Image Processing on Open Systems

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ABSTRACT: Autometric has developed a series of image processing workstations. The consistent feature of these workstations is the use of open systems hardware and software. Through the use of open systems, Autometric has created a family of image workstations that can be easily upgraded to the most recent hardware engine—without the need to make extensive software changes. The common user interface which has been developed implements an X-Windows/Motif presentation.

The PEGASUS™ workstation is a stereo compilation and elevation extraction workstation. It provides the capability of triangulating and performing compilation operations on any differentially perspective imagery, to include panoramic, SPOT, strip, and frame imagery. The WINGS™ workstation allows for the interactive generation of image perspective transformations so that terrain may be viewed from any desired direction.

INTRODUCTION

SOFTCOPY TREATMENT OF NON-METRIC CAMERA SYSTEMS, which require rectification or at least dynamic rotation of the image for stereo viewing, has recently become possible at speeds approximating those possible with hardcopy analytical stereoplotters using components which are available off-the-shelf. Furthermore, many of these systems conform to accepted standards within the computer industry, commonly referred to as open systems, which enhances the portability of software systems to upgraded versions of hardware. Open systems, in this context, describe those computer hardware and software systems which conform to standards promulgated by the Open Software Foundation (OSF), and other commonly accepted industry standards for use on UNIX (originally developed by AT&T Bell Laboratories) workstations such as X-Windows (developed by Massachusetts Institute of Technology) , MOTIF (MOTIF is a screen management system developed by the OSF), and the VME bus structure.

Two systems developed by Autometric, Inc. will be described. Based upon experience gained in the development of these systems, the authors have developed several opinions relating to the shortfalls of currently available off-the-shelf hardware and software capabilities for softcopy image processing which will be discussed. The authors will also present their vision of the future trends in the marketplace, based upon their experience in developing systems for the military community over the last 15 years.

BACKGROUND

Techniques for softcopy processing of imagery data have been known for at least 16 years (Autometric fielded its first softcopy image processing system for a classified customer in 1975). Until recently, processing of imagery in reasonable time by computer required a significant investment in either custom hardware or supercomputer technology (Gruen, 1989). Companies such as COMTAL, DeAnza, Pixar, and others grew up largely based upon their special-purpose hardware for the processing of imagery.

Although some impressive results were achieved with these special-purpose hardware systems, developers often completed the development of software for a particular system at just about the time that another, incompatible, hardware system with better capabilities was announced to the marketplace. Each hardware system required significantly different programming techniques to take advantage of the capabilities of the hardware (Gruen, 1989). Thus, the cost of changing to new hardware engines was very high. In fact, there are several instances in which installations are still buying hardware models for which marketing was discontinued over five years ago. There is no question that the hardware is unreliable and outmoded, but the cost of upgrading these operating facilities to new hardware systems precludes that approach.

For those who developed custom hardware systems for their particular application, the results have been even worse. History shows several custom developments costing millions of dollars which, when finally delivered, were only slightly more capable than commercially available hardware systems which had been developed in the intervening time interval (Case, 1982).

Approximately five years ago, several image processing systems became available which used personal computing hardware. Although these systems frequently used special-purpose processing boards, and generally restricted their functionality to rather simple photometric processing and photogrammetric processing of metric or frame camera imagery, they provided a capability to the user which was less likely to be obsoleted by the next wave of hardware development. Leica's DVP, for instance, processes any imagery which will permit viewing of stereo by simple translation of the imagery without rotation and resampling to an epipolar plane (LEICA product literature).

Autometric produced the APPS-IV analytical plotter for use with hardcopy film for many years. We had intended to implement such an instrument in softcopy, but were reluctant to develop custom hardware to achieve the processing speeds necessary, and the processing speeds which were available on either personal computers or engineering workstations were not sufficient to solve our customers' problems. With the advent of the high-speed processors, 20 Million Instructions Per Second (MIPS) and higher, in workstations coupled with wide bandwidth communication bus structures on the order of 20 megabytes per second and greater, the possibility of providing non-metric photogrammetric processing in a standard hardware chassis at speeds rivaling production rates in standard hardcopy analytical plotters became apparent. In 1987, Autometric began the development of the systems which are described in this paper, using an image processing computer to provide the high-speed capability. The image computer has recently been removed from the system, because the processing capability of the standard workstations now provides enough power to perform all functions required in suitable response time.

We are finally at the point where software for most applications can be written on computers of sufficient power to solve rigorous photogrammetric problems at rates of hundreds of pixels per second using open architecture standards, and thus execution speed can accelerate commensurate with each new hardware advance simply by loading the software on the new hardware with minor, if any, modifications. Since we have be-

PHOTOGRAMMETRIC ENGINEERING & REMOTE SENSING,
Vol. 58, No. 1, January 1992, pp. 85–89.

0099-1112/92/5801–85$03.00/0

gun this development, we have experienced a factor of ten increase in speed, with no cost of software conversion. It is evident that the time of open systems image processing has arrived.

SYSTEMS WITHIN AUTOMETRIC

The current Autometric systems grew out of two development paths. Both of these paths were funded by Internal Research and Development (IR&D). One of these paths was centered on producing a softcopy version of the APPS-IV analytical plotter and became the PEGASUS™ system. The other development was centered around multispectral analysis, but branched also into display of image perspective transformations and became WINGS™.

PEGASUS™ DEVELOPMENT

In order to develop PEGASUS™, it was necessary to create a softcopy workstation with stereo display capability which would permit rigorous photogrammetric models to be created with softcopy imagery. The approach chosen was to rectify each image of the stereopair to the epipolar plane, so that the entire field of view could be roamed with a moving cursor without losing stereo perception. Adjacent portions of the imagery can be brought into the field of view without processing, given that they have been rectified to the epipolar plane. The images were displayed using a StereoGraphics liquid crystal shutter, first with polarized glasses, and currently with the "Crystal-Eyes" infrared-driven glasses which yield higher brightness. The original PEGASUS™ development used the Pixar II image processing engine to accomplish the display and correlation processing for elevation extraction. This original engine was driven by a Silicon Graphics 4D-70 workstation.

With the announcement of the Silicon Graphics 4D-310 VGX PowerVision processor, it became feasible to accomplish the correlation and image display functions at higher rates. Consequently, the current system is simply a Silicon Graphics processor with a single screen. In this same process, the user interface was transformed from an internally derived system to an X-Windows/Motif interface to take advantage of the single screen on the 310 VGX. There is also a version of PEGASUS™ being converted to SUN workstations.

The basic application areas of PEGASUS™ are:

- Aircraft and missile mission planning systems
- Support of imagery exploitation for military and intelligence analysis requiring mensuration to any accuracy attainable from the imaging system source
- Generation and maintenance of terrain, feature, and visual data bases for flight simulators
- Site and facility modeling from overhead photography
- Registration of various map, image, and collateral data sets to one another

The PEGASUS™ product is available as a turn-key hardware and software system which can be shipped and installed as a unit. It is also available as a software package that can be user-installed on equipment which meets the minimum requirements for memory size and peripheral availability. Figure 1 illustrates the general context of the PEGASUS™ product and offers a glimpse at the internal functions needed to process the input sources and generate the products.

The basic functionality offered by PEGASUS™ includes:

- Registration of imagery to ground truth or other images in a rigorous, accurate manner
- Generation of rectified monoscopic or stereoscopic images for exploitation
- Automatic collection and interactive editing of digital terrain models (DTMs) from stereoscopic imagery
- Generation of orthorectified images from controlled imagery and DTMs

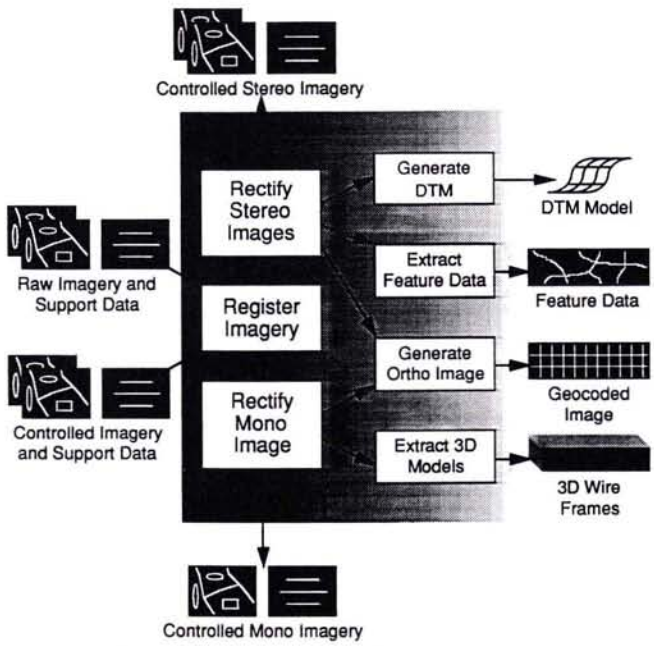

FIG. 1. PEGASUS™ functionality and products.

- Interactive collection of digital feature data from imagery in overlays for display and exporting
- Collection and data basing of wireframe representations of objects from monoscopic imagery, using relief displacement techniques.

PEGASUS™ consists of a number of modular programs and software libraries which make changes in the functionality simple and quick. Not only is the basic software kept under rigorous configuration control, but modifications to that software for special applications for specific customers are also controlled so that all delivered systems can be tracked for system maintenance and upgrades. Rigorous configuration control refers to the practice, normal in military procurements, of requiring all software changes to a system to be approved by a configuration control board prior to being implemented. This practice insures that software in such systems cannot be changed by an individual programmer without the knowledge of the program management staff, thus insuring that versions of the software which are not adequately tested and documented are not delivered to the customer.

The heart of the product is the use of rigorous and accurate imaging sensor models that provide for the simultaneous registration of up to ten overlapping or independent images to ground control. Because of Autometric's background in defense mapping, military targeting, and intelligence exploitation, we have emphasized accuracy of mathematical models and data integrity in the development of the PEGASUS™ system. Military sensors frequently have highly complex imaging characteristics, which require rigorous adherence to the modeling of the physical phenomena of the imaging event in order that the mathematical model correctly represent the sensor. Further discussion is not possible in this paper, but the mathematical models present in PEGASUS™ preserve all of the metric accuracy inherent in these complex imaging systems.

Each of the imaging sensor models is implemented in such a fashion that mapping from image space to ground space, and vice versa, are sensor independent. This means that all functions in the system are instantly available once the sensor's software is integrated. The PEGASUS™ photogrammetric software uses the rigorous models of the individual imaging systems to generate Rational Functions, which is the means by which all camera systems are represented in the same way to the applications software. The concept of Rational Functions was developed by Mr. Maurice Gyer, and has been used extensively by the Defense Mapping Agency in their Digital Production System. To the best of our knowledge, there is no published reference for the technology. The method, as implemented in PEGASUS™, is to generate polynomials of the form

$$f(u,v,w) = a_0 + a_1u + a_2v + a_3w + a_4uv + a_5uw + a_6vw + a_7uu + a_8vv + a_9ww + a_{10}uvw + a_{11}uuu + a_{12}vvu + a_{13}wwu + a_{14}uuv + a_{15}vvv + a_{16}wwv + a_{17}uuw + a_{18}vvw + a_{19}www.$$

The image coordinates, x and y, are expressed as quotients of these polynomials, as

$$x = f_1(u,v,w)/f_2(u,v,w)$$
$$y = f_3(u,v,w)/f_4(u,v,w)$$

with the "a_0" term of the denominators set to unity.

The rational function maps three-dimensional ground coordinates to image space. Addition of another sensor to the system can be accomplished in as little as two man-days because of the simplicity of the rational function model. Addition of a new sensor changes only the code which generates the rational function coefficients because all application code is independent of the sensor involved.

The automatic generation of DTM data from stereoscopic imagery source is coupled with powerful editing and quality control tools. These tools provide simultaneous viewing of the source and the product for verifiable product quality assurance. Wireframe perspectives of the DTM can be viewed either monoscopically or stereoscopically. As the operator moves the cursor within the wireframe, it also moves in stereo over the model. Thus, the operator can verify apparent anomalies in the wireframe from the position of the floating mark in the stereo model, and correct the point in both the model and wireframe simultaneously. In addition, optional color-coded views of the wireframe portray the fidelity of the automatic correlation on a point-by-point basis, so that the operator can visually detect the relative strength of correlation. The operator can constrain points inside of any desired polygon to lie on a plane, which is a convenient feature for representing water surfaces, roofs of buildings, etc.

Controlled image products within PEGASUS™ consist of controlled monoscopic images, stereoscopic pairs, and orthoproducts (orthoimages coupled with DTM data). The feature editing tool can use either of these products as a source of geographic coordinates to populate the feature data or to simply provide accurate three-dimensional coordinates of points or shapes of objects.

The feature data collected within PEGASUS™ is organized into overlays of features, with each overlay user-defined. The features consist of point, polygon, or textual tags which use a geographic reference frame. Each feature can be added, deleted, or selected and rewritten to the overlay data file associated with an image product.

PEGASUS™ organizes work into "projects" which act as an organizer of internal and external products as well as source data. Imagery is grouped into "imagery blocks" by sensor type and each block handles the retention of imagery, support data, ground control, and refined support data needed to generate image products. Monoimages, stereopairs, orthoproducts, feature data, and DTMs are tracked and retained within the project.

WINGS™

The development of the WINGS™ system began as a photometric processing system for multispectral exploitation. A small IR&D project developed an elementary capability to generate image perspective transformations from Landsat imagery—which met with high approval from customers who saw the system. Although others had generated image perspective views prior to this time, the decision was made to develop a mission rehearsal workstation centered around the Silicon Graphics workstation and the image perspective software. As the system development continued, the capability to include image patches for higher resolution imagery, such as National Aerial Photography Program, for particular areas of the scene was developed, so that areas in which more detail was desired than available on Landsat could be provided. These higher resolution patches are typically on the order of 256 by 256 pixels in size. Interfaces to intelligence systems to provide information on threats and navigation obstructions for the pilots were also added to the system.

The basic applications areas of WINGS™ are

- Mission feasibility and mission rehearsal
- Threat analysis
- Data fusion

WINGS™ presents a capability for viewing any type of imagery draped over terrain. In this context, other sources of information may be fused to provide an overall perspective to the operator of all sources of information in the context of the imagery. Geographic information, land use, military threats and intelligence information, and transportation networks are possible candidates for such display.

The WINGS™ software product operates on Silicon Graphics hardware systems—from the personal IRIS to the most powerful VGX machine. The VGX PowerVision series is recommended for optimal performance. WINGS™ is being converted to the SUN workstation series. The software may be user installed, or the hardware and software may be purchased as an integrated system from Autometric.

WINGS™ Functionality.

The basic functionality offered by WINGS™ includes

- Imagery input from SPOT, Landsat, and other systems
- Digital terrain elevation data input from various sources
- Preparation of imagery databases for areas of interest
- Transformation of imagery and terrain elevations to common datums
- Interactive perspective generation over small scenes
- Generation of stored "flythroughs" over larger scenes
- Import of intelligence and GIS data for display
- Merging of higher resolution imagery close to the target area with lower resolution imagery covering the rest of the scene

WINGS™ and PEGASUS™ share a common X-Window/Motif user interface, making the use of both systems extremely simple. The WINGS™ software and user interface are under rigid configuration management to ensure that all future developments will remain compatible with systems which are already in the field.

WINGS™ uses a forward projection model for imagery generation (Dubayah, 1986). The advantage of this model over models which perform ray tracing is that the model moves through the image and terrain model in a systematic manner, removing the necessity for searching large amounts of digital terrain from disk during image generation. A ray tracing model traces each ray of the output image to the ground, necessitating the recovery of the elevation of all points lying under the path. The forward projection model projects from the point on the ground to the image. By starting at the rear of the model, any point which is masked by terrain appearing closer to the viewpoint is automatically overwritten. Thus, a simple, one-pass solution is obtained.

For rapid projection, the Silicon Graphics' technique of "texture mapping" is used. By dividing the terrain into polygons, usually triangles, and assigning the imagery appearing on the respective planes as the texture for that plane, the Silicon

Graphics' vector processor can automatically map the imagery to the perspective view in real time at the rate of approximately 1 million polygons per second on the 4D-310 VGX machine. This capability provides a means for the operator to manipulate the perspective transformation in real time, to test hypotheses, and to plan the approach, prior to generating a detailed flythrough of the scene. Perspective views of scenes of 1000 by 1000 pixels, for instance, are generated in under one second, allowing the user interactive control of the desired perspective.

Graphics representing information contained in a geographic information system can be superimposed on the imagery in the perspective scene to allow this information to be viewed in context of the imagery. The imagery thus provides a natural backdrop for the display of various data types, yielding a capability for intelligent fusion of the various data sources in the mind of the user.

The interfaces between PEGASUS™ and WINGS™ are shown in Figure 2. Although WINGS™ can work with data produced on other systems, it achieves its most efficient form in conjunction with PEGASUS™. The orthophotos produced by PEGASUS™, along with their respective Digital Terrain Elevation Data (DTEDs), constitute a rigorous, pre-registered dataset for WINGS™. Coupled with the ability of PEGASUS™ to extract wireframes for detailed representation of building features, the WINGS™ can then display registered detail in not only SPOT or Landsat, but also higher resolution imagery which was triangulated in conjunction with the SPOT or Landsat imagery in PEGASUS™.

IMPLEMENTATION OF SOFTCOPY PRODUCTION SYSTEMS

Systems for production of map products using softcopy workstations have, in the opinion of the authors, several problems which are unique to softcopy. These problems can be grouped into categories:

- Automated elevation extraction
- Data storage
- Rapid, accurate, cost-effective image scanning

AUTOMATED ELEVATION EXTRACTION

In hardcopy production of map products, the elevation extraction is usually done in concert with the extraction of features—because both are manual processes. With softcopy workstations, the automated extraction of elevation operates so rapidly (200 or more elevation posts per second) that it is essential for efficiency that elevations be extracted prior to the remainder of the mapping process. This is also necessary to permit the implementation of the terrain—following cursor which is mentioned below, and also to avoid using the powerful elevation extraction workstation for compilation operations which are constrained by operator speed and efficiency. However, the extraction of elevations as a separate process creates problems in the data storage area, also mentioned below, because the image data must be brought into the system for elevation extraction, and then probably kept in the system until compilation is complete, because data import from normal computer compatible tapes is a time consuming process.

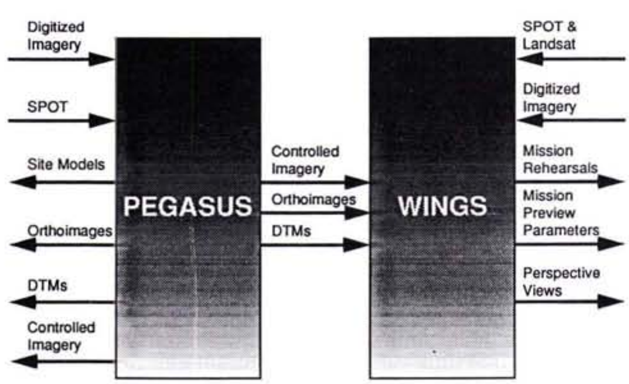

FIG. 2. Autometric's integrated capabilities in image exploitation, GIS, and mission planning.

It is also necessary to have an efficient means of editing the elevations, because automatic correlation will not find all elevations in the image (PEGASUS™ typically finds from 60 to 90 percent of the elevation posts depending upon image quality and scale), and the interpolation for points at which correlation failed must be checked. Thus, the compilation process really breaks down into three processes: elevation extraction, elevation editing, and feature extraction. These processes must be closely scheduled and controlled to enable a reasonable system configuration to operate without causing undue problems in data storage as discussed below.

DATA STORAGE

Data storage remains a nagging problem for softcopy systems. A standard 9- by 9-inch aerial image, digitized at full resolution, contains approximately 500 megapixels. A stereopair thus contains about one gigapixel (most military data have 100 percent overlap), or one gigabyte of uncompressed data (Light, 1986). Any reasonable mapping project will contain many such pairs which must be stored in the system during the compilation process. If they can be read into the system from magnetic tape, the tape reading itself takes considerable time (6250 BPI tape at 125 inches per second would take over 20 minutes of transfer time, plus six tape mounts). If, on the other hand, they must be digitized from hardcopy at full resolution, that process is even more time consuming. Therefore, it is necessary to plan production to finish all work on a pair of images while the images are loaded in the system. That amount of production planning is considerably more than is required for hardcopy production, particularly compared with analytical plotters which allow for easy model setup so that a particular model may be reset as many times as might be required.

The hardware community has not provided data storage devices, as yet, which will hold many gigabytes of information cost-effectively, yet provide seek times in the range of 0.1 seconds. Tape cartridge storage is inexpensive, but requires significant seek and transfer time, on the order of tens of minutes to locate 1 gigabyte images in databases of terabytes (10^{12} bytes) or more. While data storage costs are continuously dropping, data storage will remain a major bottleneck in large-scale production use of softcopy imagery.

IMAGE SCANNING

Because there are no readily available sources for softcopy imagery with resolution greater than that of SPOT, practical applications of softcopy photogrammetry require scanning of hardcopy images. Currently, there are few available scanners or scanning services (although more are becoming available every year), and both are relatively expensive. The scanner suffers from all of the problems of mechanical stages used in analytical plotters, because the inherent accuracy of the softcopy image is no better thân the accuracy of the scanner stage and its associated measurement techniques and the distortion and misalignment of the optical system used to scan the imagery. We believe that not only is there a potential accuracy problem in scanning, but the choice of the proper gain in the system to insure that the dynamic range of the scanned image captures the entire dynamic range of the original film is more of an art than a science at the present time, based upon our experience. It is our opinion that much of the potential benefit of softcopy systems cannot be realized today because of the delays, inaccuracy, and cost associated with the scanning of hardcopy imagery.

FUTURE PROJECTIONS FOR THE MARKETPLACE

It can be reliably predicted that the production workstations will continue to increase in power and productivity, based upon our observations of the last few years. The increased availability of softcopy imagery, and the increased availability of scanning devices to produce softcopy imagery from hardcopy, will make data readily available to softcopy production systems.

In the absence of a breakthrough in some technology which is not currently being marketed, the cost-effective storage of data for large scale production will remain a problem. The probability of near-term availability of a storage medium which will rival film for information content per unit volume is low (film can store about 225 megabytes per cubic centimetre). However, acceptable storage media are available which permit reasonable softcopy production for limited areas or from lower resolution imagery such as SPOT.

Softcopy camera systems may become available, but they also suffer from the data storage problems, and metric problems associated with linear arrays in airborne vehicles, and therefore may not become popular until these are solved. Airborne vehicles are subject to turbulence, which results in attitude perturbations which require very complex mathematical models to properly represent imagery which is imaged a line at a time from the linear arrays. Two-dimensional arrays which would duplicate the performance of standard aerial cameras (25,000 by 25,000 elements) are far beyond the 4000 by 4000 arrays which are available today in experimental quantities only.

Softcopy systems are very useful for problems which span a small area, or which must be solved rapidly, such as military targeting systems, intelligence extraction systems, and localized mapping systems. We believe that softcopy systems are unlikely to replace hardcopy compilation systems for large scale production mapping until more efficient storage media are available.

REFERENCES

Case, J.B., 1982. The Digital Stereo Comparator/Compiler, *International Archives of Photogrammetry*, Vol 24-II, pp. 23–29.

Dubayah, Ralph O., and Jeff Dozier, 1986. Orthographic Terrain Views Using Data Derived from Digital Elevation Models, *Photogrammetric Engineering & Remote Sensing*, Vol. 52, No. 4, pp. 509–518.

Greve, C., C. Molander, and D. Houck. 1986. Numerical Photogrammetric Models for High-Speed Solutions, *Proceedings of the 1986 International Society for Photogrammetry and Remote Sensing Commission II Symposium*, Photogrammetric and Remote Sensing Systems for Data Processing and Analysis, Baltimore, Maryland.

Greve, C., and C. Molander, 1987. The Architecture of the APPS-IV Analytical Plotter, *Proceedings of the 1987 American Society for Photogrammetry and Remote Sensing Spring Convention*, Baltimore, Maryland.

Gruen, A.W., 1986. Digital Photogrammetric Processing Systems: Current Status and Prospects, *Photogrammetric Engineering & Remote Sensing*, Vol. 52, No. 3.

Light, D.L., 1986. Mass Storage Estimates for the Digital Mapping Era, *Photogrammetric Engineering & Remote Sensing*, Vol. 52, No. 3.

ASPRS Staff Voice Mail Extension Directory

The ASPRS Headquarters has a new phone system! Daytime calls will continue to be answered and routed by our receptionist, Thelma Sturdivant, between the hours of 8:30 a.m. and 5:00 p.m. If the person you're calling is unavailable, you will be asked to leave a message in our voice mail. After regular business hours, the Automated Attendant System will immediately put your call into voice mail. You will be given the option of direct dialing the staff member's extension, or leaving a message in a "departmental" mailbox. It takes about 15-20 seconds for the system to transfer the call to the extension you wish to reach. Staff extensions and departmental mailbox extensions are listed below.

Staff Extensions-Alphabetical by FIRST Name

28 Anne Ryan, Sustaining Member/Region Services
16 Arlen Reimnitz, Asst. Executive Director
18 Bill French, Executive Director
11 Carolyn Cooper, Accounting
23 Cheryl Stratos, PE&RS Advertising
25 Don Hemenway, Publishing & Public Information
27 Joann Treadwell, Editorial-PE&RS/Proceedings
20 Judy Peesel, ISPRS
17 Judy Shrader, Certification/Awards
21 Julie Hill, PR-Exhibits & Marketing
12 Karen Davenport, Accounting
24 Lisa Campanella, Manuscript Coordinator
14 Marc Raffel, Finance Manager
26 Sokhan Hing, Membership & Subscriptions
10 Thelma Sturdivant, Book Sales

Department Voice Mail Extensions

3 Membership & Subscriptions
4 Book Sales
5 Editorial Information
6 PE&RS Advertising
7 Meetings & Conventions
8 Certification/Awards
9 Executive Director Office
12 Accounting
20 17th ISPRS Congress
0 General Mailbox
15 Inst. for Land Information
19 IGIF