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REMOTE SENSING AND THE MISSISSIPPI HIGH ACCURACY REFERENCE NETWORK

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ABSTRACT

Since 1986, the National Aeronautics and Space Administration's (NASA) Commercial Remote Sensing Program (CRSP) at Stennis Space Center has supported commercial remote sensing partnerships with industry. CRSP's mission is to maximize U.S. market exploitation of remote sensing and related space-based technologies and to develop advanced technical solutions for spatial information requirements. Observation, geolocation, and communications technologies are converging and their integration is critical to realizing the economic potential for spatial informational needs. Global Positioning System (GPS) technology enables a virtual revolution in geo-positionally accurate remote sensing of the earth. A majority of states are creating GPS-based reference networks, or High Accuracy Reference Networks (HARN). A HARN can be densified for a variety of local applications and tied to aerial or satellite observations to provide an important contribution to geographic information systems (GIS). This paper details CRSP's experience in the following areas: (1) design and implementation of a HARN in Mississippi, and (2) design and support of future applications of integrated earth observations, geolocation, and communications technology.

INTRODUCTION

The NASA CRSP at Stennis Space Center supports the spatial information industry through a data acquisition and processing infrastructure. In conjunction with its partnerships with companies and the private sector, the CRSP acquires and processes aerial and satellite imagery for use in the development of geographic information systems. These data are georeferenced, a process by which the geometry of image areas are made planimetric, and entered into a data base, where the layers of data are tied to local reference grid systems. Often the control-point intersections of several data layers do not overlay precisely (Figure 1) because the data are derived from a variety of sources. This occurrence is referred to as the misregistration of data layers. In 1991, in an effort to correct the misregistration problems encountered at Stennis, the CRSP decided to densify the local reference network around the site and its neighboring region using technology provided by the Global Positioning System.[1,2] At this time the CRSP became aware of the National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey's (NGS) endeavor to implement the HARN on a

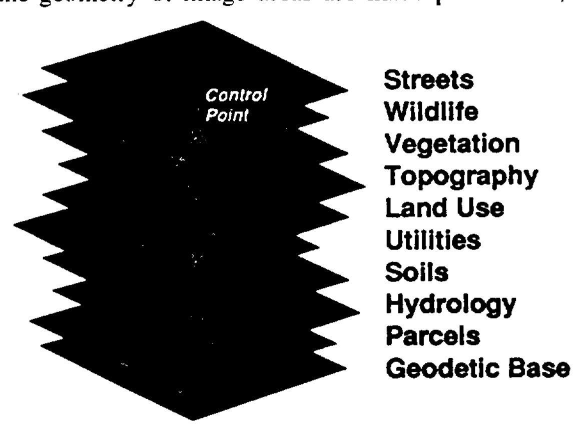

Figure 1. Misregistered Data Layers

CONCLUSION: DATA INTEGRATION

The benefits of these approaches to monitoring and modeling urban changes are evident when the various types of data are integrated into a GIS data base. While the census provides indispensable data for urban forecasting, of necessity it is aggregated both spatially and temporally. Both the remotely sensed data and the building permit information can be examined on a continuous basis at a much finer level of spatial detail than census areas. The power of this type of data integration is readily apparent when individual neighborhoods are examined. Point level data (building permits, commercial firms, and retail center locations), linear features (highways, water lines, and sewer lines), various areal features (including census polygons), and change in urban land use may be integrated. The EOCAP project is now concentrating on the creation of a robust housing model that incorporates these data sources into an improved wire center forecast.

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nationwide basis. The implementation of a HARN in Mississippi was seen as the answer to Stennis' needs, in that not only would a more accurate reference network be established, but the network would be tied to a national and universal reference system. Its usage would enable misregistration errors to be minimized.

The implementation of the HARN allowed the Stennis infrastructure to capitalize on increased geolocational accuracy. This infrastructure includes an A-order station (providing locations to within a few millimeters), a more dense grid of B-order stations (providing locations to within a couple of centimeters) along the Mississippi Gulf Coast, a permanent GPS base station, a site GIS for facilities management and environmental monitoring, and an airborne sensor upgrade that provides geolocational referencing of imagery to the HARN.

Some of the monumented stations used in the MS HARN were required to be located on and in close proximity to the Stennis site. As part of the 63-station network, one A-order and one B-order monument were installed at Stennis. The A-order site is one of four A-order stations in the MS network, and the B-order station serves as the location benchmark for a dual-frequency survey quality GPS base station. This base station provides storage and archival capability for the satellite-broadcast GPS data and will support coastal area remote sensing activities and regional public and private terrestrial, airborne, and space applications of GPS technology.

Stennis is building an environmental monitoring and facilities management data base. Layers in the GIS data base include data derived from maps, satellite remote sensing, Calibrated Airborne Multispectral Scanner imagery, and continuing in-situ surveys and observations. Utilizing the HARN to georeference these layers will minimize misregistration errors during development of the GIS. The environmental portion of the data base establishes a baseline for water, soil, and air quality and for flora and fauna assemblages for the site, while the facilities management portion of the GIS contains layers detailing positions of buildings, fire hydrants, power lines, and other infrastructure components.

The NASA/Stennis aircraft, used to support a multitude of remote sensing applications, has been upgraded with a GPS unit. This configuration provides the capability to georeference imagery acquired by the Airborne Terrestrial Applications Sensor (ATLAS) to terrestrial locations referenced to the HARN. The ATLAS serves as a testbed for evaluating remote sensing products and developing specifications for airborne and spaceborne remote sensing instrumentation for dedicated applications.[3] In conjunction, an optical target at the Stennis A-order station will be used for calibrating the registration of aircraft imagery for remote sensing projects.

A host of remote sensing applications will benefit from the highly accurate positional information provided by the HARN implementation. Four of these applications will be highlighted later in the paper.

HARN OVERVIEW

To correct inaccuracies in the obsolete geodetic North American Datum of 1927, in 1980 the NGS began updating the precision of latitudes, longitudes, and elevations for benchmark stations throughout the United States.[4] When completed, the new network was called the North American Datum of 1983 (NAD83). The HARN being implemented on a state-by-state basis readjusts these coordinates and removes most of the remaining distortion from the NAD83.

The HARN is a cooperative program that utilizes the technology brought about by GPS. The NGS leads the federal initiative but increasingly relies on participants within a state to implement and augment the process. The network consists of physical reference stations, usually with 50 to 100 km spacing, whose horizontal positions relative to one another and to the NAD83 reference coordinate system are known with very high accuracy.[5] Almost 80% of the states are either working toward or have implemented an integrated network (Figure 2). The reference stations or monuments and their associated documentation increase the efficiency of differential GPS (DGPS) correction by providing a reference for a base receiver. DGPS utilizes a base receiver (set over a station monument) that calculates the combined error in the GPS satellite range data. That correction can be applied to all other GPS receivers in the same area, eliminating the majority of error in their measurements. The occupation time required to establish differential correction data is reduced to an absolute minimum while providing the highest degree of accuracy possible. The HARN thus becomes the standard or foundation for GPS applications within that region. The network also makes the implementation of a denser network of stations within a state easier and cheaper to establish, thus improving the efficiency of the network for a variety of users.

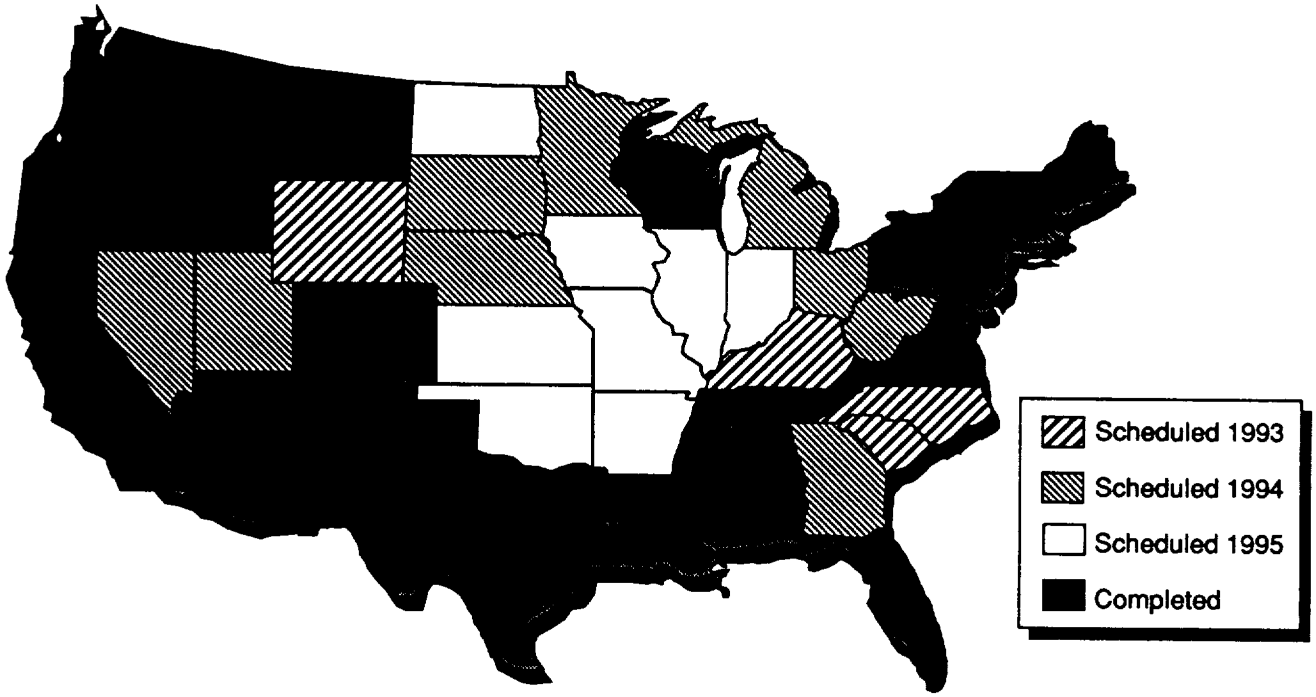

Figure 2. Statewide High Accuracy Reference Networks, September 1993

THE MISSISSIPPI HARN

The Mississippi HARN was established through a grassroots initiative that employed innovative approaches to project leadership, incentives, participation, and implementation. The effort was sponsored by NASA's Office of Advanced Concepts and Technology and represents the first time that a federal agency provided the impetus and took the initial lead to support HARN development in a state. The NASA/Stennis CRSP set the following minimum criteria for the successful establishment of this reference system:

- Priority NGS support for Mississippi,
- Support from at least one Mississippi state agency, and
- Support from one other federal agency.

Initial contacts with NGS were made in April 1992. The HARN groundwork was laid and other federal and MS state agencies were contacted. By mid-summer, the Stennis project team met at the center with representatives from NGS and other federal, state, and county agencies. Mutual responsibilities and the scope of work were established. A consensus emerged that a higher-density network would benefit a broad range of users in the state. Subject to a cooperative effort led by the State of Mississippi, a decision was made to expand the MS HARN from approximately 20 stations to 63 stations. The Mississippi Department of Transportation (MSDoT) committed itself as the lead agency for the state, and the U.S. Geological Survey (USGS) Regional Field Office in Baton Rouge, Louisiana, supported the project from the beginning, thus satisfying two of NASA's success criteria.

In late September 1992, the CRSP hosted an NGS workshop/HARN planning session at Stennis. Participants supported the project through commitments of manpower, GPS receivers, and other field equipment. A relatively simple cooperative agreement between NASA/Stennis and NOAA/NGS established the mechanism of NASA/Stennis funding to augment the development of the 63-station network. Local interest in the network was high. The original federal effort grew to a program that included participants from 21 federal, state, and local government agencies, universities, and private companies. All were eager to share in the "ownership" of the HARN (Figure 3).

Participants

- Mississippi Department of Transportation
- Mississippi Department of Environmental Quality
- Mississippi State University
- Mississippi Association of Registered Surveyors
- Pike County, Mississippi
- Harrison County, Mississippi
- Jackson County, Mississippi
- EMC, Inc.
- Electro National Corporation
- Louisiana Department of Transportation and Development
- Navigation Electronics, Inc.
- Vernon F. Meyer & Associates
- Space Development Services
- U.S. Geological Survey
- U.S. Corps of Engineers
- Naval Oceanographic Office
- U.S. Environmental Protection Agency
- National Ocean Service, Coast and Geodetic Survey
- NASA Stennis Space Center
- Johnson Controls World Services, Inc.
- Sverdrup Technology, Inc.

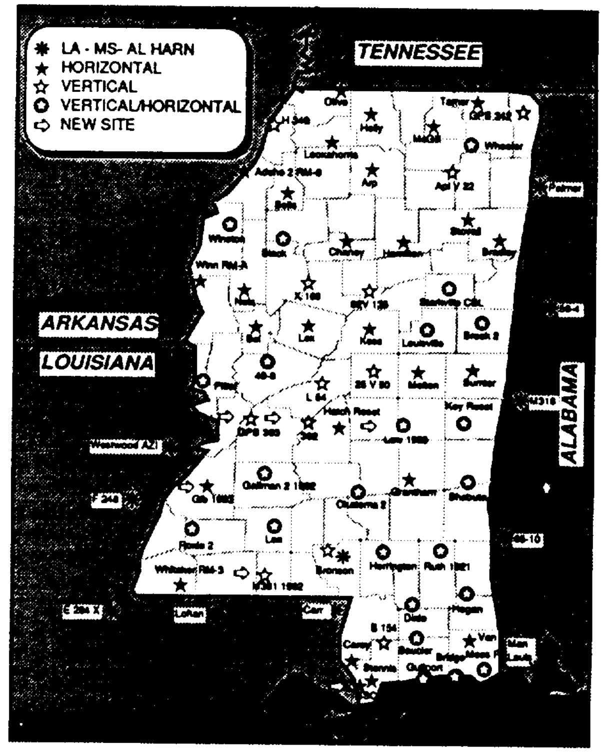

Figure 3. Mississippi HARN Stations and Participants

Sites were selected throughout the state and reconnaissance visits were made for each station by the end of November. These sites were spaced approximately 50 km apart, with more dense spacing in the Gulf Coast region and around the Stennis facility. A two-day project review and readiness session was held at the MSDoT facilities in Jackson in the middle of January 1993. Soon thereafter, confirmation of a May 3 start date for field implementation was received from NGS Headquarters. A firm schedule was established to prevent an erosion of support from participants because of other commitments.

Prior to the start date, the MSDoT hosted a three-day training session.[6] The MSDoT provided facilities for the NGS crew center of operations and supported data reduction operations throughout the field operations.

Field observations began on May 3, 1993. Data were acquired for five and one-half hours on each of two days from those GPS satellites that were visible at each site. The observers moved to the next scheduled location the following day and acquired data. Data received during each session were downloaded and sent to Jackson, MS for a preliminary quality check.

Following this plan, all regular observations were completed in three weeks. Observations were taken for three additional days at each of the four MS A-order stations. Data were collected concurrently at A-order stations in adjacent states for regional geolocational accuracy. The observations recorded during the project were coordinated with satellite observations at selected North American stations of the Cooperative International GPS Network. Final reprocessing of the Mississippi data by NGS and its corrections to the NAD83 datum are scheduled to be completed in early December. At that time, the Mississippi HARN data (project accession number GPS-585) may be acquired from NGS at the following address:

National Geodetic Survey Information Center
SSMC3 - Code N-CG174
1315 East West Highway
Silver Springs, MD 20910-3282
Telephone: (301) 713-3242
Fax: (301) 713-4172

The HARN project in Mississippi exceeded its initial success criteria of involvement. The NGS and its State Advisors responded quickly and effectively to support the interests of Stennis and the State and helped coalesce the eventual consortium. The MSDoT took the lead of state agencies and the USGS and the Naval Oceanographic Office provided significant support as federal agencies. The workshops, open to all interested parties, acted as a catalyst for program growth. The motivation among the 21 participating agencies and organizations and their cooperative interaction provided the ingredients for an overwhelmingly successful project, moving from inception to implementation in less than 18 months. In addition, the implementation of the MS HARN was coordinated with a reference network leveling (elevation) party that travelled through the western and southern part of the state, including the Stennis site.

Throughout the term of the Mississippi project, the 21 participating agencies exhibited enthusiastic cooperation. This spirit of teamwork has created an institutional reference network among these agencies. This institutional network should facilitate continued cooperation and foster increased HARN benefits, across the state and the region, in spatial information system-related activities.

APPLICATIONS OVERVIEW

Geolocational knowledge is vital to the successful application and increased value of remote sensing technology and other geographic information. Until very recently, accurate geolocational knowledge was either quite expensive to acquire (surveyed field targets for aerial photogrammetry) or was unavailable as a practical matter (e.g., ± 40 feet point accuracy was the best available national map USGS Quadrangle quality). Satellite remote sensing data, often the only source of overseas information, is rarely registered to the earth at even course accuracies.

The Global Positioning System, knowledge of the geoid, and industry innovations in GPS equipment have revolutionized the means to acquire geolocational information. Geolocation knowledge may now be acquired from spacecraft, aircraft, terrestrial and marine reference networks, and moving land vehicles. Jack Dangermond's "instrumented universe" is becoming a reality.[7]

This revolution in the acquisition of geolocation has occurred largely within the past five years. During this very short span, technology evolution and continuous cost reductions have outpaced applications development. Widespread public and commercial applications of new geolocation knowledge capability are just beginning to emerge. This section of the paper looks ahead from building the Mississippi HARN toward a future productive era of remote sensing and related applications of the new geolocational tools afforded by GPS. This brief look ahead is organized under four applications support areas that are either planned or underway at the Stennis Space Center.

Commercial Applications and Systems Testbed

Six years of remote sensing partnerships between NASA/Stennis and over fifty different companies underscore the importance of several testbed-related factors to successful commercial innovation. Successful commercial remote sensing innovation takes into account technical, financial, and other considerations of the entire acquisition-to-delivery system. Most individual remote sensing products, processes (e.g., software modules), and services are affected by dependencies (or competitive threats) involving data acquisition, data handling and distribution, data processing and integration, and options for customer packaging and delivery.

A good example of the importance of system-wide knowledge to the development of new products or services may be drawn from GPS applications in highway inventory. Major investments have been made in perfecting van-mounted highway inventory systems.[8] Early commercial prototypes using Coarse Acquisition Code GPS aided by gyros produced road alignment and directional information as the key products. These products possessed accuracies of about 15 meters and a Quadrangle View of the highway applications market. Before these applications had matured, they were superseded by DGPS applications (<5 meter accuracies) that required another system component - telecommunications. DGPS applications were in their infancy when they, in turn, were augmented by video frame camera systems.

Now that GPS is being successfully integrated with airborne scanning and photogrammetry, a fundamental reassessment of the roadway inventory market seems in order. The initial impetus for van-mounted GPS inventory may have been succeeded by advances in other areas of remote sensing.

Product or service innovation demands understanding the offering's entire systems context. Awareness and/or use of an end-to-end spatial information testbed is one key source for understanding product systems. The Airborne Instrument Test System is an end-to-end data acquisition and processing system at Stennis (Figure 4). The system provides all the engineering and computational support required for scientific and commercial remote sensing development.[9] The HARN and associated spatial data infrastructure allow the CRSP to quantify and compare alternative technology approaches to market solutions.

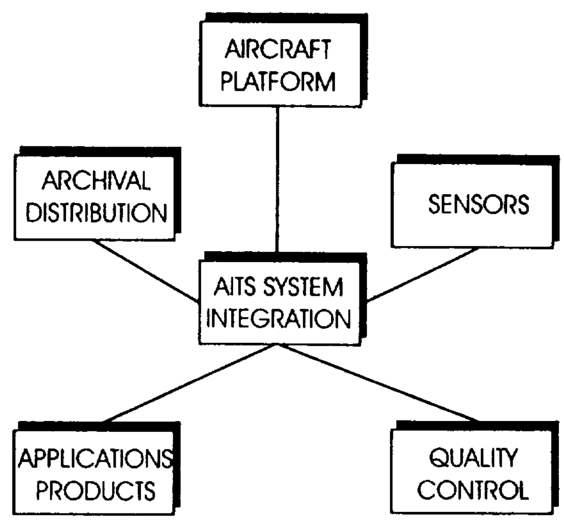

Figure 4. Airborne Instrumentation Test System Components

Successful improvements in new products, processes, or services must be demonstrated or perfected in a realistic rather than an ideal applications environment. Demonstrations and adaptations ideally take place with the prospective customer in the application setting. Prior to a customer's exposure, however, many prospective offerors would rather develop proprietary testbed demonstrations of their product, process, or service. Such tests of products are especially important when they are targeted toward completely new markets where an initial visible "failure" may close the door to customer interest. The early claims of airborne scanning, which failed to take into account the complexities of post-acquisition image processing, are good examples of the need to prototype the entire chain of dependencies from acquisition to product delivery.

Most companies and even government agencies lack the means for controlled test and evaluation of new products. The CRSP testbed has been used to prototype equipment, software, and subsystems. The HARN and its associated spatial data infrastructure will enable the CRSP to support local and regional prototype tests.

Public Applications in Pike County, Mississippi

The CRSP has found that progressive government agencies are sometimes the first entities willing to experiment with emerging remote sensing technologies. Numerous position inconsistencies in the San Diego County, CA infrastructure GIS prompted county officials to support the development of a more accurate regional ground control network in April 1991.[10] In contrast, Mississippi's rural counties often do not have the same level of infrastructure support as do more populated counties such as San Diego. However, Pike and Hancock counties in Mississippi are two exceptions to this rule. Both participated in the design and implementation of the

Mississippi HARN. (For purposes of brevity, only Pike County's network application initiative is discussed here.)

The Pike County Tax Assessor's Office has lead the GIS activities for the county. This office has experimented with GPS-based roadway applications since 1988 and has provided its own testbed for van-mounted GPS applications (Figure 5). Magnolia, a small city in Pike County, has been the setting for extensive practical tests of GPS-based roadway alignment and inventory.[11] The Assessor's Office has developed and operates its own GIS with little outside assistance. This GIS has been bootstrapped at a low cost from the ground up with only minimal support from the county's infrastructure.

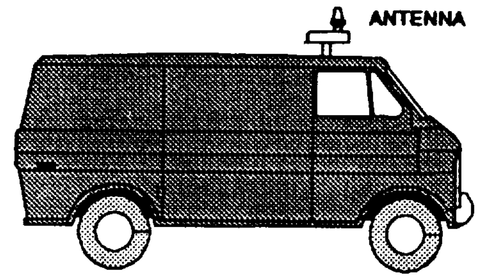

Figure 5. Van Testbed

Pike County has several applications which require the use of GPS technology. The County is currently constructing infrastructure layers for its GIS data base. Precise geolocation of such features as roads, right-of-ways, and service networks is essential for the implementation of their GIS, particularly in the few urban centers. Pike County intends to utilize this data base to determine suitable locations for industries it would like to attract to the area. Information regarding the costs of connecting to services, improving access, and acquiring properties may be readily determined using a GIS only if information regarding existing infrastructure is accurate. GPS survey techniques using the HARN provide the necessary accuracy and co-registration for various infrastructure layers.

The major portion of Pike County's tax base is generated through rural property assessment and is used largely for agriculture and silviculture (forest management). Property assessments are based on actively utilized acreage of farm lands. Such assessments require knowledge of property boundaries and activities currently in progress on the lands. The former can be obtained from existing parcel maps with GPS surveys to ensure consistency and accuracy. The latter can be obtained only through the collection and analysis of imagery. Aerial photogrammetric surveys acquired and archived by the county are over a decade old. Pike County hopes to incorporate new aerial imagery to develop a land use classification. On completion of this new base map, the county intends to investigate the utility of satellite data to develop a cost-effective means of assessing changes in land use practices on an interim basis. Such information can be used in conjunction with directed ground GPS surveys to update the imagery-based map in a cost-effective fashion.

A successful combination of vehicle and airborne spatial data acquisition referenced to the HARN and its incorporation into a GIS tax base has widespread applicability in Mississippi and elsewhere. The planned applications in Pike County may provide valuable verification for commercial GPS services and a practical test of the value of CRSP's new ATLAS scanner.

Public agency innovation in the use of the HARN, photo and digital imagery, and GIS is one key source of convergent technology applications. Pike County, through its affiliations with industry and NASA, demonstrates that significant convergent technology innovations are possible at a low cost.

Applications to State Highway Transportation

The Mississippi DoT was the lead state agency in the design and implementation of the Mississippi HARN. The MSDoT lead role in project development was more a matter of foresight than a response to proven requirements because the Department had little internal experience with GPS prior to the HARN initiative. The MSDoT benefitted from close working relationships with its NGS State Advisor and the experiences of the Louisiana and Alabama DoTs, both of which were completing their HARN development process in 1992.

Now that the MSDoT has been instrumental in making the HARN a reality in the state, what are the applications paths it is able to take? The first path will be continued training of field crews and Headquarters staff in the use of the GPS receivers and personal computer processing equipment. Traditional applications involve right of way, roadway expansion or realignment, new entrances, and other pre-construction activities.

Training and experience in the productive use of the HARN will be critical to realizing the MSDoT's benefits from a network. One key to quick realization of benefits is to apply GPS to traditional DoT survey requirements. Reports from the Louisiana Department of Transportation and Development indicate that the use of HARN and GPS in that state led to cost savings through the eradication of survey duplication in road alignment surveys.

The second path will be strengthened leadership in statewide GIS coordination and development. The MSDoT will lead the state's GIS coordination group in 1993-94 from a position of having led a successful multi-agency HARN development program. In this sense, the network helped create a successful model of institutional cooperation and investment in spatial data infrastructure.

The HARN process itself placed its lead state agency in a stronger position to coordinate and lead a statewide GIS strategy. From a technology applications standpoint, the major issue to be resolved in Mississippi will be adoption of the network as <u>the</u> spatial data reference standard for the coming decade.

The third path involves future innovation built on HARN and GPS applications to traditional MSDoT requirements. The tangible success of moving the network from concept to reality in less than two years provides support for continuing innovation in the state and within the MSDoT. The specific paths for future innovation and co-investment are less clear than the willingness to tackle the next challenge. What seems clear at the concept level is that the MSDoT will move from survey to inventory applications of GPS and HARN. From a technology evolution standpoint, a convergence of observation and geolocation technologies enables the MSDoT and other state agencies to consider realistically a statewide GIS data base for environmental and developmental decisions.

The HARN process and its successful outcome not only provide a basis for achieving short-term benefits for the MSDoT, but may enable the MSDoT to lead a broader application of convergent technology to the development and environmental concerns of Mississippi.

<u>Bringing Satellite Remote Sensing "Down to Earth"</u>

These are exciting times for commercial satellite remote sensing. With the close of the Cold War, the Federal Government appears willing to consider the licensing of National Security satellite technology for civil-commercial use. At the same time, the Land Remote Sensing Commercialization Act was amended in 1992 to allow different treatment for truly commercial systems. These two government policies coincide with significant growth in GIS markets for remote sensing data worldwide and a proliferation of products that can take advantage of these policy shifts.

As 1993 comes to a close, one application for a commercial remote sensing satellite system has been granted and another has progressed toward approval. Either or both of the World View and Lockheed systems would dramatically change the character of space-derived data and the applications of such data to public or commercial uses. World View proposes three-meter spatial resolution and Lockheed's Commercial Remote Sensing System proposes stereo spatial resolution at the one-meter level.

Satellite remote sensing (Figure 6) will truly be brought down to earth if either or both of the proposed systems are approved and launched. Geolocational technology will play a crucial role in realizing the potential of these new data sources for GIS applications. GPS and star sensors on board the satellites enable a design goal of one pixel registration to be pursued, where one pixel is a picture element having both spatial and spectral properties. (The spatial variable defines the apparent size of the resolution cell and the spectral variable defines the intensity of the spectral response for that cell.) The HARN system in the U.S., and the growth of portable DGPS system will allow sub-pixel accuracy reference to be built quickly and at low cost. On a global scale, GPS and its reference systems provide not only the basis for accurate geolocation registration of spaceborne data, but a universal means to attach ground truth to orbital or airborne observations.

CRSP plans to use its entire spatial data infrastructure to help verify and develop the opportunities provided by changes in U.S. policy coupled with commercial technology and market incentives. The applications which appear most beneficial to U.S. companies are high resolution spatial and spectral test data sets, experimentation with HARN and related forms of visual registration of digital imagery, and customer/market tests of data and information that simulate future space-derived products.

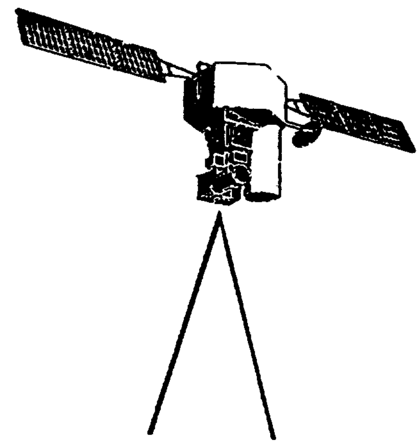

Figure 6. Satellite Remote Sensing

The applications of existing HARNs, the development of visual HARNs, airborne and terrestrial GPS, and product simulations will be critical to moving satellite imagery from the domain of the scientist and specialist to the domain of the customer. With increasing demand from its industrial partners, CRSP is planning up to ten projects to demonstrate the utility of the HARN to remote sensing applications.

SUMMARY

In addition to the benefits provided to Stennis organizations for applications research, development, and operational purposes, outside GPS users will be able to utilize the HARN to increase the accuracy and timeliness of their products. Once the NGS publishes the final computations for each Mississippi site (scheduled for November 1993), the HARN will be used by the CRSP to demonstrate the viability of a highly accurate reference configuration for GIS base maps. GIS data layers can be registered with universal accuracy, allowing adjacent areas to form a seamless mosaic and avoiding controversy over discrepancies in boundaries and site perimeters. The Mississippi HARN will provide NASA, the state of Mississippi, and private industry with the basic horizontal reference controls necessary to support a host of remote sensing/spatial information system applications, benefitting all parties concerned.

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A VISUAL DETECTION MODEL FOR DCT COEFFICIENT QUANTIZATION

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ABSTRACT

The discrete cosine transform (DCT) is widely used in image compression, and is part of the JPEG and MPEG compression standards. The degree of compression, and the amount of distortion in the decompressed image are controlled by the quantization of the transform coefficients. The standards do not specify how the DCT coefficients should be quantized. Our approach is to set the quantization level for each coefficient so that the quantization error is near the threshold of visibility. Here we combine results from our previous work to form our current best detection model for DCT coefficient quantization noise. This model predicts sensitivity as a function of display parameters, enabling quantization matrices to be designed for display situations varying in luminance, veiling light, and spatial frequency related conditions (pixel size, viewing distance, and aspect ratio). It also allows arbitrary color space directions for the representation of color. In a further development, we have developed a model-based method of optimizing the quantization matrix for an individual image. The model described above provides visual thresholds for each DCT frequency. These thresholds are adjusted within each block for visual light adaptation and contrast masking. For a given quantization matrix, the DCT quantization errors are scaled by the adjusted thresholds to yield perceptual errors. These errors are pooled non-linearly over the image to yield total perceptual error. With this model we may estimate the quantization matrix for a particular image that yields minimum bit rate for a given total perceptual error, or minimum perceptual error for a given bit rate. Custom matrices for a number of images show clear improvement over image-independent matrices. Custom matrices are compatible with the JPEG standard, which requires transmission of the quantization matrix.

1. INTRODUCTION

1.1 DCT image compression

The discrete cosine transform (DCT) has become an image compression standard (ref. 1, 2, 3) Typically the image is divided into 8x8-pixel blocks, which are each transformed into 64 DCT coefficients. The DCT transform coefficients $I_{m,n}$, of an N x N block of image pixels $i_{j,k}$, are given by

$$I_{m,n} = \sum_{j=0}^{N-1} \sum_{k=0}^{N-1} i_{j,k}\, c_{j,m}\, c_{k,n} \quad m,n = 0 \ldots N-1 \tag{1a}$$

where

$$c_{j,m} = \alpha_m \cos\left(\frac{\pi m}{2N}[2j+1]\right), \tag{1b}$$

and

$$\begin{aligned} \alpha_m &= \sqrt{1/N} \quad m = 0 \\ &= \sqrt{2/N} \quad m > 0 \end{aligned} \tag{1c}$$