filemark (in this example, filemark #2) written to tape may be erased as shown in Figure 3.4.

![Figure 3.4: Filemark Erased After Power Failure](image)

Upon power-up of the system, the 8 mm digital tape is automatically rewound to the beginning of the tape by the SCSI hardware card. Upon execution of the control software, the system will attempt to advance the digital tape to the second filemark since the number of volume sets written to tape is maintained in a hard disk data file for the control software. Since the second filemark does not exist, an error will occur. Furthermore, with this condition, no more data may be written to the 8 mm tape since data may be appended only to a filemark that is followed by blank tape.
EXABYTE Corporation claims that this hardware problem should not exist in their 8 mm tape drives. However, since power failures at the Rabbit Lake field site showed that this problem occurred consistently, a software solution to this hardware problem was devised. In this algorithm, after each volume set of images from a single night of data collection is written to tape, a spare volume set is written with a spare filemark. Each spare set consists of five 2 kB files named BLANK1 through BLANK5. In Figure 3.5 below, two volume sets and two spare sets with the appropriate filemarks are shown written to the 8 mm tape.

![Figure 3.5: Tape Archiving Using Spare Sets and Filemarks](image)

Then after a power failure, the fourth filemark would be erased as shown in Figure 3.6.

![Figure 3.6: Fourth Filemark Erased After Power Failure](image)

Upon power-up of the ASC system, the 8 mm tape will again rewind automatically to the beginning. However, now upon advancing the tape forward, the program CTCTRL.EXE is used with an erase option. The tape is advanced to the third filemark. The third filemark is erased along with a short section of tape afterwards,
and a new third filemark is written. Now a filemark exists at the logical end of the tape with blank tape following it as shown in Figure 3.7.

![Figure 3.7: New Third Filemark Written Followed by Blank Tape](image)

Then, a spare set (as described above) and a fourth filemark are written to tape to arrive at the state shown in Figure 3.5.

This algorithm uses the same principles in properly taking into account the possibility of a power failure occurring while writing a volume set of images to tape. In this case, the third volume set is incompletely written to the tape when the power failure occurs as shown in Figure 3.8.

![Figure 3.8: Power Failure Interrupts Writing of Data Volume Set](image)

Whenever data is being written to the 8 mm tape under the control of RABBIT40.EXE, a status flag written to hard disk signals this condition. When the system restarts, the status flag is detected and shows that the data was not completely archived. The tape is advanced to the last properly written filemark, which in this example is filemark #4. The fourth filemark is erased and rewritten, and a short
section of tape afterwards is also erased. Then the third volume set is completely re-
archived. Therefore, power failures no longer prevent digital image data from being
archived properly to the 8 mm data cartridges.
4. Results and Analysis

4.1 Introduction

The results of the analysis of the digital images from the new ASC are discussed in this chapter. With respect to the digital images, two key aspects were investigated. The first is the improvement in signal-to-noise ratio (SNR) by the averaging of images. The second aspect is the limitations in SNR improvement. Also, a brief discussion of sampling is included.

4.2 Digital versus Analog Image Quality

The quality of the digital images and the VCR images are compared qualitatively and quantitatively. Each image shown here is the negative of the actual image. Therefore objects which are normally bright in the sky, such as the aurora and stars, appear as dark gray or even black depending on their original intensity. All images were taken at the Rabbit Lake field-site CNSR observatory. Sample digital images (which averaged 8 separate one-thirtieth of a second video frames spread out over 3.35 seconds) from the ASC were extracted from the 8 mm data cartridges for presentation. The corresponding VCR images, which are video fields over one-sixtieth of a second, were digitized through the same frame grabber at the same brightness and contrast control settings (5 and 25 respectively) used for the field-site ASC system, in an attempt to minimize variables and to facilitate valid comparison between the decompressed digital images and the digitized VCR images.

The first two images shown in Figures 4.1 and 4.2 were taken on December 7, 1994 at 4:53:45 UTC without any optical filters. Figure 4.1 is a digitized video field image from videocassette tape. Figure 4.2 is a full frame, 512 x 480 pixel image restored from EXABYTE tape. It was collected directly by the digital imaging system. At this time, the sky was mostly clear with stars clearly visible in the image.
In the VCR image of Figure 4.1, the parabolic mirror is the large oval-shape in the picture. Three tripod legs above the mirror can be seen along with the camera, at the intersection of the tripod legs. The top of the picture is north-facing, the left side is west, the right side is east, and the bottom is south. The lights at the south are from light installations at the nearby airport. The small dark gray points in the mirror are stars in the sky. Five stars can be seen clearly in the south-east portion of the mirror.
The gray section of the image just behind the north-west tripod leg is faint aurora.

The digital image (Figure 4.2) taken at the same time is clearly less noisy than the VCR image. The tripod legs and camera are more sharply defined. Nine stars can be seen in the south-east portion of the sky as opposed to only five in the VCR image. The aurora is seen more clearly as well. Also in the digital image, there is diffuse
aurora which can be seen in the upper right of the mirror. This aurora is not easily seen in the VCR image.

Figure 4.3 and Figure 4.4 were both also taken with no optical filtering. A very strong auroral event can be seen taking place at that time. While both images show the general shape of the aurora quite well, the digital image shows more fine
Figure 4.4: Digital ASC Image (No Filter) December 7, 1994 (5:02:52 UTC)

detail in the structure of the aurora in terms of varying light intensity with location on the image.
The images in Figures 4.5 and 4.6 were taken with a green (557.7 nm) optical filter. Figure 4.5 shows the exaggeration that appears in the horizontal scan lines in the video field along the edges of the tripod legs and the camera housing which are not sharply defined. The horizontal scan lines can also been seen in the aurora near the top left of the mirror. The sky is also extremely noisy and details are difficult to discern.
The image above in Figure 4.6 avoids the problems shown in Figure 4.5. The digital image taken directly at the field site shows clearer definition in the aurora and tripod legs as well as less noise.
Figures 4.7 and 4.8 were taken with a red (630.0 nm) optical filter. The VCR image in Figure 4.7 is extremely noisy. The mirror and tripod legs can be seen but the tripod legs are not sharply defined. No actual details in the sky can be seen in the VCR image due to the extreme noise.

The digital image in Figure 4.8 not only shows more sharply defined tripod
legs but also faint aurora that could not be seen in the VCR image.

The signal-to-noise ratio, or SNR, is defined as the power in the signal of interest divided by the power of the noise signal. In the digital ASC images, averaging is used to reduce the power in the white noise. The effect of the averaging in terms of the noise reduction is shown in Figures 4.9, 4.10, and 4.11. In these
images, the ISIT camera was pointed at LBS #2 from the ISAS Optics Lab, so that there was uniform light intensity input into the camera across the field-of-view. The LBS #2 output was set at 41 kR and no optical filters were used. Black cloth sheets minimized contamination of the LBS output by external light. The ISIT camera was connected to the ASC digital imaging computer and the ASC data collection program was set up to collect images with different numbers of frames averaged per image. The negatives of three images are shown. Figure 4.9 shows a single digitized video
Figure 4.10: Image of LBS #2 Screen with 8 Frames Averaged

frame; no averaging was performed.

Figure 4.10 has 8 separate digitized video frames averaged in the image. The image of Figure 4.11 shows the result of averaging 64 separate digitized video frames. An improvement in the image quality can be seen as a result of increasing the number of frames averaged per image. The last image also shows that, although the
input light is uniform, the output video is non-uniform. As a result, all ASC images must be calibrated by a flat-field correction before use in scientific studies.

During the tests with LBS #2, digital 512 x 480 pixel images were acquired with no averaging as well as averaging of 2, 4, 8, 16, 32, and 64 video frames per image. To analyse the images, a horizontal cut of the gray scale values in each pixel
in the image from position (0, 260) to (511, 260) was taken. This line of pixels goes through the peak bright section of the image.

The autocorrelation function was used to estimate the SNR [35]. In general, the autocorrelation function for a signal, $x$, is:

$$R_{xx}(k) = \sum_{n = -\infty}^{\infty} x(n) x(n+k) \quad k = 0, \pm 1, \pm 2, \ldots$$ (4.1)

Equation (4.1) above shows that the index of sampled values ranges from negative infinity to positive infinity. (In the analysis of the digital images, this index range is practically limited to 512 pixel values in the case of taking a horizontal cut from (0, 260) to (511, 260) as noted previously. Since this signal does not go from negative to positive infinity, energy is not infinite and therefore, power in this signal should be more correctly described as energy.)

For the analysis, the assumption is that each image (and therefore any section of pixels taken from the image) is the sum of two components. One component, $S(n)$, is the amplitude of signal of interest; in the analysis the images of LBS #2, this signal is the grayscale value, at each pixel location from (0, 260) to (511, 260), resulting from the camera and framegrabber conversion of the input light signal into a digital representation. The signal of interest at each pixel is assumed to be constant over the duration of the averaging of separate images because the constant voltage input to LBS #2 creates a light output of 41 kR over the spectral band of 400 nm to 700 nm. The second component, $N(n)$, is the amplitude of white noise. The white noise is assumed to have a zero mean where the noise amplitude is evenly distributed and is as likely to be positive as negative. The white noise is also assumed to be uncorrelated for $N(n_i)$ and $N(n_j)$ for every $i$ not equal to $j$. (In the discussion below, the "signal" refers to the signal of interest, $S(n)$, and the "noise" refers to the noise signal, $N(n)$.)

Assuming that the image signal, $x(n)$, is the sum of the signal and the noise, that is $x(n) = S(n) + N(n)$, the first point in the autocorrelation at $k = 0$ becomes:

$$R_{xx}(0) = \sum [S(n) + N(n)] [S(n) + N(n)]$$ (4.2)

$$R_{xx}(0) = \sum S^2(n) + \sum 2 S(n) N(n) + \sum N^2(n)$$ (4.3)
The signal, \( S(n) \), and the noise, \( N(n) \), are uncorrelated. The product, \( S(n)N(n) \), is as likely to be positive as negative and in the summation will add up to zero overall. The result is that:

\[
R_{xx}(0) = \sum S^2(n) + \sum N^2(n) \quad (4.4)
\]

\[
R_{xx}(0) = P_S + P_N \quad (4.5)
\]

If power is considered to be squared gray scale amplitudes, the first point of the autocorrelation is the sum of the signal power, \( P_S \), and the noise power, \( P_N \).

The second point in the autocorrelation at \( k = 1 \) becomes:

\[
R_{xx}(1) = \sum [S(n) + N(n)] [S(n+1) + N(n+1)] \quad (4.6)
\]

\[
R_{xx}(1) = \sum S(n)S(n+1) + \sum S(n)N(n+1) + \sum S(n+1)N(n) + \sum N(n)N(n+1) \quad (4.7)
\]

As before, the signal and noise are uncorrelated so that in the summation, the terms, \( S(n)N(n+1) \) and \( S(n+1)N(n) \), will add up to zero overall. The signal is assumed to be highly correlated between adjacent pixels, so that \( S(n) \) is approximately equal to \( S(n+1) \), and the product \( S(n)S(n+1) \) is approximately the signal power, \( S^2(n) \). Under the assumption of the properties of the white noise, the summation of the products, \( N(n)N(n+k) \), is zero for any \( k \) not equal to 0. Therefore, the second point in the autocorrelation at \( k = 1 \) becomes:

\[
R_{xx}(1) = \sum S(n)S(n+1) \quad (4.8)
\]

\[
R_{xx}(1) \approx \sum S^2(n) = P_S \quad (4.9)
\]

The second point in the autocorrelation is approximately the signal power.

Since the number of pixels in a single horizontal line cut from a digital image is only 512 and not infinite, the following autocorrelation function is used with trapezoidal integration to provide a more accurate result in the estimation of the SNR:

\[
n = 512 - k
\]

\[
R_{xx}(k) = \sum x(n)x(n+k) - \left[ \frac{x(1)x(1+k) + x(512)x(512-k)}{2} \right] \quad (4.10)
\]

where \( k = 0, 1, 2, \ldots, \text{etc.} \). To calculate \( R_{xx}(k) \), zero padding is used for \( x(n) \) when \( n \) is outside the range of \((1, 512)\).

Since the first point (at \( k = 0 \)) in the autocorrelation is the sum of the signal and noise power and the second value (at \( k = 1 \)) in the autocorrelation is approximately...
signal power only, the white noise power and signal power can be determined and therefore, the SNR can be estimated using:

\[
\text{SNR in dB} = 10 \log\left(\frac{P_s}{P_n}\right) \tag{4.11}
\]

These results are summarized in Table 4.1. For each case of number of frames averaged per image, the autocorrelation results from three different images are averaged below for the Signal + Noise Power and the Signal Power.

<table>
<thead>
<tr>
<th># Frames Averaged Per Image</th>
<th>Signal + Noise Power (R_{xx}(0))</th>
<th>Signal Power (R_{xx}(1))</th>
<th>Noise Power</th>
<th>SNR (dB)</th>
<th>SNR Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>38202123</td>
<td>3795854</td>
<td>24359</td>
<td>156</td>
<td>21.9</td>
</tr>
<tr>
<td>2</td>
<td>3803553</td>
<td>3792652</td>
<td>10901</td>
<td>348</td>
<td>25.4</td>
</tr>
<tr>
<td>4</td>
<td>3838372</td>
<td>3831470</td>
<td>6902</td>
<td>555</td>
<td>27.4</td>
</tr>
<tr>
<td>8</td>
<td>3853560</td>
<td>3850241</td>
<td>3318</td>
<td>1160</td>
<td>30.6</td>
</tr>
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<td>3813428</td>
<td>2407</td>
<td>1585</td>
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</tr>
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<td>2292</td>
<td>33.6</td>
</tr>
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<td>3820810</td>
<td>3819450</td>
<td>1360</td>
<td>2809</td>
<td>34.5</td>
</tr>
</tbody>
</table>

Table 4.1: Summary of Effect of Averaging Frames on SNR

The use of \(R_{xx}(0)\) and \(R_{xx}(1)\) to estimate the SNR depends on the noise being uncorrelated when the index, \(k\), is shifted by one pixel. In a real system, this may not always be the case. Therefore, using the same images above, the SNR improvements were estimated using \(R_{xx}(2)\), \(R_{xx}(3)\), and \(R_{xx}(5)\) in place of \(R_{xx}(1)\) in the same calculations performed for the results in Table 4.1. The results for using \(R_{xx}(1)\), \(R_{xx}(2)\), \(R_{xx}(3)\), and \(R_{xx}(5)\) to estimate the SNR are shown in Table 4.2 below.

The results of Table 4.2 indicate that there may be some very small correlation in the noise between adjacent pixels as the SNR figures improve slightly for \(R_{xx}(2)\) when a slight decrease would be expected (since using an index value of \(k=2\) should result in a slightly lower signal power value as an extra two terms are dropped in the autocorrelation sum compared to when \(k=1\)). However, the results still show that the SNR improvement is below what theory predicts.
<table>
<thead>
<tr>
<th># Frames Averaged Per Image</th>
<th>SNR Improvement using $R_{xx}(1)$</th>
<th>SNR Improvement using $R_{xx}(2)$</th>
<th>SNR Improvement using $R_{xx}(3)$</th>
<th>SNR Improvement using $R_{xx}(5)$</th>
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<tbody>
<tr>
<td>1</td>
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<td>2</td>
<td>2.23</td>
<td>2.24</td>
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<td>10.2</td>
<td>10.4</td>
<td>9.52</td>
<td>7.35</td>
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<td>16.2</td>
<td>12.9</td>
<td>9.52</td>
</tr>
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<td>18.0</td>
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<td>17.0</td>
<td>10.6</td>
</tr>
</tbody>
</table>

Table 4.2: SNR Improvement Using Different $R_{xx}(k)$ for Signal Power

Mathematical theory shows that the improvement in SNR should be a factor of $N$ for $N$ separate images averaged per picture [24, 25, 26]. The improvement for 2, 4, and 8 frames averaged per image are quite close to theory for $R_{xx}(1)$ and $R_{xx}(2)$ and averaged over a large number of images, the improvements in SNR are expected to approach the theoretical values. The SNR estimation using $R_{xx}(k)$ as the signal power (when $k$ is greater than 2 in the above examples) shows that SNR drops since the autocorrelation sum is over a finite sum.

For more than 8 frames averaged per image, the numbers do not match what the mathematical theory predicts. Part of the problem results from quantization noise which is the error introduced by representing a continuous-valued signal (in this case, the analog video signal from the video camera) by a finite set of discrete value levels (in this case, the 8 bit representation created at each pixel by the frame grabber digitization of the analog video signal) [36]. The quantization noise is always present but with no averaging or when averaging small numbers of images together, the white noise power is much larger than the quantization noise power. Therefore, averaging small numbers of images together creates improvements in SNR that follow the theory as noted above. When the white noise power is on the order of the same magnitude as the quantization noise power, then averaging more images beyond that point will continue to reduce the white noise power. However, the quantization noise is not reduced by averaging images together since the quantization error is not a random process but a systematic error.
In the quantization process, the sampled signal amplitude is rounded to the nearest quantized output level. The difference between the quantized signal amplitude, $s_q(n)$, and the actual signal amplitude, $s(n)$, is the error, $e(n)$, in the quantization process:

$$e(n) = s_q(n) - s(n) \quad (4.12)$$

Assuming that the actual signal amplitude is normalized in the range (-0.5,+0.5), a quantizer of $b$ bits gives a quantization step size of

$$\Delta = 2^{-b} \quad (4.13)$$

To find an expression for the effect of the quantization error, $e(n)$, a few assumptions are made. One assumption is that the quantization error signal, $e(n)$, is evenly distributed in the range (-$\Delta/2$,+$\Delta/2$) so that the mean value of the error is zero. Another assumption is that the error signal sequence, $e(n)$, is a white noise sequence such that $e(n)$ and $e(m)$ are spatially uncorrelated for $n$ not equal to $m$. Finally, the error sequence, $e(n)$, is assumed to be spatially uncorrelated with the actual signal amplitude sequence, $s(n)$.

Equation (4.12) can be rewritten as:

$$s_q(n) = s(n) + e(n) \quad (4.14)$$

The effect of the additive noise signal, $e(n)$, on the desired signal, $s(n)$, can be quantified by calculating the SNR as given in equation (4.11). To find the error noise power, $P_e$, the integral of $e^2p(e)$ is taken, where $p(e)$ is the probability of an error of amplitude, $e$.

Since $e(n)$ is assumed to be evenly distributed over (-$\Delta/2$,+$\Delta/2$), the probability for any error, $e$, in this range is a constant $\Delta^{-1}$ and the probability of $e$ outside this range is 0. This distribution is shown in Figure 4.12 below.
The result of the integral is:

\[ P_e = \Delta^2/12 \quad (4.15) \]
\[ P_e = (2^{-2b})/12 \quad (4.16) \]

When quantization noise power dominates the noise in the images, then the only way to further improve the SNR is to have more quantization levels (i.e. - increase the number of bits representing a single pixel) [32]. Averaging images together does not decrease the quantization noise because the actual signal level, \( s(n) \), at each pixel is assumed to remain constant during the interval of integration and the quantizer is expected to behave in a linear, time-invariant manner. Under this assumption, the quantization error, \( e(n) \), at a given pixel is constant given that the same actual signal level, \( s(n) \), at the given pixel is also constant over the duration of the averaging period.

Another error occurs in the averaging process by truncation of any fractional bit values. When averaging \( N \) images to form a single image, the bits in the summed byte value representing each pixel is shifted right by \( b \) bits, where \( b = (\log N)/(\log 2) \). In the case of averaging 8 images together, the bits in the byte value of each pixel are
shifted right by 3 bits. The right-most b bits are lost in the shifting process since fractional values between 0 and 1 are not permitted.

For example, a double byte is used to sum the byte values at pixel position (0,0) from eight images to get the 16 bit binary value, 0000000100101111 (a base 10 value of 303). The averaging process shifts the bits three places to the right obtain a binary value of 000000000100101 (a base 10 value of 37). The loss of the three right most bits (which totalled a value of 7 in the example) meant that the true averaged value should have been 37.875 and not 37. This truncation error also limits the SNR improvement from averaging.

4.3 Sampling

The digital image data collected by the ASC is used by scientists in conjunction with data collected by other scientific instrumentation such as magnetometers and radar in order to study the aurora. As stated previously, the mean time interval between successive averaged digital ASC images is 6.60 seconds during the data collection period each night. While the existence of white noise in the images means that some small temporal aliasing component is present in the digital ASC images, only one or two consecutive images at a time (instead of a large sequence of images) are typically used for correlation studies with data from other scientific instrumentation.

For radar systems, data is typically averaged over time periods of 20 seconds up to 120 seconds. For example, the Scandanavian Twin Auroral Radar Experiment (STARE) has been used to study auroral activity with the temporal resolution set at 20 to 60 seconds [37]. As well, the radar system now known as Super Dual Auroral Radar Network (SuperDARN) was previously operated with a full-scan acquisition time of 80 seconds and is now used with an integration time of 120 seconds [38]. Such radars are used to study slow processes (such as Pc5 micropulsations) with periods exceeding one minute. As a result, while temporal aliasing could arise in the use of the digital ASC images, the aliasing effects are minimized when the 7 second image acquisition time is much less than the periods of the physical phenomena being investigated.
5. Image Intensified CCD Cameras

Since the ISIT type cameras are no longer manufactured (although the ISIT tube is still available), a possible replacement system was investigated. Such a camera system would be needed if the current ISIT camera in the digital imaging ASC was damaged to a point of being unrepairable or if a new digital imaging ASC were to be built and implemented at another field site. This is also an important consideration since the low supply of available ISIT camera parts at repair centers results in extremely high prices which can extend into the tens of thousands of dollars.

5.1 Intensified CCD Video Cameras

Although ISIT type cameras have been used in ISAS ASC systems for about a decade, the development of other camera technologies in the same time span may permit new auroral detection capabilities. In particular, cameras based on the charge coupled device (CCD) have become readily available commercially in the last few years. The CCD is essentially a silicon integrated circuit based on Metal Oxide Semiconductor (MOS) technology. These devices consist of a two-dimensional array of closely spaced, polycrystalline silicon (also known as polysilicon) electrodes on an oxide covered silicon substrate. Each electrode is equivalent to the gate of a MOS transistor. Since the polysilicon is semi-transparent to light, light photons focused on the image section of the CCD penetrate the electrode structure and generate hole-electron pairs in the underlying silicon substrate. The electrons diffuse to the nearest biased electrode to be collected as signal. The holes diffuse into the substrate where they recombine with other electrons. When the exposure to the image is complete, the charge from each element in a line of the array is then transferred out to an adjacent analog shift register cell. Then, a line readout transfers the charges in each TV line to a charge detection amplifier for video output [39]. See Figure 5.1 for the basic structure of a CCD image array.
Currently, many commercial manufacturers provide television cameras (using RS-170 video output) with CCD arrays of 512 x 480 elements or more. The solid state quality of the CCD array allows the cameras to be small and physically durable. However, to produce significant signal output for low-light imaging applications, a CCD array acting alone must be exposed to the image scene for long periods of time, which reduces the temporal resolution of the camera.

Therefore, an image intensifier must be used to amplify the light from the scene of interest before focusing the photons on the CCD array. Currently, the most advanced image intensifiers are known as Generation III. An evacuated tube consists of a Gallium Arsenide (GaAs) photocathode, electrodes for an electron lens, a microchannel plate (MCP) which multiplies electrons, and a phosphor screen which reconverts the electrons back into light photons. The GaAs photocathode provides better signal-to-noise over previous Generation II Intensifiers as well as improved response in near infrared light. These image intensifiers may be coupled to the CCD array by fiber optics or by a relay lens [40]. An example of a Generation III image intensifier is shown in Figure 5.2.
The MCP consists of an array of millions of glass channels fused into the form of a thin disk. When an electron enters and hits the channel wall, secondary electrons are emitted. These electrons are then accelerated by a potential gradient across the MCP and go on to strike a point further along the inside wall of the cylinder, emitting even more secondary electrons. This multiplication effect provides the gain.

Generation II and III Intensifiers provide good amplification. Even after they are combined with a CCD camera, the complete unit is smaller and lighter than the ISIT currently in use and, as a result, requires less applied voltage. However, Generation II and III Intensifiers suffer a short life span from the effects of ionization of the photocathode.
5.2 Electrophysics Corporation Intensified CCD Camera System

For purposes of testing a new camera system, the RCA TC1040/H ISIT camera is used as a baseline because its capabilities are known. It is desirable that a new camera system should have capabilities better than or at least close to that of the ISIT camera in terms of light sensitivity and mechanical characteristics.

A CCD camera with a Generation III Image Intensifier was obtained from Electrophysics Corporation [41, 42]. The camera was a model 1350 CCD camera with a 512 x 480 CCD array, RS-170 video output, and Automatic Gain Control circuitry that was left on for all of the testing. The image intensifier was a model 9300 Astroscope. A model 9300-02 relay lens was used to couple the CCD camera with the image intensifier. An f/1.4, 25 mm objective lens with a manual iris (set at f/1.4 for all tests) was connected to the front of the image intensifier. A Sceptre power supply converted 120 V AC into +12 V DC for the CCD camera. The 9300 Astroscope is powered by two 1.5 V DC AAA batteries. The Electrophysics system cost about $10000 Canadian in 1994. This low cost is due to the modularization of

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Figure 5.3: Block Diagram of Electrophysics Camera System
the system components which allows for easy substitution of different cameras or lenses. This system is shown in the block diagram above in Figure 5.3.

For the baseline testing, the RCA TC1040/H ISIT camera system was set up exactly as it was used in the field. The AGC circuitry is left on for maximum light sensitivity and an auto-iris, f:1.4, 25 mm objective lens is used. The ISIT itself is contained in one unit within the camera body unlike the Electrophysics system in which all parts are modularized. The ISIT camera uses 120 V AC directly and thus does not require an extra power supply.

The source of illumination for all tests was Low Brightness Source #2 from the ISAS Optics Lab. This LBS was used in previous tests to determine the ISIT camera's AGC voltage response to varied input light intensity. The LBS was warmed up for one minute before each test and cooled down for at least five minutes after each test.

Each camera system was used with an optical filter (green 557.7 nm, red 630.0 nm, or a 100 times attenuation neutral density filter for the spectral broadband tests) and pointed at the screen of LBS #2. The video signal of each was input into the digital imaging ASC frame grabber. The frame grabber controls for brightness and contrast were set at values of 5 and 25 respectively for both systems. Eight separate video frames were averaged together to form a single digital image. With each filter and camera system, images were recorded at the various settings of the LBS and compressed to JPEG format as in the field-site operation of the ASC system.

The JPEG images were decompressed to the PGM format and a horizontal cut through the peak bright spot of each image was taken. The autocorrelation function was used to determine the SNR of each image at each input light intensity level. The average, maximum, and minimum gray scale values were also found, in order to indicate the changes in image brightness and flat-field qualities of each camera system at the various LBS settings. It should be noted for the tables below that LBS setting number 0 has an unknown light intensity level. It does output some light at this setting as the human eye can detect the change from having the LBS turned completely off without any electrical power to having the LBS turned on to setting number 0. The results are given in Tables 5.1 to 5.6.
<table>
<thead>
<tr>
<th>LBS Setting</th>
<th>Brightness (kR)</th>
<th>SNR</th>
<th>SNR (dB)</th>
<th>Average Gray Scale Value</th>
<th>Maximum Gray Scale Value</th>
<th>Minimum Gray Scale Value</th>
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Table 5.1: Electrophysics Camera Response to Green (557.7 nm) Light

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Table 5.2: ISIT Camera Response to Green (557.7 nm) Light
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Table 5.3: Electrophysics Camera Response to Broadband Light

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Table 5.4: ISIT Camera Response to Broadband Light

All of the averaged test images gathered at LBS setting 4 for broadband light with the Rabbit Lake ISIT camera showed poor SNR. The extreme noise could not be seen in the video while the images were acquired. There may have been unknown outside factors which may have disrupted this particular part of the test. The ISIT camera is currently operational in the field so that this test point cannot be repeated until a future time.
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<td>7.00E+00</td>
<td>8.50</td>
<td>0.20</td>
<td>4</td>
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<td>49.0</td>
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<td>62.3</td>
<td>100</td>
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</tr>
<tr>
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<td>5.12E+03</td>
<td>37.1</td>
<td>64.1</td>
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<tr>
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<td>63.8</td>
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<tr>
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<td>39.0</td>
<td>64.8</td>
<td>105</td>
<td>0</td>
</tr>
<tr>
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<td>7.90E+03</td>
<td>39.0</td>
<td>64.7</td>
<td>105</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.5: Electrophysics Camera Response to Red (630.0 nm) Light

<table>
<thead>
<tr>
<th>LBS Setting</th>
<th>Brightness (kR)</th>
<th>SNR</th>
<th>SNR (dB)</th>
<th>Average Gray Scale Value</th>
<th>Maximum Gray Scale Value</th>
<th>Minimum Gray Scale Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>n/a</td>
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<td>29.6</td>
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</tbody>
</table>

Table 5.6: ISIT Camera Response to Red (630.0 nm) Light
In comparing the two systems, it can be seen that the Electrophysics system does not match the sensitivity of the ISIT camera at the lowest input light levels. For example, the Electrophysics system does not detect any light below 10 kR in the green (557.7 nm) line, below 1 kR in the spectral broadband, or below 5 kR in the red (630.0 nm) line, whereas the ISIT camera system can detect light well below these levels. Below these light levels, it was noticed that the images from the Electrophysics camera system also had shot noise which looked like stars. Compared to the ISIT camera, the Electrophysics camera does have superior SNR at relatively bright levels of light input (e.g. - above 200 kR in the green line, above 3 kR in the broadband, and above 24 kR in the red line). However, in the detection of aurora, a camera system should be able to detect the development of aurora from the diffuse stage to the discrete arc. Since the Electrophysics system is capable of detecting only strong auroral activity, it is not suitable for use for detecting the development of auroral activity.

Mechanical aspects of the Electrophysics system with regards to use in the digital imaging ASC are also limiting as well. The 9300 Generation III Image Intensifier is not to be stored below -30°C as the intensifier tube may crack. Normally, this would not be a problem as the heating circuitry in the thermal protective case keeps the camera at a temperature of 2°C. However, power failures at the Collins Bay field-site have occurred and lasted up to a day or two in length. As the temperatures at field-sites such as Collins Bay may drop to below -45°C, the Electrophysics camera system may be damaged severely in the event of an extended power failure.

Another mechanical difficulty is the use of two AAA, 1.5 V DC batteries by the 9300 Astroscope. A battery-powered unit would operate only for approximately 30 hours which is unacceptable since the field-site is to be visited once every 30 days or so. The image intensifier would have to be modified to accept 3.0 V DC from a power supply that would have to be designed and built for the system since Electrophysics does not manufacture such a supply for use with their image intensifiers.
6. Conclusions and Future Work

The goal of this thesis was to investigate, develop, and implement a digital imaging system for auroral processes. This chapter outlines the results and conclusions from the thesis project. Suggestions for future investigation are also given.

6.1 Conclusions

The 1991 ISAS All-Sky Camera system, which was based on analog VCR tape recording, was redesigned to be a digital imaging system subject to the financial and engineering constraints outlined in Chapter 1. As a result, several important issues were investigated and resolved in relation to the ASC system including the application of data compression, the use of an 8 mm digital tape drive for recording, the use of time references for time stamping the data, and the improvement of the signal-to-noise ratio of the images over that provided by the previous ASC system.

The digital imaging ASC system was implemented at Collins Bay, Saskatchewan and currently acquires digital image data for periods of up to 30 days with minimal intervention by a field-site operator. The data is stored as JPEG files on 8 mm data cartridges.

The digital imaging system provides several benefits to scientists who are studying the aurora. One benefit is that the images are already in digital format and ready for use by scientists. Previously, when images were stored in analog format on video cassette tape, time and effort were required to take each single video image and digitize it through a frame grabber for image processing and analysis. This extra effort is not required with the new digital imaging system.
The digital images also have improved resolution and signal-to-noise ratio compared to the analog VCR images. Whereas the VCR images are only single video fields (either the odd or the even lines of a 525 TV line frame), the digital images provide full 512 x 480 pixel resolution in 8 bit gray scale. The digital images permit scientists to discern finer structures in the aurora and to locate them more accurately due to the improved spatial resolution and the increased signal-to-noise ratio created by the averaging of digitized video frames at the field site. Averaging 8 separate video frames into a single image was found to improve the SNR by about 7.8 when the theory predicts an improvement by 8. Averaging more than 8 images together improved the SNR but the factor of improvement was less than that given by mathematical theory due to limitations in signal resolution created by quantization and truncation of bits during the averaging process.

While the digital images provide improved resolution and SNR, users of the data must be cautious in the use of the images. Temporal aliasing exists in the images. This is to be expected as there is no low pass filter on the digital imaging ASC to attenuate the high frequency fluctuations in the aurora. However, the image data normally are only used for finding the location and brightness of aurora in one image. Image data are used in conjunction with data, from other scientific instrumentation such as radar, that is averaged over periods considerably longer than the 6.60 second average to acquire a single ASC image. In other words, the digital images are most useful for investigations by scientists of slow, low frequency phenomena (where event cycle periods are over one minute in duration). In such cases, the effects of aliasing are minimized.

The new digital imaging ASC system also recovers properly from power failures. Software techniques make proper power failure recovery possible so that the ASC system continues to record data properly, in both digital and analog format, upon restoration of power at the field-site.

The digital images do not deteriorate in quality with repeated playback, unlike video signals recorded on video cassette tape. The only way that deterioration of the digital data would occur is through direct damage to the recording medium such that the data can no longer be read properly. As well, the digital images are much more
convenient for sending data to other computers or research sites as they may be transmitted over computer networks.

6.2 Future Work

While the new digital imaging system does indeed provide several benefits, there are numerous areas of research which should be investigated in future efforts. These efforts often evolve from an advance in technology. With such advances, improvements to the digital imaging All-Sky Camera can be realized and implemented.

One of the first areas for possible improvement to the digital imaging All-Sky Camera system is to use a frame grabber which digitizes the video signal and integrates the digitized video frames in real-time in hardware. The averaging of digitized video frames of a stationary scene has been shown to improve the signal-to-noise ratio by reducing the power in the white noise in the images. The current frame grabber, the Redlake Spectrum NTSC+, does not provide the capability to integrate in hardware in real-time and forces a software based transfer of the frames to an expanded memory buffer to provide the integrating capability. This method of integrating is slow since each frame must be transferred over the computer's ISA bus. Therefore, the current imaging system only uses 8 frames (out of a possible 96) in a 3.2 second time span as each frame requires about 0.40 seconds to digitize and transfer over the ISA bus.

A frame grabber which has real-time integrating capability would permit 64 frames to be integrated over a shorter 2.13 second time interval. As well, only one single frame would be transferred over the computer bus. The benefits of this are twofold. First, more images are integrated in the same time span which would allow for further improvements in image quality through improved signal-to-noise ratio even if this is limited by quantization noise and truncation effects. Second, the actual time span of integration can be reduced as in the above case to minimize the movement in the aurora within one integrated image and thereby reduce the smearing within an image due to movement of the aurora. However, a real-time hardware
integrating frame grabber with 512 x 480 x 8 bit capability currently costs about $5000 US while the Redlake Spectrum NTSC+ cost $2000 US in 1993.

Another area of research is the investigation of a suitable camera for the detection of aurora. In this thesis project, a Generation III Image Intensifier was optically coupled with a CCD camera. While this system proved superior to the ISIT camera currently in use at the Rabbit Lake field site when viewing relatively bright scenes, the intensified CCD camera could not discern any details in dark images (e.g. below 20 kR in the green 557.7 nm line). This is unacceptable for determining the development of auroral processes. It should be noted that the intensified CCD camera tested consisted of two distinct units: a Generation III Image Intensifier and a CCD camera. This arrangement necessitated the use of an optical coupling unit. Investigation of a new camera system should concentrate on an intensified CCD camera which is one integral unit and which uses fiber optic coupling which may improve gain in the image.

A final area of research stemming from this thesis project involves the use of pattern recognition of the digital images. It should be noted that typically over 100 MB and about 8000 digital images are acquired from the digital imaging ASC in a single night during periods of peak data acquisition. It may be possible to find some combination of statistical features which may be measured using computer software to not only separate the images containing aurora from those which do not, but also to determine the type of aurora existing in each image. The automation of the image sorting process would minimize the time used by scientists to search for valid and useful data.
7. References


[20] Yee, Ronald, Rabbit Lake ASC Software, Version 4.0, software source code and executables available from ISAS Computing Department, University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.

[21] Yee, Ronald, Rabbit Lake All-Sky Camera Software Manual, University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.


[24] CJPEG, TMAKE3 and CTCTRL Software, software source code and executables available from ISAS Computing Department, University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.


[32] MPEG Compression Software, software source code and executable available from ISAS Computing Department University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.

[33] Fractal Compression Software, software executable available from ISAS Computing Department University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.

[34] TAR and TARCHIV Compression Software, software source code and executables available from ISAS Computing Department University of Saskatchewan, Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, Saskatoon, Saskatchewan, 1994.


[40] Image Intensifiers, pp. 5 - 7, Hamamatsu Photonics Electron Tube Center, Bridgewater, New Jersey, 1992.


8. Appendix

A. Software

The digital imaging ASC control software source code is not included in this appendix due to the length of the code. The software coded by the author plus the external software units used for the creation of RABBIT40.EXE can be found in the Rabbit Lake ASC Software Manual at the Institute of Space and Atmospheric Studies, Department of Physics and Engineering Physics, University of Saskatchewan.

The noise analysis program, NOISE.CC, determines the spatial signal-to-noise ratio of the digitized images using a horizontal strip of 512 pixel values from each image. NOISE.CC was written in C++ on a Sun Sparc LX workstation. The program uses the autocorrelation function defined in equation 4.10 from Chapter 4 to estimate the SNR:

\[
R_{xx}(k) = \sum_{n=1}^{n=512-k} x(n)x(n+k) - \left[ \frac{x(1)x(1+k) + x(512)x(512-k)}{2} \right]
\]  

(4.10)

where \( k = 0, 1, 2, \ldots \), etc.

The source code for the noise analysis program is listed below and can be compiled on a Sun Sparc workstation under SunOS 4.1.3 using the C++ compiler gcc:

```
gcc noise.cc
```

The output executable file is called `a.out` by default. To perform the noise analysis on a horizontal cut of 512 pixels from an image, the following steps must be performed first on the JPEG compressed images:

1. Decompress the JPEG image into a PGM image using

   `jpeg -pnm ascimage.name > test.pgm`.

2. Select a cut out of the image using pnmcut:
\texttt{pnmcut 0 y 512 1 test.pgm > cut}

The \textit{y} value is specified according to which row, of the 480 in the image, is to be cut. For analysis purposes, this has generally been through the visual peak bright section of the image (between rows 240 to 260).

3. Run the analysis program \texttt{a.out}:

\texttt{a.out}

The results are placed on the computer screen.
This program is used to calculate the signal to noise ratio of images gathered from the Rabbit Lake ASC system.
It reads the grayscale pixel values from file "cut". "cut" is created from a horizontal cut of the image using DJPEG (to convert the JPEG file of interest to a PGM file called "testpgm") and PNMCUT (to extract one horizontal strip of 512 pixel values from the image).

Once the values are in the file "cut" they are read into the array, gray, in the program.
The autocorrelation function is used to estimate the signal-to-noise ratio. Triangular integration is used to get a more accurate estimation of SNR.

Also, the average value of the 512 grayscale values in the file, "cut", is calculated. The maximum and minimum grayscale values of the cut are found.

#include <stdio.h>
#include <string.h>
#include <iostream.h>

int main()
{
    int flag, index1, index2, status;
    char name[4];
    unsigned char gray[512];
    unsigned char value;
    int grayint[512];
    double temp;
    double autocor[512];
    int nk, ndk;
    float average, snr, noisepwr;
    float sum, minvalue, maxvalue;

    name[0] = 'c';    /* This is the name of the file from which the */    /* grayscale values are read */
name[1] = 'u';
name[2] = 't';
name[3] = '0';

FILE *fp;
fp = fopen (name, "r"); /* open the file "cut" */
if (fp == NULL)
{
    fprintf (stderr, "Cannot open file : %s : ", name, ".
    return (2);
}

for (index1 = 1; index1 < 14; index1++) /* strip off the first 13 bytes of
the PGM file "cut". The first
13 bytes contains header
information only */
{
    fread (&value, sizeof (char), 1L, fp);
}

/* read in the 512 grayscale values into array gray */
status = fread (&gray, sizeof(char), 512L, fp);

if (status == 0)
{
    fprintf (stderr, "No grayscale values read from file : %s : ", name, ".
    return (2);
}

if (status < 512)
{
    fprintf (stderr, "Less than 512 values read from file : %s : ", name, ".
    return (2);
}

for (index1 = 0; index1 < 512; index1++)
{
    grayint[index1] = gray[index1]; /*convert from char to int type */
    /* printf ("%i\n", grayint[index1]); */
}

/* do the autocorrelation on the grayscale values */
for (index1 = 0; index1 < 511; index1++)
{
    autocor[index1] = 0; /* initialize autocorrelation value to 0 */
    nk = 511 - index1;
    for (index2 = 0; index2 < (nk + 1); index2++)
    {
        ndk = index1 + index2;
        temp = grayint[index2] * grayint[ndk];
        autocor[index1] = autocor[index1] + temp;
        /* use triangular integration; subtract half of the first and last
values calculated for each autocorrelated value */
        if ((index2 == 0) || (index2 == nk))
            ;
    }
}
{  
temp = 0.5 * grayint[index2] * grayint[ndk];
  autocor[index1] = autocor[index1] - temp;
}
/* printf ("%i\n", index1); */
/* printf ("%f\n\n", autocor[index1]); */
/* calculate the noise power and the signal-to-noise ratio */
noisepwr = autocor[0] - autocor[1];
  snr = (autocor[1])/noisepwr;
/* calculate the average grayscale value and find the maximum and minimum */
/* grayscale value in the cut */
sum = 0;
minvalue = grayint[0];
maxvalue = grayint[0];
for (index1 = 0; index1 < 512; index1++)
{
  sum = sum + grayint[index1];
  if (grayint[index1] > maxvalue)
    maxvalue = grayint[index1];
  if (grayint[index1] < minvalue)
    minvalue = grayint[index1];
}
average = sum/512;
/* output the results to screen */
printf ("\nThe (S+N) power is %f.\n", autocor[0]);
printf ("The (S) power is %f.\n", autocor[1]);
printf ("The (N) noise power is %f.\n", noisepwr);
printf ("The Signal-to-Noise ratio is %f.\n", snr);
printf ("The average grayscale value of the cut is %f.\n", average);
printf ("The maximum grayscale value of the cut is %f.\n", maxvalue);
printf ("The minimum grayscale value of the cut is %f.\n", minvalue);
return (0);
}    /* end of Noise.CC */