Aerial Image Databases for Pipeline Rights-of-Way Management

Mark A. Jadkowski, Patrick Convery, Ronald J. Birk, and Shihjong Kuo

Abstract
Pipeline companies that own and manage extensive rights-of-way corridors are faced with ever-increasing regulatory pressures, operating issues, and the need to remain competitive in today's marketplace. Automation has long been an answer to the problem of having to do more work with less people, and Automated Mapping/Facilities Management/Geographic Information Systems (AM/FM/GIS) solutions have been implemented at several pipeline companies. Until recently, the ability to cost-effectively acquire and incorporate up-to-date aerial imagery into these computerized systems has been out of the reach of most users. NASA's Earth Observations Commercial Applications Program (EOCAP) is providing a means by which pipeline companies can bridge this gap. The EOCAP project described in this paper includes a unique partnership with NASA and James W. Sewall Company to develop an aircraft-mounted digital camera system and a ground-based computer system to geometrically correct and efficiently store and handle the digital aerial images in an AM/FM/GIS environment.

This paper provides a synopsis of the project, including details on (1) the need for aerial imagery, (2) NASA's interest and role in the project, (3) the design of a Digital Aerial Rights-of-Way Monitoring System, (4) image georeferencing strategies for pipeline applications, and (5) commercialization of the EOCAP technology through a prototype project at Algonquin Gas Transmission Company which operates major gas pipelines in New England, New York, and New Jersey.

Introduction
Pipeline companies are faced with ever-increasing regulatory and operating pressures. New regulations are proposed or enacted each year that require mapping, facility inventories, pipe inspections, rehabilitation, environmental reporting, and public safety and notification programs (see Figure 1). These pressures are compounded by the need to stay competitive in today's rapidly changing marketplace.

Automation has long been an answer to the problem of having to do more work with less people, and AM/FM/GIS solutions are being proposed and implemented at a number of pipeline companies. The U.S. pipeline industry, which operates over 453,000 miles of gas, crude, and refined products lines, is expected to be a significant growth segment of the AM/FM/GIS market. Important issues such as oil pipeline database design and implementation have been largely neglected.

Pipeline companies index and track the location of their facilities using a system of survey stations which can at times baffle even the most seasoned AM/FM/GIS professional. A small pipeline system can cross three or four state boundaries and map coordinate systems. A medium-sized company can have as many as 50 district offices which may require on-line AM/FM/GIS accessibility. A large company might operate over 30,000 miles of pipeline and manage 15,000 miles of rights-of-way and associated parcel easement records!

These and other technical issues suggest the need for new and innovative mapping techniques, database design and management strategies, and approaches to providing system accessibility.

Until the development of digital aerial photographic imagery, the ability to cost-effectively acquire and incorporate up-to-date land information into an AM/FM/GIS had been out of the reach of most pipeline companies. Existing alignment sheets, the most common pipeline facility maps, are almost always out of date. New photogrammetric mapping is cost-prohibitive in most cases. Existing county maps and U.S. Geological Survey 7.5-minute quadrangle maps are not detailed enough. Satellite imagery is too coarse in resolution, and manual handling of hundreds or thousands of hard copy aerial photographs is unmanageable.

The use of digital aerial photography provides an economic and versatile alternative. The images provide the location of roads, hydrography, wetlands, cleared rights-of-way, structures, and other cultural features. Image processing is a mature technology which has been made affordable through competition in the desktop publishing industry. Disk storage capacity and laser printers capable of producing sharp images are relatively inexpensive. Today, major vendors of AM/FM/GIS systems provide the capability to integrate computerized aerial images with a facilities database. With these developments, it is possible to perform rapid on-line query and display of aerial photography for day-to-day operations of pipeline emergency management.

NASA's Earth Observations Commercial Applications Program
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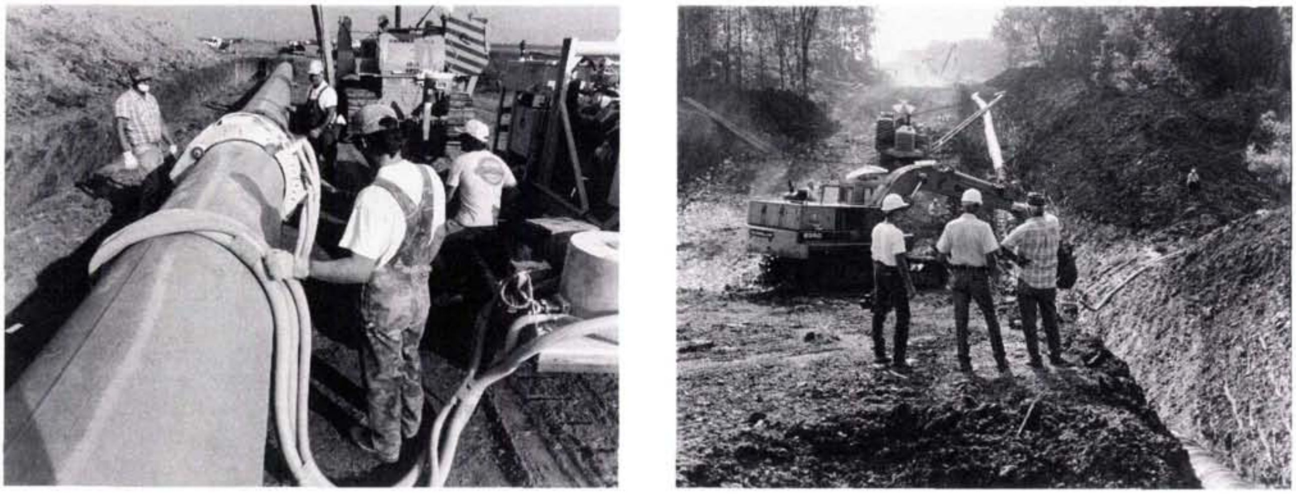


Figure 1. Pipeline rehabilitation project underway.

submitted a winning proposal to the National Aeronautics and Space Administration (NASA) to develop an aerial photography-based system that can be used commercially for pipeline management. A third partner in this development effort is NASA's John C. Stennis Space Center. Stennis Space Center's role in the project is to provide access to NASA technological resources. Sewall is the prime contractor, and Algonquin together with its parent, Panhandle Eastern Corporation, are responsible for defining all operational parameters. The project was funded by NASA's Earth Observations Commercial Applications Program (EOCAP). The goal of EOCAP is to commercialize remote sensing technology originally developed to support scientific and space exploration missions.

The technical objectives of the EOCAP project are threefold. First, the Project Team is developing a computerized system of storing and retrieving digital aerial photography of pipeline rights-of-way. The computerized system provides an accurate inventory of rights-of-way locations and pipeline surroundings for engineering, maintenance, and regulatory purposes. The system also provides very rapid access to much needed information in case of emergencies. It should be noted that the original scope of the project also included the use of satellite imagery. After further defining the functional parameters necessary for digital imagery to be useful for pipeline AM/FM/GIS applications, it became clear that the spatial resolution offered by commercial satellite technology could not fulfill most user needs. The two commercial Earth observation satellite systems operating today, SPOT and EOSAT, offer 10-metre and 30-metre spatial resolutions, respectively, whereas optimal image resolutions for most pipeline applications range between 0.3 and 1.0 metres.

The second technical objective of the project is to adapt a digital camera system for more routine aerial pipeline rights-of-way monitoring. The Digital Aerial Rights-of-Way Monitoring System (DARMS) was designed and assembled for this purpose from commercially available components and specialized software. A similar system had already been developed and tested by NASA for scientific research applications. The pictures taken directly with the digital camera are stored and managed in the same computerized system as storage and retrieval of scanned pipeline aerial photography.

The third technical objective of the EOCAP project is to unite the digital aerial images described above with Algonquin's AM/FM/GIS system development. This involves the development of a series of specialized computer programs that facilitate pipeline-specific applications. This effort serves as a prototype project that will be used to refine the results from the EOCAP technical initiatives in marketable products.

Pipeline Monitoring

Many monitoring applications of digital aerial photography exist for pipeline rights-of-way, including general map updating, marketing, pipeline planning, and wetland delineation. Pipeline companies that handle crude and refined products are concerned with environmental damage from pipe rupture. They can use the imagery for locating sensitive areas and to plan access and boom placement in case of emergencies.

Gas pipeline companies are required to perform annual dwelling surveys. The surveys are federally mandated by the Department of Transportation as a function of its jurisdiction over pipeline safety issues.

These studies involve the determination of dwelling densities within 200 metres of each pipeline. There are four density classifications that are used to set the operating stress level for the pipeline. The higher the dwelling or population density, the lower the stress level in the pipeline. It is common for a company to have to decrease the movement of gas or replace a pipeline at costs of millions of dollars because of the construction of a few dwellings. Digital aerial photography in an AM/FM/GIS can greatly add to the efficiency with which pipelines are monitored and the accuracy of these regular safety-related surveys. However, the cost of flying, processing, and then scanning conventional aerial photography can still be cost-prohibitive for a large pipeline company. The technical solution to this economic problem is to cut costs drastically through the use of a low-cost and

Table 1. DARMS Engineering Specifications.

Lens compatibility:	C-mount, 2/3"	Aircraft speed:	280 km/hr (typical)
Lens focal length:	16-28 mm	Flight altitude:	1700–3000 metres
Pixel FOV:	0.24-0.42 mrad	GPS data recorded:	Lat/long, velocity, time
Frame width (TFOV):	1000 metres	Image digitization:	8 bit
Frame overlap:	Up to 70%	Video output:	RS-170
Resolution:	1320H × 1035V	Data frame format:	1320 × 1035 pixels
Spectral response:	0.4-0.7 μm	Image throughput:	500 kB per second
Exposure time:	1 ms	Storage capacity:	4.9 Gbytes per tape
Flight monitor:	RS-170, 9"	Interface:	SCSI-2
Computer display:	SVGA	Compatibility:	Zeiss camera mount
Keyboard functions:	REC/PAUSE/STOP	Chassis:	Shock-mounting
Total weight	36 kg	Power:	110VAC, 300W

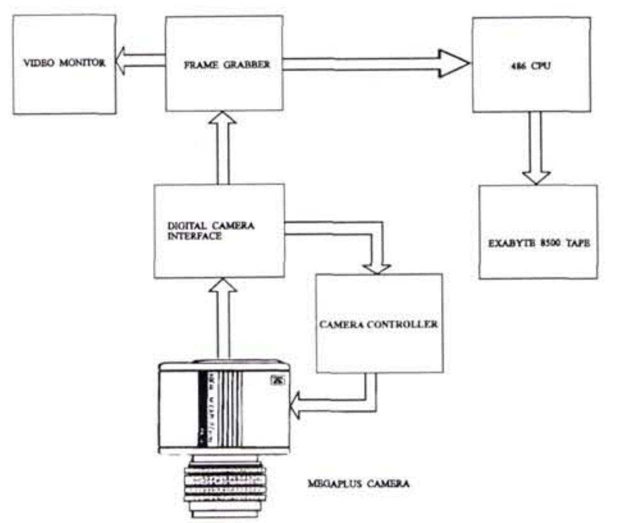


Figure 2. Block diagram of the major camera system components.

simple-to-operate digital camera system for monitoring pipeline rights-of-way.

Digital Aerial Rights-of-Way Monitoring System

The Digital Aerial Rights-of-Way Monitoring System, or DARMS, is a PC-based digital charged-coupled-device (CCD) camera integrated with a high-capacity tape recorder. DARMS was developed through NASA by the Stennis Space Center for use in a Sewall aircraft. Sewall is responsible for its operational testing and the development of image products for pipeline monitoring.

DARMS consists of a PC main control unit (MCU), Kodak Megaplus 1.4 CCD camera head, a monochrome video monitor for in-flight operation, and an Exabyte 8500 8-mm tape recorder for image data storage. Figure 2 shows a block diagram of the major camera system components. The key operational characteristics of this system include

- Ground pixel resolutions of 0.6 to 1.0 metres;
- A 1000-metre cross-track swath that provides adequate coverage for pipeline safety surveys;
- Simple in-flight single pilot operation using "RECORD," "PAUSE," and "STOP" buttons;
- Spatial overlap between successive frames of up to 70 percent;
- Three-hour recording capacity for continuous recording over long rights-of-way; and
- Positioning and time-tagging of each image frame using data from a Global Positioning System (GPS) receiver mounted in the aircraft.

DARMS is designed to be operated in a small unpressurized aircraft flown by a single pilot. The pilot controls DARMS operation with a mini-keyboard using the DARMS Control Program (DCP) which is specially developed software that runs under DOS. After the power is turned on, the MCU boots up, loads DCP, and lets the software DCP take control of the system. A subsystem functional check is performed, and then DCP goes into a "PAUSE" mode. In this mode, the system acquires and displays images periodically but does not record any images to the tape recorder. In the "RECORD" mode, images are acquired, written to the tape recorder, and displayed on the video monitor. The DCP will exit DOS when instructed by the pilot using the "STOP" command, or when the capacity of the tape cartridge is reached. Images are acquired at a fixed rate to obtain consistent spatial overlap between successive frames. GPS data are received from a Trimble TNL 2000 receiver and written to the tape along with each image frame.

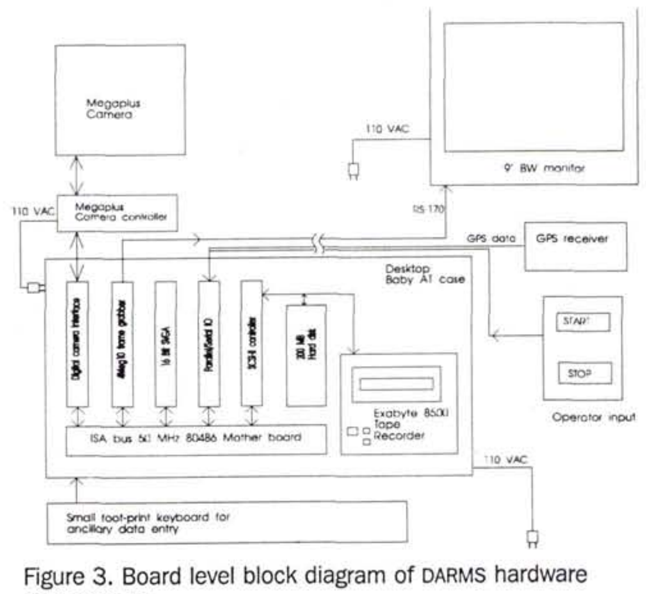
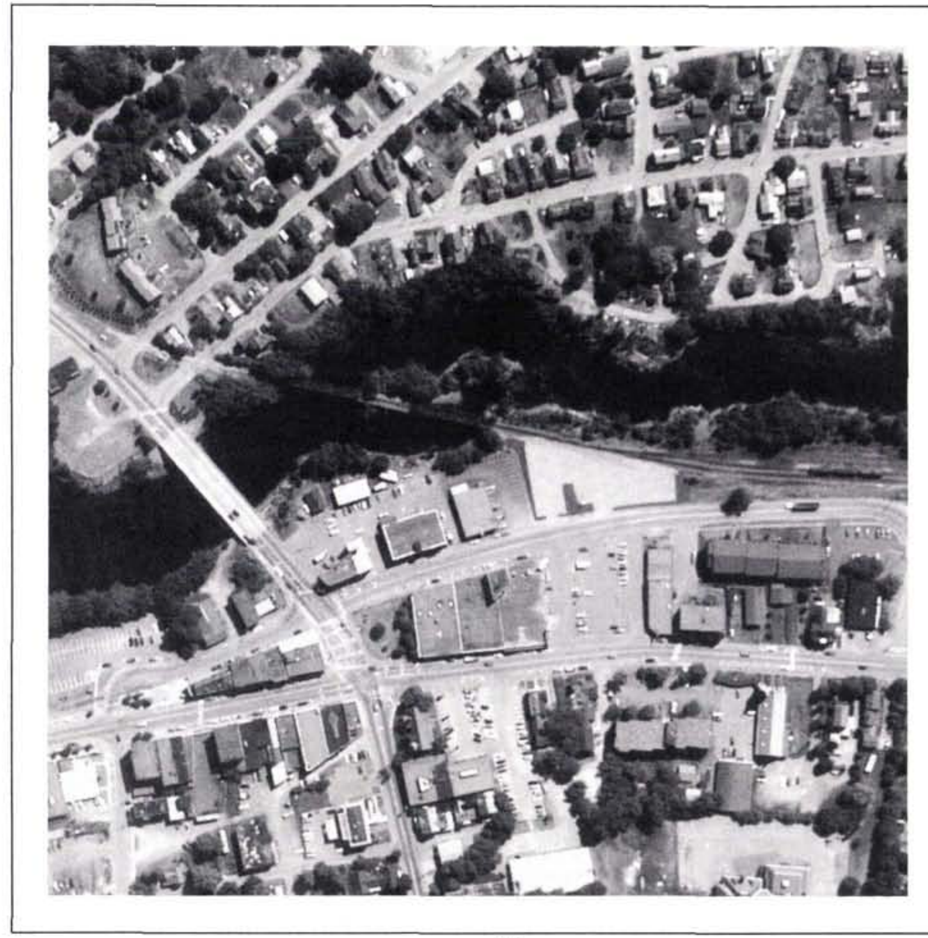


Figure 3. Board level block diagram of DARMS hardware components.

(a)



(b)

Figure 4. (a) Scanned aerial photography for a test area near Bangor, Maine. Pixel size is 0.6 metres. (b) DARMS image for the same area near Bangor, Maine. Pixel size is 0.6 metres.

The Kodak Megaplus 1.4 camera head, which uses a CCD array, provides frame images of 1320H by 1035V pixels. The 1320H axis of the camera is oriented across the direction of flight. High-speed 17-mm and 19-mm focal length lenses are used with the camera head at a design aircraft altitude of 2000 metres. The CCD array has square pixels 6.8 micrometres on each side with a 100 percent fill factor. The spectral response of the camera head is 400 to 700 nm using an IR filter. Pixel blurring is reduced to less than 0.3 metres by using exposure times shorter than 2 ms. Image data, GPS data, ancillary mission data, and system configuration data are merged into each data frame. High speed digital recording to an Exabyte 8500 tape drive is then performed. The Exabyte 8500 tape drive has a maximum capacity of 4.9 GB and continuous data throughput of 500 kB per sec. The maximum recording rate for DARMS is 0.33 image frames per second. At a ground speed of 75 metres per second, the spatial overlap between successive frames is 70 percent. The maximum recording capacity at 0.1 metres per second is 2 hr 55 min (approximately 800 kilometres of rights-of-way). Table 1 provides DARMS engineering specifications. Figure 3 provides a board level diagram of the DARMS hardware components.

The DCP software provides a highly autonomous turnkey operation that is needed for operation by a single pilot. Once a mission has been flown, the Exabyte tape is loaded onto a Sun workstation and the images are contrast-balanced and spatially enhanced using a mid-high filtering algorithm. Depending on client requirements, the images may also be georeferenced to a coordinate system or mosaicked "pixels" together. The resulting image frames are indexed using their GPS location, delivered to the client, and archived. Figure 4 compares a DARMS image for a test area near Bangor, Maine to a conventional aerial photograph that was scanned at an equivalent spatial resolution.

Georeferencing Strategies

In order for digital aerial images (either scanned conventional photography or DARMS) to be most useful in an AM/FM/GIS environment, they must be georeferenced to a map projection and coordinate system. In this way, surveyed pipeline alignments and other reference map features, such as political and tax boundaries, can be graphically superimposed on the images relative to their coordinate locations. Similarly, digital map information available from municipalities and governmental agencies and other utilities, such as parcel boundaries, wetland and soil classification, and underground facilities, can also be utilized with the imagery.

Aerial photography that has been corrected to a map projection and coordinate system is generally referred to as "orthophotography." Orthophotography can be made through a variety of photo-optical or digital processes that attempt to remove the effects of tilt, relief, and lens distortion from standard perspective aerial views. Three computerized methods of geometrically correcting aerial photography have been evaluated for pipeline applications:

- Polynomial rectification,
- The finite element method, and
- Photogrammetric terrain corrections.

All three methods rely on knowledge of the ground coordinates of a certain number of picture points, such as road crossings or structures, to relate the image to a reference map. They differ in the required number of "ground control points" and in how these points are used to correct the image. Additionally, digital photogrammetric terrain corrections require a digital terrain model (DTM) to correct relief distortions due to changing topography along the pipeline. The three methods also differ in accuracy, reliability, and cost.

After careful evaluation, it has been concluded that polynomial rectifications, while being the most simple and inexpensive, are not accurate or reliable enough for most pipeline AM/FM/GIS applications. Photogrammetric terrain corrections, while the most accurate and reliable, are simply too expensive to implement. This is due to the costs involved in controlling the photography and creating accurate DTMs. The finite element method provides the best practical compromise between technical and cost considerations, and is able to account for local relief distortions. This method is capable of providing consistently useful imagery for pipeline applications.

Commercial Implementation

As a result of a Corporate AM/FM/GIS Requirements Study and successful pilot project, Algonquin initiated MAPS (Mapping Algonquin's Pipeline System). The objective of MAPS is the development of an operational image-based AM/FM/GIS to replace Algonquin's current method of manual mapping and facilities information management. The project is currently in the third year of its four-year implementation period. The project also serves as a test case for commercial implementation of the digital image technologies being developed through EOCAP.

The MAPS project consists of a five-step AM/FM/GIS system building process, followed by continuing maintenance. These steps include

- System design and software/hardware selection,
- Tabular facilities database development,
- Digital mapping and aerial image processing,
- AM/FM/GIS application programming, and
- Database maintenance and ongoing operations.

It is important to note that these technical initiatives are being carried out concurrently rather than sequentially. This concurrent implementation approach allows Algonquin to focus its efforts on completing priority applications and databases.

Tabular facilities database development, digital mapping, and aerial image processing are being developed concurrently. Many pipeline AM/FM/GIS applications, such as annual DOT facility inventory reports, can be accomplished using tabular information only. This information can be assembled relatively quickly, and the effort can be phased by priority application. Prior to the MAPS project, Algonquin had started a simple database with basic pipe information. After careful quality control procedures, edits, updating, and restructuring, these data were incorporated into MAPS.

A base map of Algonquin's pipeline is required to provide information on roads, railroads, cultural features, hydrography, and political boundaries. In addition, a base map provides a geographic foundation onto which other data, such as digital aerial photography, can be referenced with consistency. The MAPS project utilizes U.S. Geological Survey 7.5-minute quadrangle base maps for this purpose. These maps were available in digital form from state and federal agencies for approximately 50 percent of Algonquin's rights-of-way. These existing digital maps required significant format translations, edge-matching, quality assurance, and editing. Base maps for the remaining 50 percent of the rights-of-way were digitized using a scanning and semiautomated line-following approach, at a higher cost than incorporating

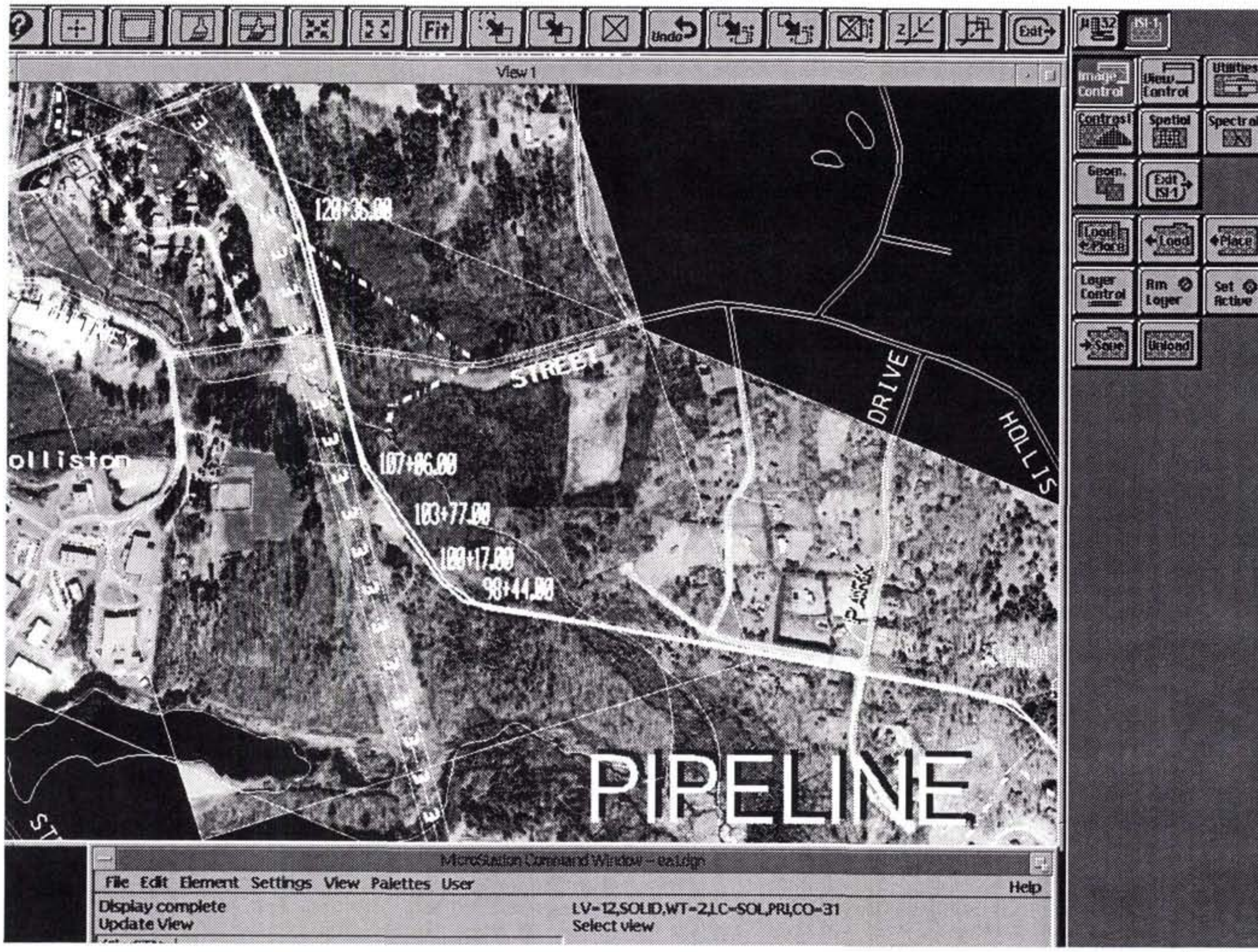


Figure 5. MAPS aerial photograph displayed on a computer screen together with graphic pipeline overlay.

the digital data. A base map two miles wide and centered on Algonquin's rights-of-way was created utilizing these procedures.

The processing of aerial imagery for the MAPS project involves four procedures:

- Aerial photo acquisition,
- Digitization or scanning,
- Distortion removal using the finite element method, and
- Preparation of final file layouts.

All photography was taken using black-and-white aerial film. In the future, film photography will be updated with DARMS imagery.

Algonquin's aerial photography was flown by Sewall at two scales: 1:14,400 and 1:18,000. Each photograph is scanned at a density required to produce 0.6-metre picture elements or "pixels." The instrument used for scanning was a Sharp JX600R that is capable of scanning black-and-white or color negative and positive transparencies and paper prints. The scanned aerial photographs were then georeferenced to the base map using the finite element method. The final procedures involved contrast enhancements, merging images into mosaics of a predetermined size and layout, and file format translations to make the digital images compatible with Algonquin's computer systems.

The mapping of Algonquin's pipeline alignments was accomplished through several processes. First, pipeline alignments were computed with a least-squares computation procedure using original as-built survey data. This procedure utilizes map coordinates at road crossings and other distinguishable base map features as a reference, and "best fits" the survey data between the known points on the base map. In some instances, the digital base maps provide insufficient detail for the above process. In these cases, the coordinates of reference points can be established using the Global Positioning System (GPS). Where the use of GPS is not possible due to cost constraints, an approximate pipeline alignment was established by tracing the centerline of the maintained Algonquin rights-of-way from the georeferenced digital images (where visible). An integrated base map, aerial image, and pipeline alignment product is shown in Figure 5.

Algonquin is building its AM/FM/GIS utilizing the map and image products described above. A key ingredient to the success of its MAPS project and the EOCAP commercialization effort will be the extent to which specialized pipeline application programs can be developed to make the data useful. An application program is used to customize an off-the-shelf AM/FM/GIS software package to meet special needs, and allows the users to reap the full benefits of having integrated data available though a single system. In short, application programs make the system simpler and easier to use. Application programs being developed for MAPS include those to

- Create hard copy alignment sheets,
- Perform class location safety studies,
- Support gas flow studies,
- Support dig-safe and emergency response,
- Facilitate maintenance scheduling,
- Support risk-based pipeline integrity programs, and
- Produce numerous statistics and summaries needed to support various regulatory governmental reporting obligations.

Conclusions

Digital scanned aerial photographs provide a wealth of important information for pipeline monitoring and management. These images are most useful when utilized in an AM/FM/GIS environment. CCD-based digital cameras can also be adapted for airborne use in pipeline rights-of-way monitoring. These fully digital systems have the potential for substantially reducing monitoring costs, thereby allowing more frequent aerial overflights. The finite element method was determined to be the most practical and cost-effective method for georeferencing digital aerial images to collateral maps and AM/FM/GIS data sets.

There are several new and upcoming developments related to digital aerial photography that are worth noting. The U.S. Departments of Interior and Agriculture are co-funding the development of digital orthophotography for the entire United States. This exciting initiative is about to begin and is expected to take five years to complete. The benefits of integrating digital aerial photography and AM/FM/GIS are not limited to the pipeline industry. We look forward to some exciting developments in transportation, electric transmission, and other corridor applications.

The NASA EOCAP project is a vital component of Sewall's development of future innovative services. It has afforded the company the opportunity to stay on the cutting edge of change detection techniques by supplying research and development and market testing funding as a valuable commodity.

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References

Brown, Dennis H., and Mark A. Jadkowski, 1993. Aerial Image Databases for Gas Transmission Rights-of-Way, presented at AM/FM International Conference XVI, March.

Jadkowski, Mark A., 1993. Digital Aerial Photography For Pipeline Management, *AM/FM/GIS Networks*, 9(1):10-11.

Kuo, Shihjong, 1993. *High Resolution Airborne Video Imaging System*, Sverdrup Technology, SSC Group.