DATA OVERLOAD IN UNMANNED AIRCRAFT SYSTEMS:

IMPROVING BANDWIDTH UTILIZATION THROUGH WAVELET COMPRESSION

by

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ABSTRACT

Between 2008 and 2010, the number of unmanned aircraft systems (UAS) in the military increased by 330% in support of operations throughout the Middle East (Iraq, Afghanistan, Iran, etc.). The Pentagon has developed numerous initiatives to enhance the overall performance of UASs, demonstrating that reliance on and deployment of these systems is expected to continue. Via real-time aerial imagery, UASs provide commanders with continuous intelligence-gathering in hostile territories, without placing personnel in imminent danger; however the intelligence collected is valuable only if it is accessible.

The data communications capabilities of UASs are severely restricted due to the limitations of bandwidth in the battlefield. Transmission of imagery, in raw form, consumes large amounts of bandwidth. Increasing transmission bandwidth is not a feasible solution in battlefield conditions. Reducing the size of transmissions, imagery in this case, is the only realistic approach.

This thesis demonstrates the use of wavelet compression on UAS imagery to better support military combat operations, thereby reducing the "fog of war" and saving lives. Specifically this thesis studies ERDAS®' Enhanced Compression Wavelet (ECW) technology, which allows compression and decompression of imagery without placing a large burden on processors and memory (necessarily limited in UASs) and thereby economizing the use of data communications networks. Tests using simulated battlefield

equipment show that image compression of 93%, and a concomitant decrease in bandwidth demands, is possible.

INTRODUCTION

Military technology advances steadily, at the same time reducing the value of previous technologies. Human life, though, never loses its value. The motivation for enhancing the capabilities of unmanned aircraft systems (UAS) in combat operations is simple: to reduce human loss. UASs provide the military continuous access to intelligence without having to risk the lives of troops being assigned reconnaissance missions. Also, UASs provide continuous observation of areas of interest, allowing both defensive and offensive measures to be taken effectively and in a timely manner. Overall, the information gathered through UASs reduces the “fog of war” by improving situational awareness and preparedness.

Although the capabilities of both airborne imagery and data communication have improved significantly in the military over the past decade, the amount of data that can be transmitted between the UAS’ ground control station (GCS) and external units remains limited, especially in the battlefield. With tactical communications equipment, the resources may be intermittent and often must be distributed amongst multiple units operating within a region. Entire communication links to and from the GCS cannot be dedicated to UAS feeds without severely degrading command and control of all functions supporting military operations. Because transmission bandwidth cannot be increased, in order for the benefits of UASs to be fully realized the amount of data they transmit needs to be reduced. Image data compression is not widely used by UASs presently, but could be, as this thesis demonstrates.

The overarching goal of this research is to save lives by improving bandwidth efficiency in the battlefield, providing commanders with imagery of hostile territories in a timely manner. UASs can certainly reduce the loss of both American warfighters and noncombatants, as well as increase the overall strength of the American military, both offensively and defensively.

CHAPTER ONE: BACKGROUND

UNMANNED AIRCRAFT SYSTEMS

UASs have been operating in the Marine Corps for over 30 years but have only recently supported the complete integration of the Marine Air Ground Task Force (MAGTF) (Bertagna, 2010). In 2008 the Marine Corps purchased almost 2000 UASs from the Army and the Air Force in order to fill the urgent need identified in support of operations in Iraq and Afghanistan (Defense Daily, 2008). UASs have proven successful in intelligence, surveillance, reconnaissance, cargo movement, defense, and target identification (Bertagna, 2010). The reduction in personnel and resources required for a UAS to execute an intelligence mission as compared to a ground force is compelling: the same tasks can be accomplished with one vehicle and zero personnel entering hostile territory. UASs also contribute to the readiness of a fighting unit by reducing demands on personnel and equipment, allowing the unit to maintain operational strength.

UASs have taken the lead as the preferred system for surveillance tasks in the military in the past decade. The systems involve remotely piloted aircraft together with battlefield communications and control equipment that supply commanders with real-time images, providing the capability to "view developing situations in their geographic context, track and visualize events as they unfold, and predict possible outcomes" (Luccio, 2009). The MQ-1 Predator, the most popular UAS available to the military, can reach altitudes of 25,000 feet, and can stay airborne for approximately 40 hours (Luccio, 2009). Daily missions have nearly tripled since the launch of operations in Afghanistan (OEF) and Iraq (OIF)[1] with the systems being deployed in support of combat troops on the ground, as well as battle damage assessment, coalition operations, disaster relief, counter-terrorism, and homeland defense, to name a few.

The Predator UAS is equipped with a targeting system, an X-band[2] synthetic aperture radar, a variable aperture day camera, a variable aperture infrared camera (for low light/night), as well as two Hellfire missiles; it is supported by a ground control station and satellite links (Figure 1). Predators are able to detect and engage targets, and have been successful in identifying and destroying targets of interest, as well as identifying targets to other combat assets through optical sensors and a laser designator (Luccio, 2009). The system is controlled from the GCS via a line-of-sight or a satellite data link, and is capable of full motion video or still frames. Streaming video, real and near real time, is a valuable asset to a commander, but the massive amounts of data needs to be transmitted and analyzed quickly.

The GCS serves as the hub for information collection and dissemination, downloading the data

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[1] Operations Enduring Freedom (OEF) is the official name for the war in Afghanistan beginning in October 2001 and still ongoing. Operation Iraqi Freedom (OIF) is the official name for the war in Iraq beginning in March 2003 and ending in December 2011.

[2] X-band is a segment of the microwave radio region of the electromagnetic spectrum and is set at 8.0 – 12.0 GHz for radars. The shorter wavelengths of the X band allow for higher resolution imagery from high-resolution imaging radars for target identification and discrimination.

collected by the UAS via line-of-sight data link or satellite link and forwarding it to the end-user via satellite link (McHale, 2010). The GCS is equipped with two satellites which utilize the commercial Ku-band[3]. The GCS, which is located at the UAS launch site, is designed to forward information and not store information for security reasons. This ensures that in the event the UAS is recovered by the adversary, the entire mission is not disclosed.

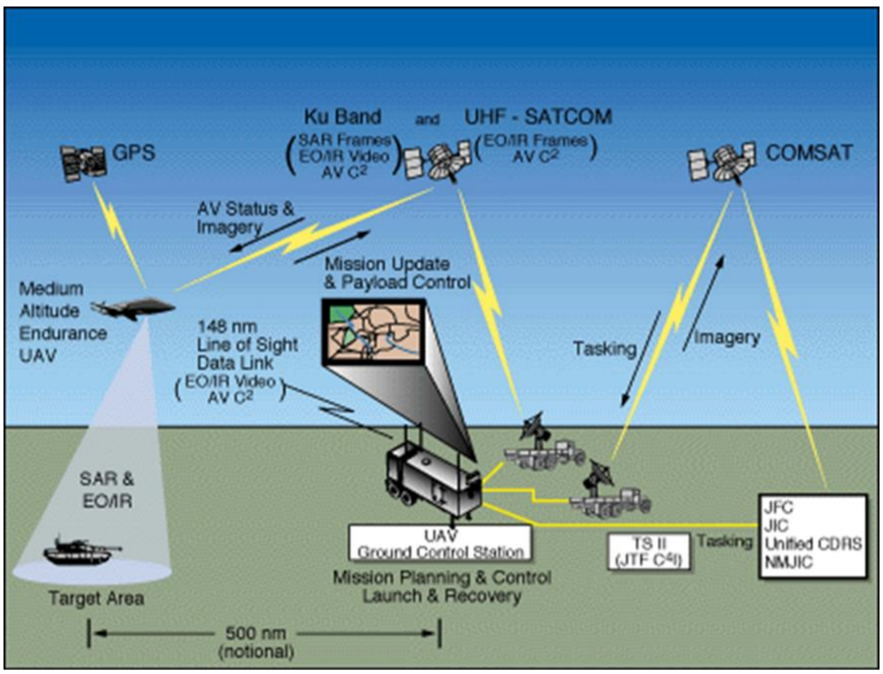

Figure 1: Concept of Operations for Unmanned Aircraft System (UAS).
(Image from Federation of American Scientists, fas.org)

With traditional intelligence operations, narrative reports at the end of a mission are the primary means of communications. With UASs, by contrast, communications needs are digital, ongoing, and voluminous throughout the mission. Currently the

[3] Ku Band is a segment of the microwave radio region of the electromagnetic spectrum and is set at 12.0 – 18.0 GHz. This band is used for broadcasting satellite services and supports the use of receiver antennas as small as 18 inches.

military uses commercial satellites for digital data transmission purposes, but with steadily increasing demands, from commercial as well as military sources, these satellites become saturated quickly. Also, relying on extra-military services in battle situations is perilous. In short, the data communications bandwidth available is limited and it needs to be partitioned among a number of communication *links*: voice and video-teleconferencing capabilities, email, Web, etc. It is noteworthy that commanders of current operations are not necessarily co-located in combat zones, but rather may be anywhere in the world; they depend on these communication links to make decisions at the strategic, operational, and tactical levels.

The military's reliance on UASs is expected to continue and even accelerate. Between 2008 and 2010 the number of UASs deployed in support of operations in the Middle East increased by 330% (Defense Industry Daily, 2010). As UASs continue to advance their technology, it is essential that communication systems advance too, so that data acquired by UASs can be disseminated to military commanders and other decision-makers in a timely manner. As this thesis demonstrates, commercial software, such as ERDAS' Imagine™, provides an attractive alternative to building up data communications architectures to provide additional bandwidth for the massive UAS datasets.

The widespread deployment of UASs over the past decade has provided many additional capabilities to the warfighter and has significantly increased the amount of information available to the battlefield commanders. In 2009 alone the Army generated 24 years worth of video from UASs (Defense Industry Daily, 2010). The advancements in the quality of video and images collected by UAS have resulted in massive amounts of data requiring advanced transmission, storage, and retrieval capabilities. As UAS missions rapidly grow so does the need for resources that reduce the burden placed on existing systems. Although significant effort has been devoted to enhancing UAS as remote-sensing platforms, there has been a lack of research on improving the interoperability between UAS and existing communications platforms. Avoiding the degradation of services resulting from data communications "overload" is essential to utilizing UASs to their full potential.

The Department of Defense spent over $1 billion in 2010 on UAS technology improvements, reflecting a reliance and desire to continue using these systems to support military operations (Keller, 2011). Research and development devoted to the improvement of imagery transmission is essential in reducing the burden of massive amounts of UAS data on tactical communication.

The U.S. Army Research Laboratory (ARL) is currently conducting various research projects on so-called Command, Control, Communication, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems to address the information overload. The ARL objective is to develop theories for C4ISR data processing, information extraction, and information integration to undertake the rapidly increasing quantities of data overwhelming commanders (U.S. Army Research Office, 2011).

In one initiative, ARL is researching High Performance Computing (HPC) on large-scale mobile networks to provide sufficient speed, fidelity, and security for UAS data communications (U.S. Army Research Laboratory, 2011). Another initiative is exploring less computationally burdensome methods for viewing digital imagery, anticipating development of new techniques for interactive identification of regions with visibility discontinuities (U.S. Army Research Office, 2011). These capabilities were showcased at a C4ISR network modernization event in 2011 where simulated real-time data to a tactical network and Command and Control (C2) systems were able to interact with simulated HPC-generated entities.

An internal U.S. Marine Corps white paper by Neushal (2011) describes specific communication requirements to support the increase in UAS deployment and the challenges presented by UASs in battlefield conditions. Major Neushal, an Amphibious Communications Officer[4], highlights a need for standardized communication and system architectures on open UAS platforms which are capable of high data rates, data preservation in non-proprietary formats, and accessible through standard web based tools. He identifies information exchange requirements (IER) that

[4] Amphibious communications is relevant because it is the essence of tactical communications: movement from ship to shore with limited communications capabilities that can be installed and operated in a timely manner. The size of the footprint depends solely on the amount of assets that can be transported via landing craft.

are necessary for the transmission of information, i.e. network load necessary to handle the throughput of still imagery, geodesy data, digital terrain elevation data, and meta-data. He also stresses the importance of taking a holistic approach because in order for any of these IERs to be useful they must be integrated with others.

IMAGE COMPRESSION

For UASs, an alternative to increasing transmission bandwidth is reducing the volume of data transmitted, referred to as “data payload”, through image compression, i.e. creates a shorter encoding of images by reducing the amount of redundant and/or irrelevant data in them. Image compression can be accomplished through either technical or perceptual approaches, or some combination.

A digital image is a rectangular array of dots, or *pixels* (picture elements), arranged in m rows and n columns; thus the product $m \times n$ represents the size in pixels of the image (Salomon, 2008). A digital representation of color is the usual attribute of each pixel, which is stored as a fixed-size code, typically 1 to 3 bytes. In raw form, images are large: for example, the average Smartphone is equipped with a 5-6 megapixel camera and can produce in raw images as large as 18 megabytes (Wall, 2010).

Redundancy arises because neighboring pixels display spatial auto-correlation (Getis & Ord, 2010). In addition to color, the brightness of neighboring pixels is correlated, even if neighboring pixels have different colors, they generally will be similar in brightness.

Because human vision is sensitive to small variations in brightness but not small variations in color[5], compressing

[5] The human eye contains 6-7 million cones, which perceive colors, and 120 million rods, which perceive brightness, causing human vision to be more sensitive to brightness.

information in the color components reduces the size of the image by introducing distortions that are not noticeable to the eye (Salomon, 2008). For example, converting pixel representations from three color components, such as RGB (Red, Green, Blue; 8-bits each), to one brightness component and two admixed color components, such as YCbCr (luminance, Change in blue, Change in red; 8-bits plus 2 x 5-bits), referred to as chroma subsampling, achieves compression (to 18/24 bits = 133% in this example) (Salomon, 2008). There are numerous methods for image compression, but all remove redundancy based on the same principle: given a pixel selected at random in an image it is likely its neighbors will have the same or similar colors (Salomon, 2008).

Lossless image compression reduces bits by eliminating statistical redundancy, exploiting the redundancy in order to represent the data more concisely without losing information. Variable-length coding and run-length encoding are examples of lossless compression.

Variable-length coding is an approach to compression that encodes source symbols, here color pixels, to a variable number of bits. Redundancy is reduced by assigning short codes to common symbols and longer codes to rare symbols, resulting in a low expected bit length (Salomon, 2008). An example of variable-length encoding is Huffman coding, developed in 1951 by David A. Huffman, a MIT information theory student. Huffman coding uses a specific method of assigning binary codes to symbols and encoding higher weighted (frequency of occurrence) symbols with fewer bits. First a binary tree of nodes containing the symbols and the weights is created, then the two nodes with the lowest probability are combined to form an equivalent symbol that equals the sum of the two symbols. The combining process is repeated until only one symbol exists at which point the tree is read backwards (right to left) and bits are assigned to the branches, see Figure 2. Variable-length coding is primarily used in other compression methods, such as JPEG, to encode data units in the final stages of compression.

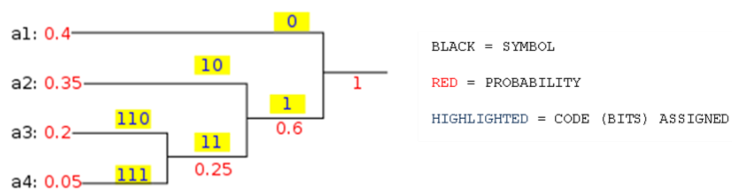

Figure 2: Example of Huffman Coding.
(Image from wikipedia.org/wiki/Huffman_coding)

Run-length encoding (RLE) is a simple form of data compression where sequences in which the same data value occurs consecutively are replaced by a repeat count and a single data value. RLE reduces the size of a repeating string of characters (run) and is typically encoded into two bytes, the number of characters in the run (run count) and the value of the character in the run (run value) (Murray & VanRyper, 1996). For example, a character run of 10 "B" characters would originally require 10 bytes but after RLE encoding would require only 2 bytes and be stored as simply 10B (RLE packet). In this example 10 is the run count and contains the number of repetitions and B is the run value and contains the actual value in the run (Murray &

VanRyper, 1996). A new packet is created each time the run character changes. For example, the character string XXXXXyyyyqqBBBB would convert to 5X4y2q4B, reducing the string from 15 bytes to 8 bytes. Typically an image is encoded in row-major order (row by row) starting at the upper left corner and scanning left to right across each line to the bottom right corner, easily recognizing intra-column redundancy. Because small variations in color differ numerically but are not visually important, RLE is best suited for bi-level (black and white) images, such as fax machines.

By contrast, lossy image compression reduces bits by removing marginally important information, accepting loss of information that is not detectable to the human eye. Orthogonal image transform and sub-band image transform are examples of lossy image compression.

In general, an image transform is a mathematical technique that transforms original pixels into an easily compressible form in either or both of two ways: (1) curtailing redundancy by aggregating similar but not idenitcal pixels, effectively reducing their number and (2) isolating "high-frequency" detail (see below) in the image to identify less important parts (Salomon, 2008). Compression occurs when the transformed pixels are written to the output, at which point they are quantized. Quantization is the process of converting values to a single quantum value, such as rounding real numbers to the nearest integer or reducing large numbers to small numbers by converting them to an average integer. The most efficient method for doing this is to replace the raw pixels (24 bits) by their indexes (8 bits) within a quantized array of pixels; the array is built-in to both the encoder and decoder. Beyond simple indexing, image transform is offered in two forms, orthogonal and sub-band.

Orthogonal transform converts pixels to a ranked set of coefficients according to frequency, with the first coefficient being most important (containing much of the data from the original image) and the remaining coefficients being progressively less important (containing the less important details of the original data) (Salomon, 2008). The *frequency* of an image is measured by the number of color changes along a row and/or column. For example, white Christmas lights on an evergreen tree would be considered high frequency; the green background would be low frequency. Low frequencies correspond to the basic image features, whereas high frequencies correspond to details in the image, which beyond some cutoff, are less important (Salomon, 2008). By isolating various frequencies, pixels corresponding to high frequencies can be greatly modified and pixels corresponding to low frequencies can be modified only slightly or not at all, resulting in effective compression that only loses unimportant details. The most popular orthogonal transform is the discrete cosine transform (DCT) which takes correlated input data and concentrates only the first few transform coefficients, i.e. the important low frequency components (Figure 3). The DCT uses real numbers as coefficients to express the data points in terms of a sum of cosine functions oscillating at different frequencies. Through use of cosine functions, blocks of the image can be examined and the colors averaged to create an image with far fewer total colors. DCT is the compression method that is used in JPEG-93.

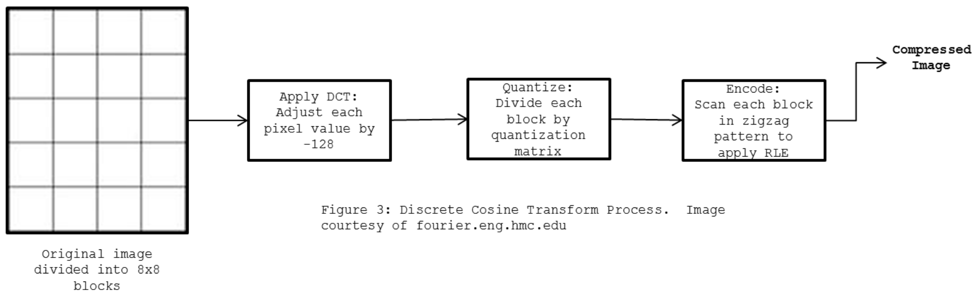

Figure 3: Discrete Cosine Transform Process. Image courtesy of fourier.eng.hmc.edu

Sub-band transform, also known as wavelet transform, decomposes an image into two orthogonal frequency bands, separating the sharpness/contrast bands from the signal/noise bands (Figure 4). This allows for each band to be independently quantized. “The wavelet transform is a tool that cuts up data (or functions or operators) into different frequency components, and then studies each component with a resolution matched to its scale” (Daubechies, 1992). Correlated values are converted to ranked transform coefficients, and compressed by quantizing the difference and encoding with variable-length codes (Salomon, 2008). Discrete wavelet transform (DWT) replaced discrete cosine transform (DCT) in the upgraded JPEG-2000 due to its superior compression performance and quality of images delivered. DCT suffers from “blocking” artifacts that are introduced when the image blocks are sub-divided, leading to very noticeable loss in image quality upon reconstruction. DCT also only performs well for compression ratios of 25:1 or lower, while DWT performs well for ratios beyond 100:1 (Nanavati & Panigrahi, 2005).

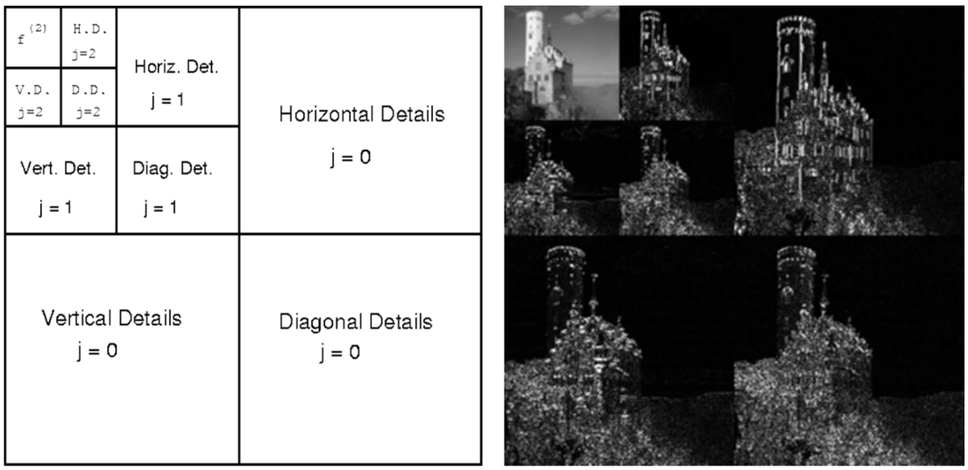

Figure 4: Discrete Wavelet Transform Process. Images are passed through a series of filters resulting in three large images containing the high frequency image details, three smaller images containing an average of the low and high frequency details, and an image (top left corner) containing the low frequency (important) information.
Images from eso.org/sci/software/esomidas/doc/user/98NOV/volb/node316.html and wikipedia.org/wiki/discrete_wavelet_transform respectively.

This thesis examines wavelet compression, specifically ERDAS’ Imagine technologies to compress and disseminate imagery data thereby increasing bandwidth efficiency and reducing the time it takes to view images. ERDAS’ Enhanced Compression Wavelet (ECW) algorithm provides fast compression and decompression rates without heavily burdening computer memory or processors, at the same time maintaining high compression ratios and visually lossless image quality (Intergraph Corporation, 2012a). ERDAS claims that Imagine has the ability to process images at >25MB/second, resulting in up to 95% compression depending on file size.

CHAPTER TWO: RESOURCES AND RESEARCH PHASES

To test the capability of ERDAS' Imagine software in improving bandwidth efficiency and promoting timely dissemination of UAS imagery, a simulation facility was set-up within the Marine Corps Communication-Electronics School located on Marine Corps Air Ground Combat Center (MCAGCC) at Twenty-nine Palms, California. Computer devices (nodes) were linked together to share simulated image data and transfer as a wide-area network (WAN)[6] comprised of two Virtual Local Area Networks (VLAN)[7] (Figure 5). $VLAN_1$ included the server and a computer that managed access to the centralized UAS image data and ERDAS software in the network, representing the UAS ground-station. $VLAN_2$ included the laptop retrieving the UAS image data, simulating a remote user. A "Layer-3" switch[8] was used to connect the two VLANs to the WAN, simulating data leaving the network and travelling across the internet to reach a destination in a different geographic location.

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[6] A WAN is a network that covers a large geographic area (links across metropolitan, regional, or national boundaries).

[7] A VLAN is a group of general network devices within a smaller geographic area (home, office, school).

[8] A Layer-3 switch provides routing capabilities and allows the VLAN to connect to the WAN.

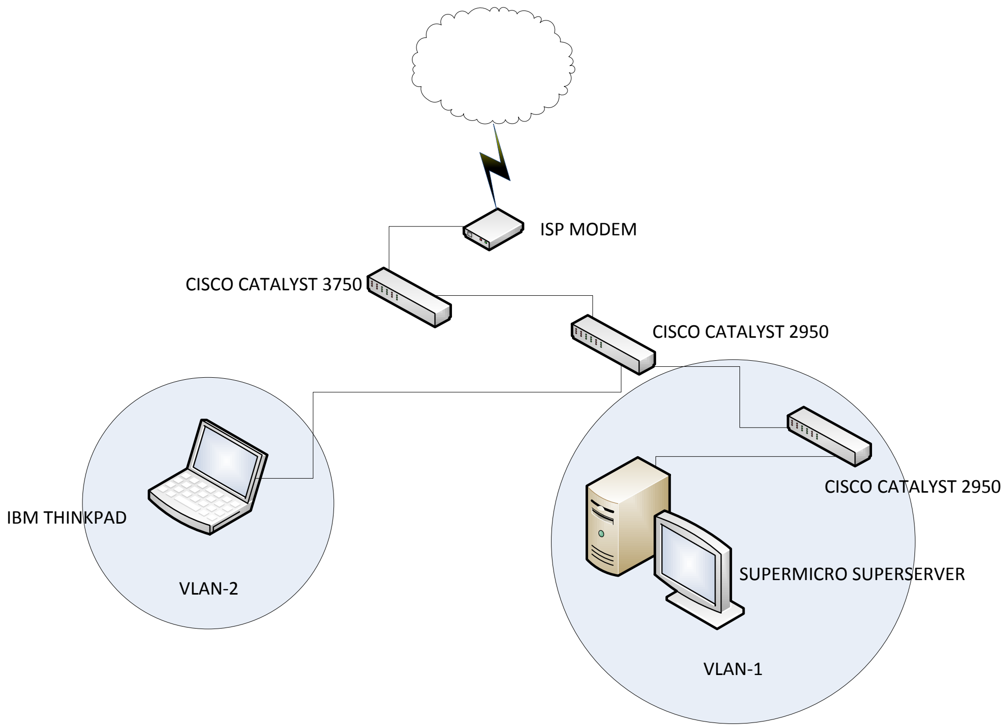


Figure 5: Network Diagram.

The ERDAS software was installed on a SuperMicro SuperServer® 1026T-URF serving as the “start node” (representing the system where the data originates and the transmission process begins), running Microsoft Windows Server® 2008 R2 and supporting two Intel 64-bit Xeon processors. The two Cisco Catalyst® 2950 12-port switches and one Cisco Catalyst 3750 switch installed allowed communication between the different devices on the network. The Catalyst 3750 is an Open Systems Interconnection model Layer-3 switch and served as the distribution switch, local area network, and the VLAN routing device for the entire network. An IBM ThinkPad served as the “end node” (final destination) and received information from the SuperServer. Finally Solarwinds® Network Performance Monitor software was installed on the

SuperServer and used to monitor and record bandwidth utilization, packet loss, latency, errors, and CPU load for all the nodes on the network.

Bandwidth is the amount of data the network can transmit at a given time and bandwidth utilization measures the percentage of that bandwidth being consumed. Packet loss occurs when packets (units of data) fail to reach their destination initially and must be resent, resulting in degraded or slower performance. Latency is the amount of time it takes for a packet to traverse nodes over the network. For Solarwinds, errors are any event that trigger a warning alert, such as sustained, high levels of bandwidth utilization overburdening the network. CPU load is the number of instructions being executed by the system.

The image data used for the research was acquired through the Marine Unmanned Aerial Vehicle Squadron which provided 219 GB worth of data to test. All data were viewable using FalconView®, a Microsoft Windows® based mapping application that is used as a moving map display within the UAS GCS (FalconView, 2012). The simulated FalconView map data included three types of files: DTED (digital terrain elevation data), RPF (raster product format), and MrSID® (multiresolution seamless image database).

DTED is the military standard for medium-resolution terrain datasets, which includes a matrix of terrain elevation values described as the height above the Earth Gravitational Model 1996 (EGM96) geoid, and provides medium resolution, quantitative data.

RPF is a military standard for geospatial databases, composed of rectangular arrays of pixel values that comprise digital maps, images, and other geographic data for military applications (National Digital Information Infrastructure and Preservation Program, 2011). Although RPF supports imagery data it is restricted to raster images of vector maps in the Marine Corps. An example of RPF data compression is the National Geospatial-Intelligence Agency's Compressed ARC Digitised Raster Graphics (CADRG), which achieves a nominal compression of 55:1. Because of their widespread use in maps, RPF data are colloquially referred to as "map data."

MrSID is a file format developed and patented by LizardTech for encoding georeferenced raster imagery and optionally compressing large raster image files, also through wavelet compression, but restricted to be lossless, which limits its compression features. Both RPF and MrSID divide image into *zoom files*, which allows for quick retrieval without having to decompress the entire file.

These three data types were chosen due to their commonality in the military and because they comprised a vast majority of the data delivered by the UAS through FalconView.

CHAPTER THREE: EXECUTION

Researching the performance of ERDAS' compression and data management software was conducted in two parts. Part 1 consisted of first compressing map data then decompressing map data and gauging visual loss. Part 2 consisted of transmitting both raw and compressed map data across the network to monitor bandwidth utilization.

Part 1 consisted of using ERDAS Imagine geospatial "data authoring" software to compress the raw data representing a mix of DTED, RPF, and MrSID imagery, converting it to ECW format. Management of the data authoring was accomplished through the use of a simple, user-friendly interface. Batch conversion of multiple DTED, RPF, and MrSID files within a folder are supported; however, all files in a batch must be of the same format, resulting in three separate conversion cycles necessary for the three file formats being tested. On average the compression of the DTED and RPF files, approximately 1 MB each, took less than 2 seconds but because of the large number of files (67,648) being converted the process took over 10 hours. On average the compression of MrSID files, approximately 133 MB each, took about 5 minutes, and although significantly fewer (624) it required an additional 13 hours. In total 68,272 files were converted to ECW format.

Part 2 involved transmitting both the raw data and the ECW data across the network, simulating the transfer of large datasets containing the imagery of a single mission, and determining the extent to which the burden on the network was reduced through the use of ECW compressed files. Access to the data from an end node located in a different VLAN was enabled through Layer-3 switching, representing different geographically located regions. Monitoring traffic reaching Layer-3 switching allows for the evaluation of network performance as if the data was travelling between distant networks.

To test the impact raw data transfer had on the network, two separate transfers were conducted: the first transfer of raw data involved the end node “pulling” all the raw map data (49.6 GB) across the network, and the second pulling a subset of the raw map data similar in size to the compressed data (23.7 GB). To test the impact of a large ECW data transfer on the network the entire ECW folder (22 GB) was pulled in one transfer.

CHAPTER FOUR: RESULTS

PART 1

Using Imagine, the size of the test map data was reduced from approximately 135 GB raw data to 22 GB ECW data, as shown in Table 1.

Table 1: File sizes before ECW conversion and after. Note: DTED files are individual 1 degree cells, resulting in a substantially smaller file size than either RPF or MrSID.

	DTED	RPF	MRSID
RAW DATA	1638.4 MB	49.9 GB	83.5 GB
ECW DATA	112.0 MB	16.2 GB	5.5 GB
% REDUCED	93%	67%	93%

The MrSID imagery being converted to ECW format resulted in a 93% reduction in total file size for two reasons. First, although both MrSID and ECW are wavelet compression technologies, in the UAS application, MrSID is lossless[9] and ECW is lossy compression. The MrSID file will lose only marginally important information upon conversion to ECW, further reducing the size of the file. Second, the Imagine software has proven to achieve a compression percentage that increases as file size decreases. For example, a 3.3 GB MrSID file showed a 16% reduction to 2.8 GB ECW and a 650 MB MrSID file showed a 45% reduction to 290 MB ECW (Pursch, 2013). This behavior coupled with the fact that MrSID images coming to the GCS are only slightly compressed, explains the large ECW compression

[9] For automatic analytics and archival purposes, which are not of concern to battlefield commanders.

percentages achieved during this research, where the MrSID files averaged 5 MB each.

Although reducing the size of the imagery data has obvious benefits to transmission, storage, and retrieval of data on a network, they are meaningless if the imagery suffers significant loss during compression. The assessment of losses was limited to visual quality because it will be humans alone making battlefield decisions based on the imagery. The process proved to be visually lossless for the MrSID imagery files which were indistinguishable with and without compression (Figure 6), but both the DTED and RPF map files suffered significant visual degradation as a result of compression (Figure 7).

The reason for the quality loss seen with RPF files is due to these files being 8-bit with a color lookup table (CLUT) (Pursch, 2012); this is a naïve transform technique. The CLUT is a matrix of color data that is indexed by the pixel values in order to portray these pixels as colors. Compression causes the pixel values to change and those changed values no longer correctly index to the color table, creating the result seen in Figure 7. The pixel data values for an RPF frame before and after ECW conversion can be seen in Figure 8 (Pursch, 2012). Notice how the pixel data changes, for example, if the original pixel value was 21 and that mapped to Blue in the CLUT, after compression 21 might become 16, which in the CLUT is Green. The result is a very colorful, incorrect image.

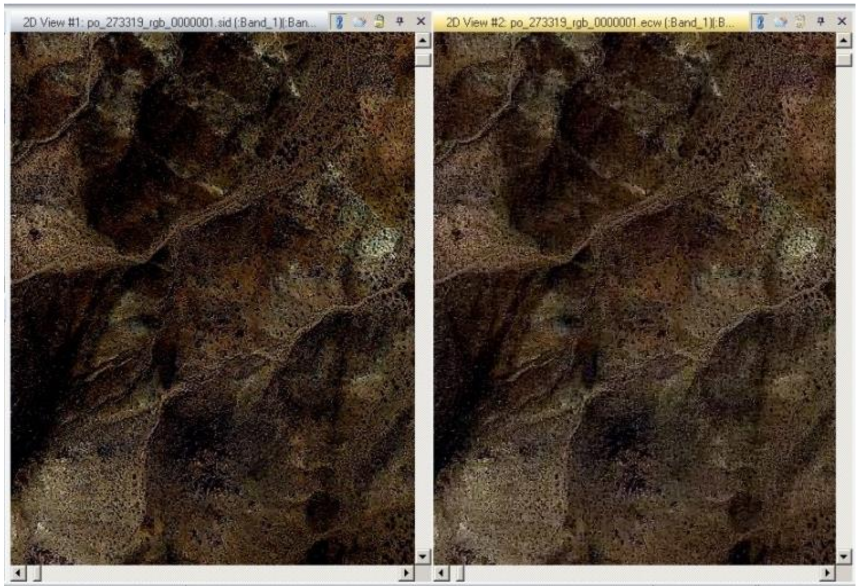


Figure 6: Comparison of MrSID Raw Data (left) and ECW data (right).

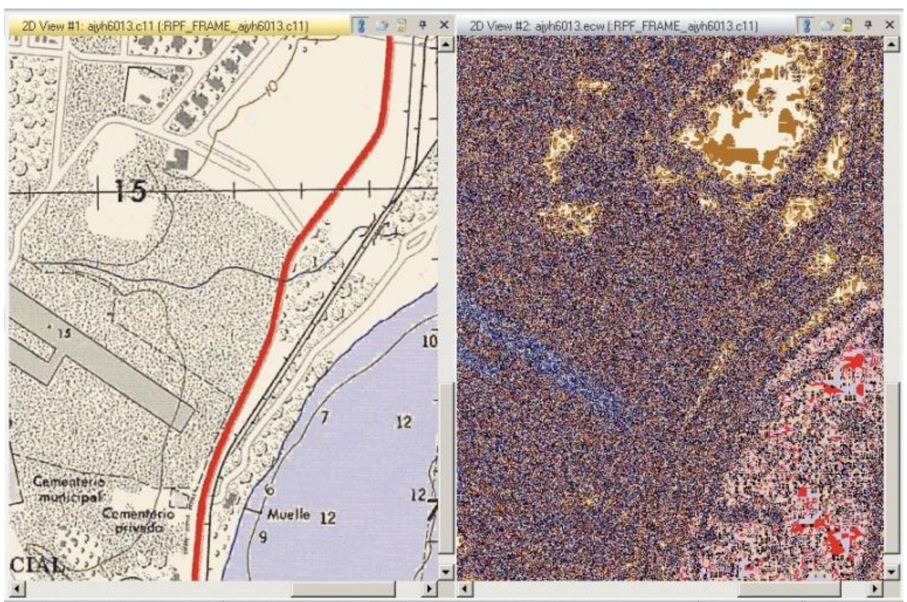
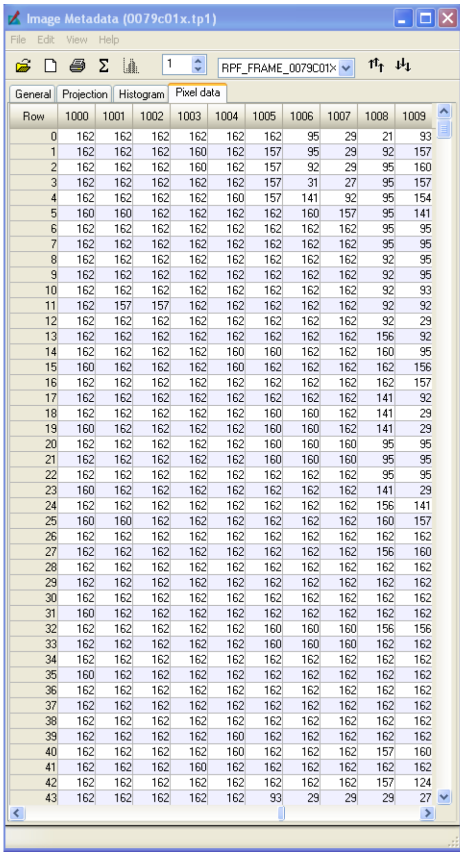


Figure 7: Comparison of RPF Raw Data (left) and ECW data (right).



Row	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009
0	162	162	162	162	162	162	95	29	21	93
1	162	162	162	160	162	157	95	29	92	157
2	162	162	162	160	162	157	92	29	95	160
3	162	162	162	162	162	157	31	27	95	157
4	162	162	162	162	160	157	141	92	95	154
5	160	160	162	162	162	162	160	157	95	141
6	162	162	162	162	162	162	162	162	95	95
7	162	162	162	162	162	162	162	162	95	95
8	162	162	162	162	162	162	162	162	92	95
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11	162	157	157	162	162	162	162	162	92	92
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17	162	162	162	162	162	162	162	162	141	92
18	162	162	162	162	162	160	160	162	141	29
19	160	162	162	162	162	160	160	162	141	29
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21	162	162	162	162	162	160	160	160	95	95
22	162	162	162	162	162	162	162	162	95	95
23	160	162	162	162	162	162	162	162	141	29
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26	162	162	162	162	162	162	162	162	162	162
27	162	162	162	162	162	162	162	162	156	160
28	162	162	162	162	162	162	162	162	162	162
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30	162	162	162	162	162	162	162	162	162	162
31	160	162	162	162	162	162	162	162	162	162
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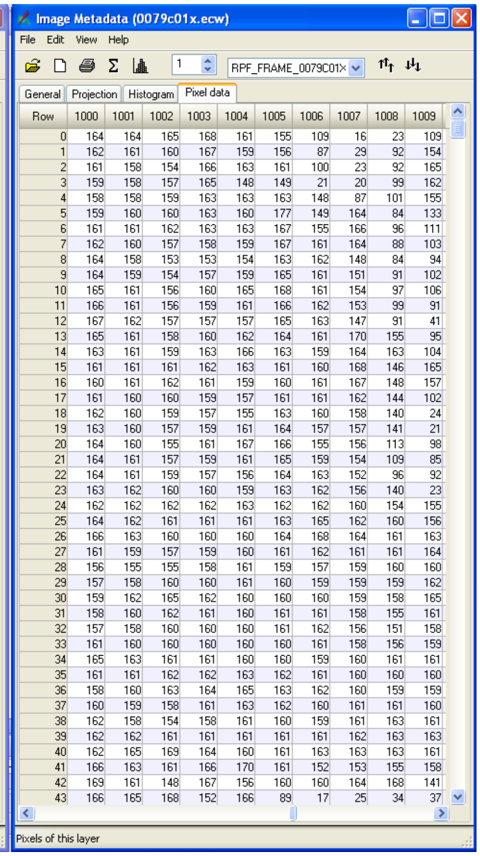
38	162	162	162	162	162	162	162	162	162	162
39	162	162	162	162	160	162	162	162	162	162
40	162	162	162	162	160	162	162	162	157	160
41	162	162	162	160	162	162	162	162	162	162
42	162	162	162	162	162	162	162	162	157	124
43	162	162	162	162	162	93	29	29	29	27



Row	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009
0	164	164	165	168	161	155	109	16	23	109
1	162	161	160	167	159	156	87	29	92	154
2	161	158	154	166	163	161	100	23	92	165
3	159	158	157	165	148	149	21	20	99	162
4	158	158	159	163	163	163	148	87	101	155
5	159	160	160	163	160	177	149	164	84	133
6	161	161	162	163	163	167	155	166	96	111
7	162	160	157	158	159	167	161	164	88	103
8	164	158	153	153	154	163	162	148	84	94
9	164	159	154	157	159	165	161	151	91	102
10	165	161	156	160	165	168	161	154	97	106
11	166	161	156	159	161	166	162	153	99	91
12	167	162	157	157	157	165	163	147	91	41
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14	163	161	159	163	166	163	159	164	163	104
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16	160	161	162	161	159	160	161	167	148	157
17	161	160	160	159	157	161	161	162	144	102
18	162	160	159	157	155	163	160	158	140	24
19	163	160	157	159	161	164	157	157	141	21
20	164	160	155	161	167	166	155	156	113	98
21	164	161	157	159	161	165	159	154	109	85
22	164	161	159	157	156	164	163	152	96	92
23	163	162	160	160	159	163	162	156	140	23
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25	164	162	161	161	161	163	165	162	160	156
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31	158	160	162	161	160	161	161	158	155	161
32	157	158	160	160	160	161	162	156	151	158
33	161	160	160	160	160	160	161	158	156	159
34	165	163	161	161	160	160	159	160	161	161
35	161	161	162	162	163	162	161	160	160	160
36	158	160	163	164	165	163	162	160	159	159
37	160	159	158	161	163	162	160	161	161	160
38	162	158	154	158	161	160	159	161	163	161
39	162	162	161	161	161	161	161	162	163	163
40	162	165	169	164	160	161	163	163	163	161
41	166	163	161	166	170	161	152	153	155	158
42	169	161	148	167	156	160	160	164	168	141
43	166	165	168	152	166	89	17	25	34	37

Figure 8: Pixel data for RPF frame (left) and after ECW conversion (right). (Courtesy of Andrew Pursch, Intergraph)

As mentioned above, although RPF can be used for continuous imagery its use is limited to raster graphics (raster images of vector maps) in the Marine Corps, preventing this research from testing if ECW properly compresses continuous images coded in RPF.

DTED is a 16-bit data representation, stored in a column major format (Department of Defense, 2000). The ECW conversion of DTED produced an image as severely degraded as the RPF file. DTED can be thought of as a gray scale image where latitude and longitude identify the pixel, and elevation is the pixel value (Jacobs & Boss, 1992). Quantization results in a smoother distribution of pixel values, leading to poorer fidelity of the compressed images.

Maintaining visual integrity is essential in the military because lives depend on the decisions made on the basis of intelligence imagery. Although Imagine does not properly compress RPF and DTED files, for the reasons explained above, the MrSID files comprise the bulk of UAS imagery in terms of raw size and using the program to only convert these images would still enhance the performance of the network.

PART 2

The first transfer of 49.6 GB of raw data caused the bandwidth utilization to increase from less than 20% to 79%, resulting in an alert from the system notifying that the network was operating at a transmit utilization above the 75% threshold. The bandwidth utilization remained above threshold throughout the entire transfer of raw data, lasting 98 minutes (Figure 9). Response time increased on multiple occasions throughout the transfer reaching levels of 90 ms and 135 ms, identified as in the 95th percentile, meaning only 5% of applications experienced worse response time. The total average utilization remained over 85% throughout the transfer of the raw data and also achieved a 95th percentile rating. The network utilization reports collected during the transfer can be found in Appendix A-F.

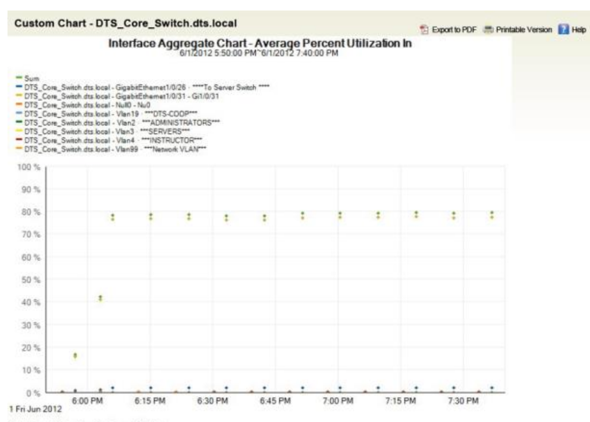

Figure 9: Solarwinds analysis of bandwidth utilization during raw data transfer.

Even with a smaller folder of 23.7 GB raw data, the same trends were identified on the network. The average utilization increased to over 80% for the duration of the transfer and the response time increased to 80 ms, triggering the same alerts and

95th percentile rating. The transfer only took 51 minutes for a smaller data transfer but the reduced size did not reduce the burden on the network.

By contrast, the transfer of ECW-compressed data lasted 78 minutes (vs. 98+51 for the raw data). The bandwidth utilization reduced to an average of 44% and never going above the 75% threshold (Figure 10). The demand on the network decreased due to the reduction in files sizes, allowing for smaller files to travel the pipe quicker, which prevented “clogging” and reduced the strain on the network to get the files to their destination. Response time remained below 20 ms throughout the transfer except on two occasions where it peaked at 140 ms and 80 ms. The military network on which the transfer was being conducted commonly receives patches and updates after working hours, explaining the presence of these random spikes. The total utilization never surpassed 54% during the transfer and stayed below 40% throughout most of the process.

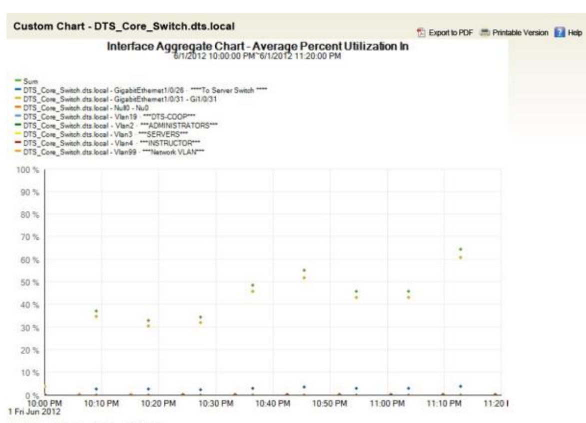

Figure 10: Solarwinds analysis of bandwidth utilization during ECW data transfer.

These tests determined that the ERDAS Imagine software significantly reduced the size of the imagery data, by an average of 80%, while delivering a visually lossless image for MrSID imagery data. The burden on the network was also reduced with the transfer of ECW-compressed data across the network compared to raw data because of the reduction in the amount of bandwidth being consumed. For the purposes of this research it was determined that one test of the data transfer was sufficient. The total utilization percentages varied between the three tests yet remained steady within each individual test. It was determined that this validated a stable network and that further testing would produce the same results. Although the ECW data transfer did reach levels of 65% utilization on one occasion, it did not maintain a utilization percentage outside the 75% threshold for the entire transfer as did the raw data transfer. Particularly in a combat environment, a reduction of 35% in total network utilization is of significant value.

CHAPTER FIVE: FUTURE RESEARCH

Further research is required to determine if ERDAS software is the solution most appropriate and supportable for the military to enhance network performance and allow for the timely transfer of imagery data. First, it may be advantageous to use ECW in place of MrSID in the UAS-to-GCS downlink, reducing imagery file size and network utilization at the outset.

Second, the issue of compressing RPF and DTED data needs to be addressed. Although these files are significantly smaller than the MrSID imagery files, not being ECW-compatible prevents these files from being handled transparently with ERDAS products used to compress, store, or retrieve imagery and introduces unnecessary complexity (along with network burden) whenever the files are accessed. The ability of software to process all data relevant to UASs is essential to improve the efficiency of the network, promote dissemination, and reduce the burden on both bandwidth and storage.

A third concern relates to the need for data management in the Marine Corps. Apollo Data Manager (ADM) is a companion product to Imagine, integral to the ERDAS software suite, that allows users to comprehensively manage and deliver massive amounts of file-based and Web-enabled data (ERDAS, 2009). The ADM is capable of managing terabytes of data through an enterprise-class system, which "catalogs information through metadata and provides a user-friendly interface allowing users to easily modify server configuration parameters" (ERDAS, 2012). The Apollo

Web client supplied with ADM delivers data quickly through Web service interfaces, allowing customers to easily find and deliver data through custom designed websites that support commonly used GIS and CAD software packages (ERDAS, 2012). ERDAS itself provides an "out-of-the-box" Web client (Figure 11).

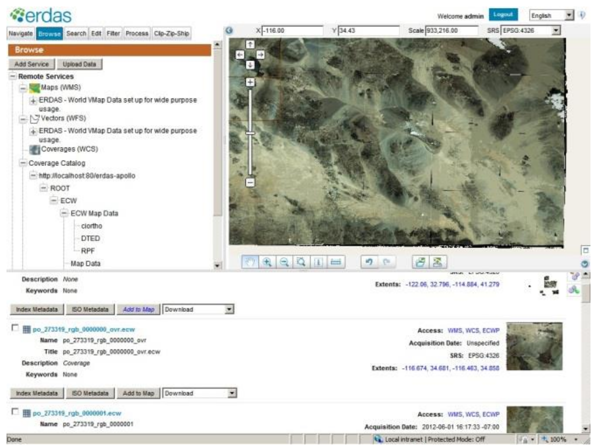

Figure 11: Apollo Web Client.

However, Microsoft SharePoint®, a web portal that centralizes information and applications, is inoperable with Apollo Web client. SharePoint is the primary means of sharing data in the Marine Corps and the ability to embed Apollo within SharePoint will not only support timely dissemination but will also prevent data from being retrieved from and stored in multiple locations. Solving the authentication issue that arises when Apollo Web client is embedded into SharePoint would allow the user to retrieve imagery data while maintaining view of the additional "Web parts" on the page, increasing situational awareness and promoting speedy decision-making.

In addition to ECW compression tests, a follow-on test was conducted importing the compressed data into ADM and publishing it on the web through Web client and Microsoft SharePoint. The goal was to establish a link between Apollo Web client and Microsoft SharePoint to support accessibility and retrieval of all stored map data.

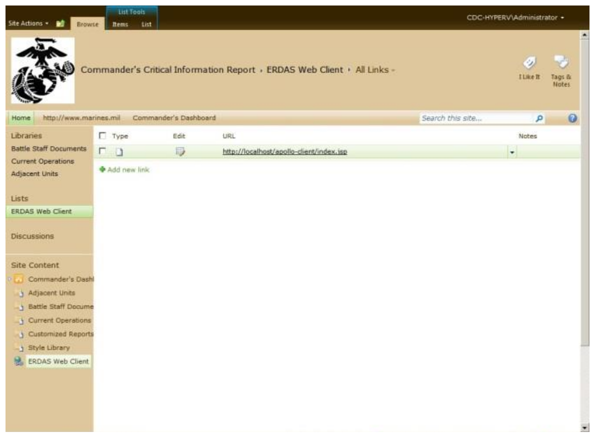

Figure 12: SharePoint® site with Apollo Web Client link.

A SharePoint site was established, as well as an additional collection of sites to including Shared Document Libraries, Web Parts and a Commander’s comprehensive “dashboard” to simulate the basic design of SharePoint Portals used by the Marine Corps (Figure 12). The tests determined that the ERDAS Imagine software catalog file list was viewable through Microsoft SharePoint 2010; however, authentication to the ERDAS FireLogin, a utility that identifies users and passwords, failed while viewing the Apollo Web Client through SharePoint, with the result that the actual images were not displayable. The only option was to create a link to the Apollo Web Client website on the SharePoint site for use as a pass through to reach the Web client.

CONCLUSION

This research provides a possible solution to the bandwidth burdens placed on military battlefield networks, specifically due to the increased reliance on UAS data for mission accomplishment. The employment of UASs will continue to grow and the amount of data collected will increase substantially as UAS technology advances and these systems' flight time and onboard storage increase, but the number of communications nodes will not be significantly expanded. The GCS data communications systems deployed in support of UAS operations are designed to be tactical and easily transported, and increasing the number of systems defeats this purpose. Finding a solution to the bandwidth burden placed on the network by the sudden abundance of UAS-collected data allows for the UASs to collect as much intelligence as possible and for military personnel to access that information in a timely manner. Commercial software such as ERDAS' Imagine and Apollo provide a possible solution to improving the bandwidth utilization of the limited battlefield networking resources available to the military. In order for these commercial solutions to be beneficial though, further research is required to allow interoperability between other software, such as SharePoint, already widely used within the military. Still, finding a solution to bandwidth limitations to support the benefits of UAS imagery data is critical to future military operations. Lives depend on it.

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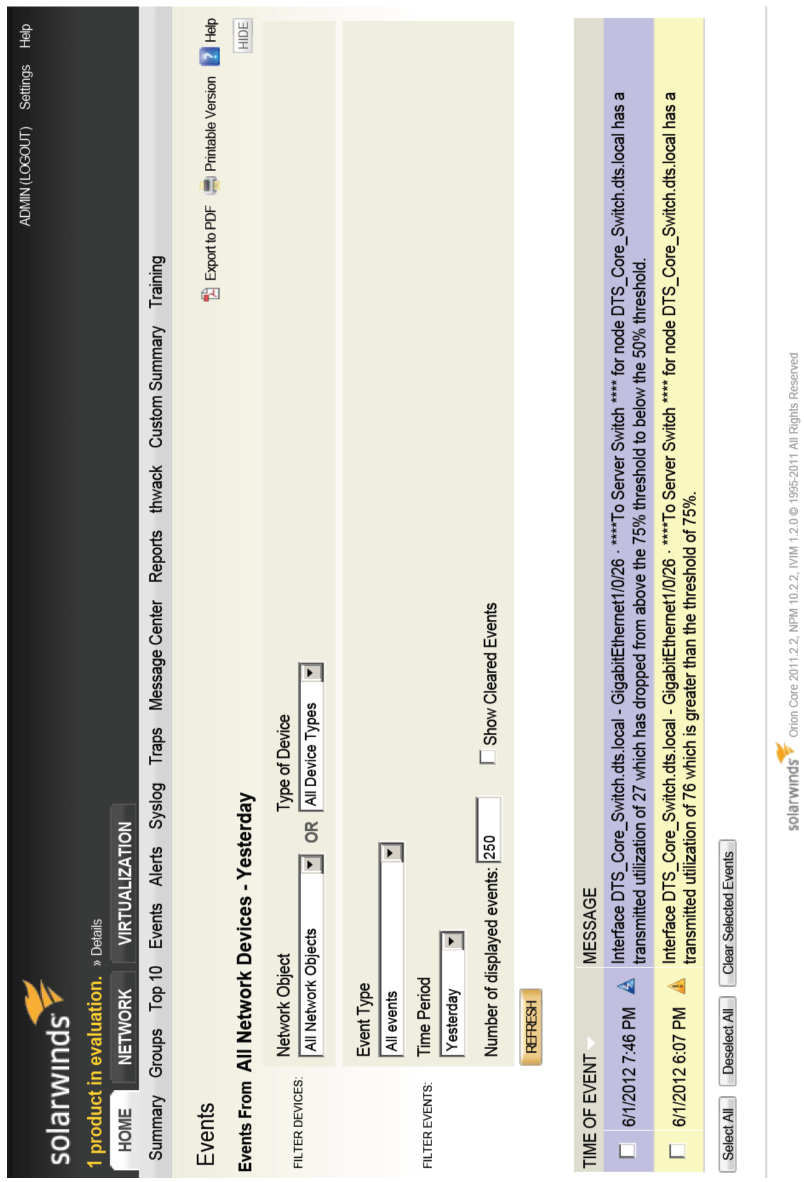
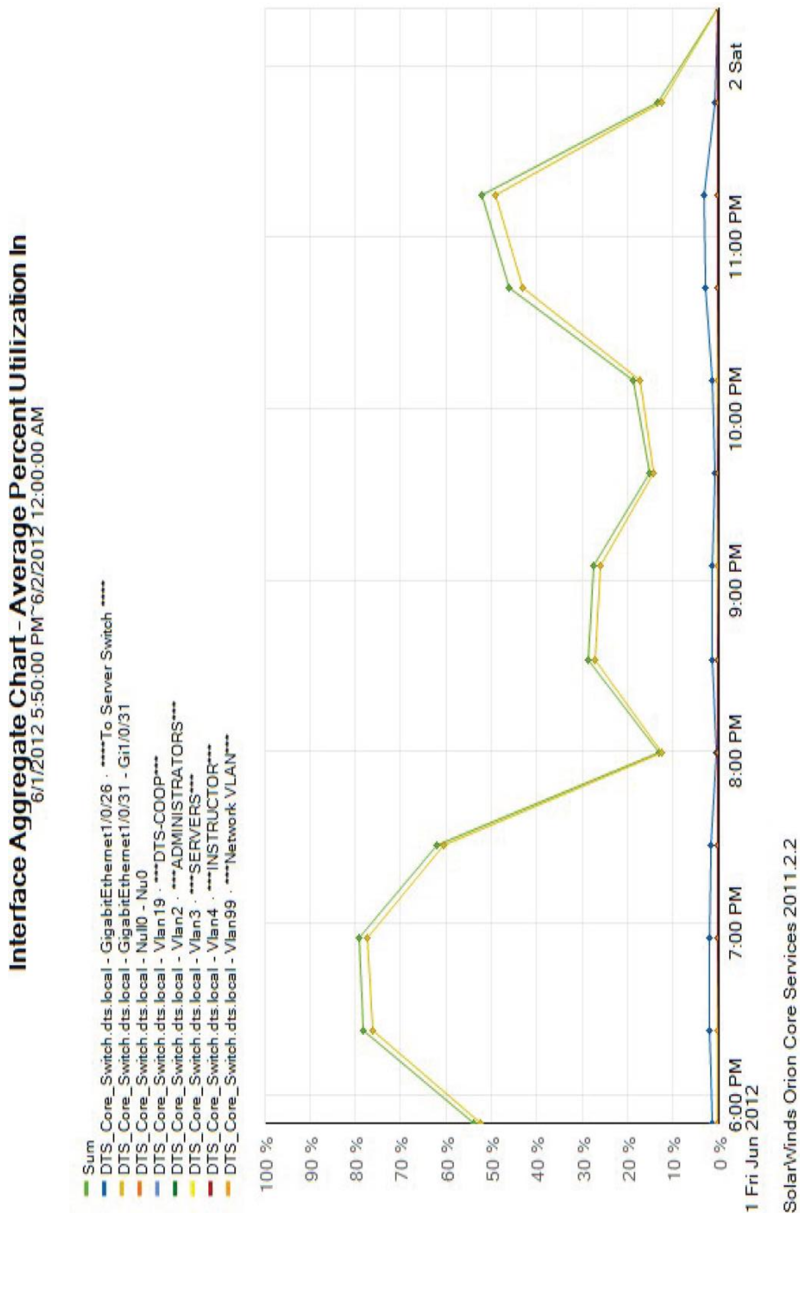
APPENDIX A

EVENTS LOG FROM SOLARWINDS



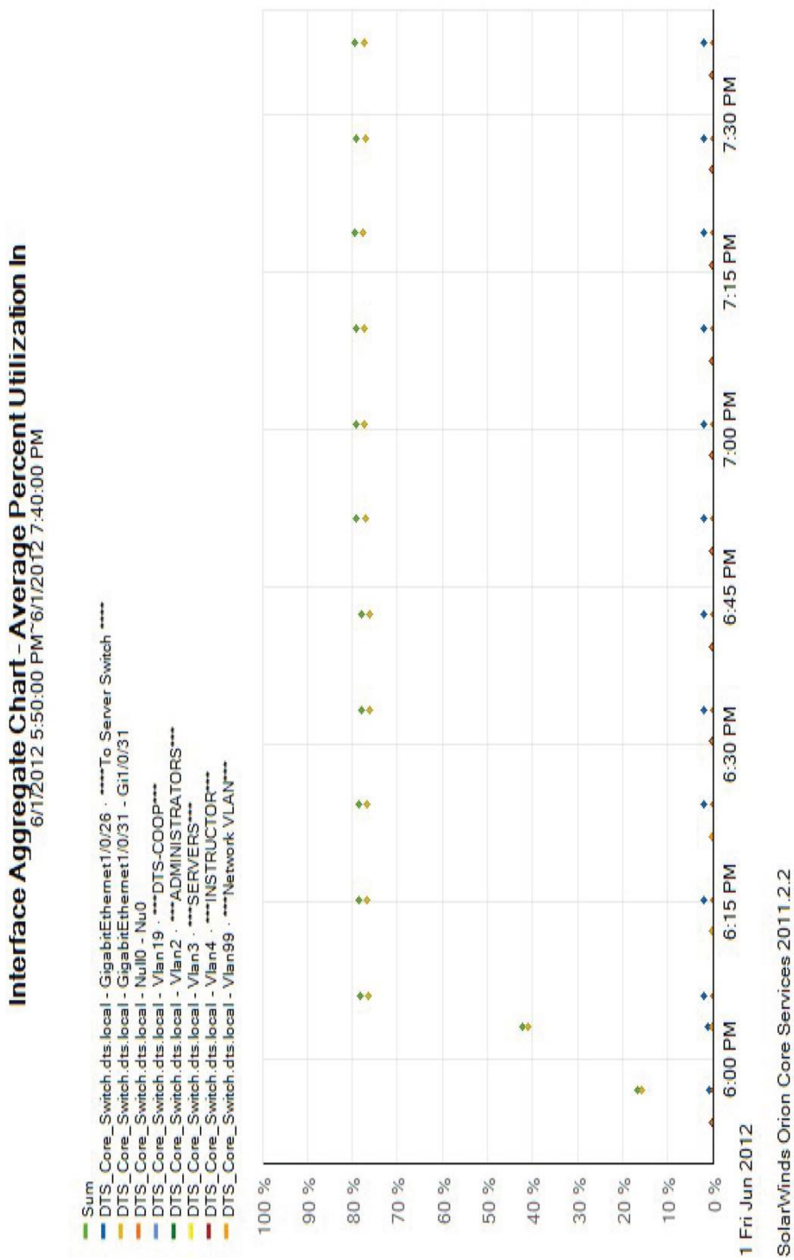
APPENDIX B

TOTAL BANDWIDTH UTILIZATION THROUGHOUT DATA TRANSFER FROM SOLARWINDS



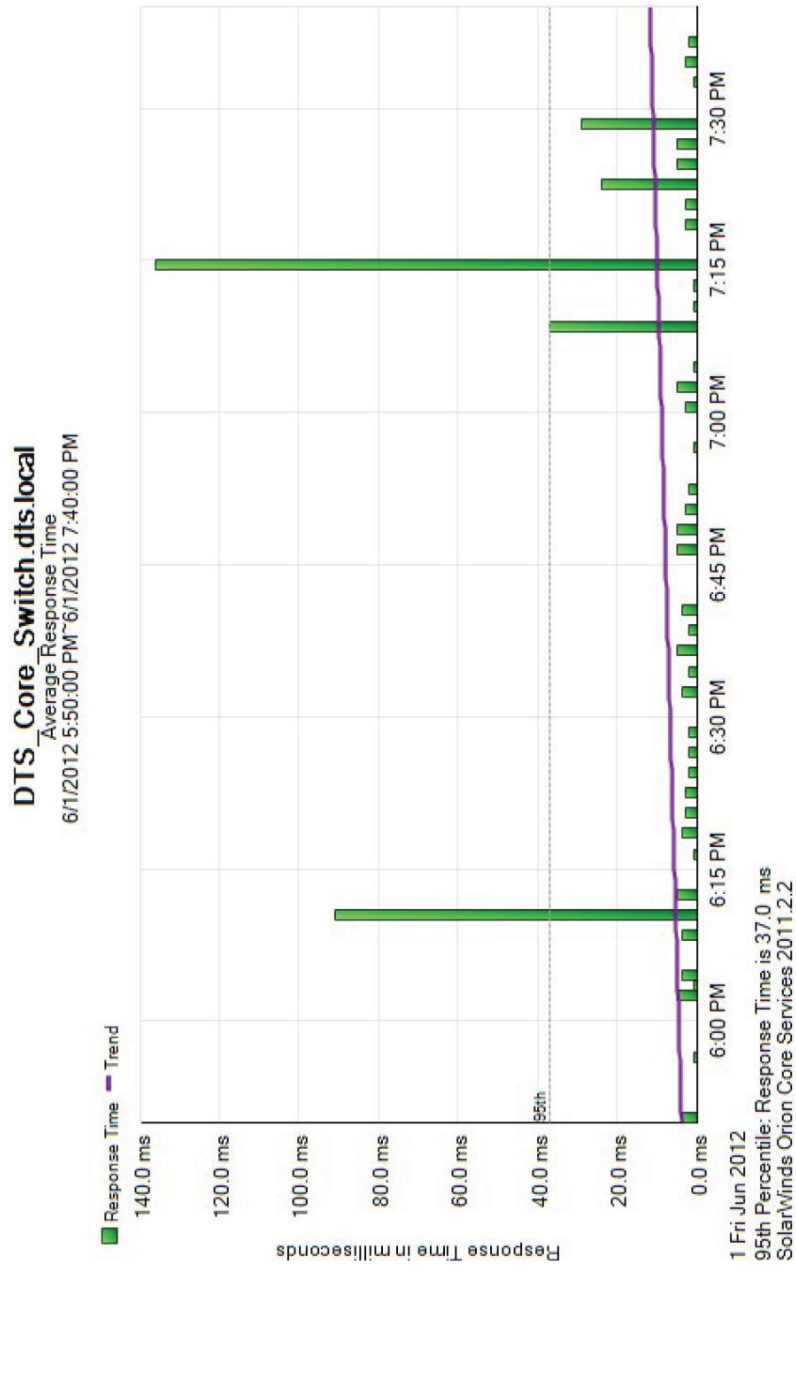
APPENDIX C

RAW DATA TRANSFER BANDWIDTH UTILIZATION FROM SOLARWINDS



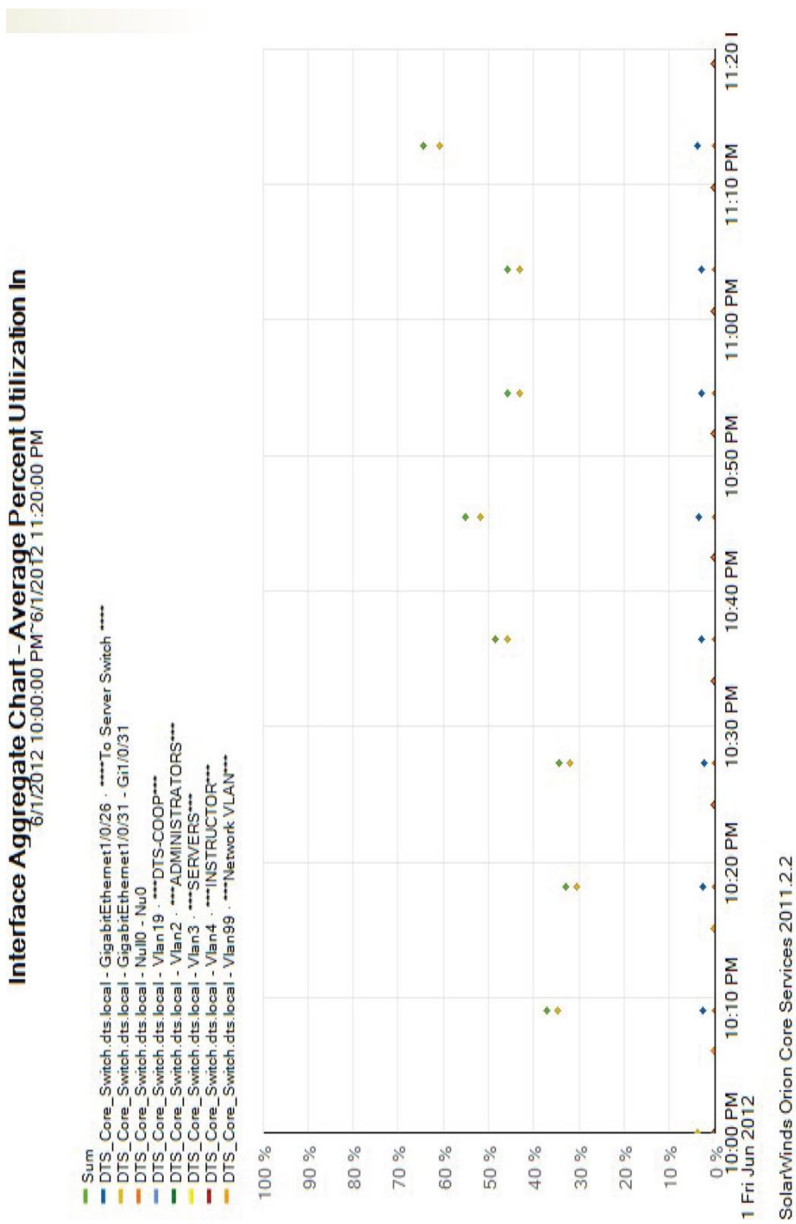
APPENDIX D

RAW DATA TRANSFER RESPONSE TIME FROM SOLARWINDS



APPENDIX E

ECW DATA TRANSFER UTILIZATION FROM SOLARWINDS



APPENDIX F

ECW DATA TRANSFER RESPONSE TIME FROM SOLARWINDS