High-Tech Tools and Techniques in Missouri

In St. Charles, Missouri, water, sewer, and stormwater structures are inventoried and then built into a comprehensive GIS.

By Matt Schrader and Sean Martin

No maps, no charts, no GPS. Try a compass, a transit, a level. These were the surveying tools of 200 years ago, during the time of Lewis and Clark, the men immortalized for their exploration of the American west and northwest. America's most famous trail-blazers started their journey on May 14, 1804, in St. Charles, the site of a 2003-2004 surveying and inventory project that used today's cutting-edge technology. In fact, one of the technologies—Height Modernization (HM), which uses global positioning system (GPS) satellite surveying to gain horizontal and vertical controls—was unprecedented in Missouri. HM is still rare in the United States, although its use is growing.

St. Charles needed the control monuments to establish a constant and historically accurate geodetic control network before it could move on to an even larger project: surveying and inventorying the city's water, sewer, and stormwater infrastructure. Data-collection technologies included Light Detection Imaging and Ranging (LiDAR) and high-resolution digital orthophotography for populating a GIS and developing a topographic survey for use in digital terrain models (DTMs); and GPS and ruggedized laptops loaded with specialized software to conduct the field inventory of the city's water-sewer-stormwater infrastructure, partially building the GIS right in the field.

About 20,000 structures were inventoried among the water, sewer, and stormwater systems. All the data were combined into the complete GIS. The city now has an accurate record of not only where structures are located, but also sizes of structures, top and flow-line elevations, and other data. Eventually, the city will connect the data to a computerized maintenance management system. Here's how this massive surveying and inventory project was conducted from January 2003 to April 2004.

Vertical control being transferred from a monument under a bridge to nearby new "GPS'able" monument by running Second-Order geodetic levels.

St. Charles is on the edge of the St. Louis metropolitan area. Just 15 minutes away from this bustling gateway to the west, St. Charles has seen tremendous growth in recent decades. Today, the city's population stands at 62,000 over a land area of 26.5 sq mi. However, with this growth, the city has faced the challenge of maintaining records for its water-related infrastructure. The city until recently only had limited mapping of these systems—some of which were decades old.

But, in addition to needing updated maps to deal with development, the city—like others its size—was facing a federal mandate: National Pollutant Discharge and Elimination System (NPDES) Phase II. The unfunded mandate's requirements jump-started St. Charles' quest to survey and inventory its water, sanitary sewer, and stormwater infrastructure; to build a comprehensive GIS; and to develop a program for managing future infrastructure. St. Charles selected Woolpert LLP (www.woolpert.com) to assist with these efforts.

Woolpert met with city representatives to begin project planning, discuss project administration, review technical specifications, and finalize pilot and full project areas. By design, the city was actively involved in the project from inception. Woolpert project team leaders would continue to meet regularly with city staff and also with internal staff over the course of the 16-month project. With the large number of consulting staff involved (30-plus people at one point), a communication protocol was developed to ensure that messages delivered to different staff reached a primary focal point within the company and that any responses to those messages were delivered with one "voice" back to the city. Additionally, learning to "speak the language" of the various disciplines involved was important to accurate communication and overall project success.

The consultant also established a secure, dedicated Web site specifically for use by St. Charles staff. This Web site contained contact information, a current calendar of scheduled events, new events, an up-to-date Gantt chart showing the project schedule and percent completion by task, a document management section, a data repository, and a message board.

Woolpert recommended a two-phased approach: a pilot and a citywide conversion phase. The pilot refined the project approach and provided tested procedures to complete the citywide phase of the project. After the pilot project conversion was complete, the city had the opportunity to use the data for a limited amount of time before citywide conversion began. After about two weeks of giving the data a "test run," Woolpert and the city met to discuss results of the pilot and any further needs. The consultant worked with the city to define the intricate details of the utility conversion effort, including attribute collection and definition by object and source document, quality control standards and acceptance criteria, lessons learned during the pilot conversion, any exceptions to conversion rules, and problem resolution rules and procedures.

The consultant integrated agreed-upon changes to the utility conversion and data creation methods before beginning conversion of the remaining areas. The findings of the evaluation were also documented and incorporated into a final procedures document that served as a guide for the remainder of the city's utility conversion.

Woolpert surveying crew performing primary GPS observation on control along the Mississippi River.

Before the field inventory project could even begin, the city needed a geodetic control network. Initially, the consultant recommended using static GPS to gain horizontal control and conventional leveling to gain vertical control. Crews did a reconnaissance mission and found that only three vertical control monuments in St. Charles were listed in the National Geodetic Survey (NGS) database. Additional vertical control existed, but was on the east side of the Missouri River or ten miles west of the city limits—too far away for line-of-sight leveling. The consultant recommended the HM method to establish the vertical coordinate component and to establish new, reliable monuments while maintaining an accurate, cost-effective solution.

The National Oceanic and Atmospheric Administration's NGS—whose mission is to define and manage the system of geographic reference points known as the National Spatial Reference System (NSRS)—defines Height Modernization as "a series of activities designed to advance and promote the determination of elevations by GPS satellite surveying rather than by spirit (conventional) leveling." The NGS began allowing GPS-derived orthometric heights (North American Vertical Datum of 1988) in the 1990s. So far, only a handful of states are using HM methods—including North Carolina, California, Wisconsin, and Louisiana—but the NGS hopes more will start using the method, thereby improving the quality and quantity of vertical information within the NSRS.

Until recently, surveyors had to rely on line-of-sight survey measurements, much like Lewis and Clark did, to determine and establish control stations. But there are limitations with conventional surveying: Most methods not only require line of sight, but also involve miles of walking while carrying heavy equipment, call for at least three surveyors, pose accessibility problems, and produce accuracy levels that are duly precise but relative because of the gravitational effects of the earth experienced during each observation session.

GPS, on the other hand, enables geodetic control stations to be established without having to physically see or measure distances between survey points. Only five individual surveyors, each equipped with one geodetic-grade GPS setup, were needed to establish the St. Charles geodetic control network. Absolute accuracies—between 2 and 5 centimeters—can be determined after a rigorous post-processing and adjustment regiment is completed. A survey that once took months to complete now can be done in a couple days or weeks and at a much lower cost. In St. Charles, the HM method enabled surveyors to meet relative geodetic control station accuracies in half the time and for about $50,000 to $75,000 less than conventional leveling methods.

The NGS has developed standards, specifications, and techniques for ensuring a successful vertical GPS survey. The process, to which Woolpert carefully adhered, includes the following:

- Conduct thorough existing control station research
- Conduct detailed onsite reconnaissance mission
- Establish new survey monuments
- Develop an observation scheme
- Perform GPS observations and leveling operations
- Perform data processing and adjustments
- Report on the survey to NGS

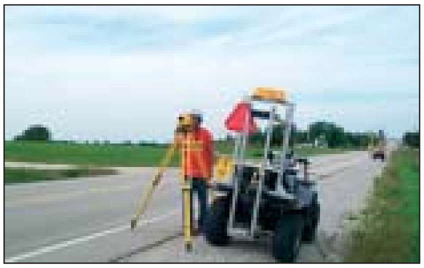
Specifically, here is how the HM process was conducted in St. Charles. After researching the NGS station database, the consultant also discovered four non-published Missouri Department of Natural Resources control stations, which met monument dimensional standards. Next, the consultant plotted the existing station locations to gain a better understanding of their dispersement and to allow the consultant and St. Charles to determine the best locations for new control station monuments.

Before the start of field observations, the consultant submitted its plan to the NGS, the Geodetic Section Chief, the Missouri Department of Natural Resources, and to the city for review and approval. Once the plan was approved, field observations began.

The consultant used a specially created GIS and additional analysis to determine a required one-mile grid spacing between the proposed monuments. The analysis found that 28 NGS Class "C" type monuments would achieve the required density. Once reconnaissance and evaluation were complete, the consulting engineer designed a GPS observation and high-accuracy control network scheme to meet and exceed the specifications for First-Order horizontal control and 2-centimeter, GPS-derived, orthometric-height, vertical-control surveys.

With the locations determined, an underground utility check was initiated to begin the mark-setting activities; these activities involved digging a 4.5-ft deep by 1-ft diameter hole, filling the hole with concrete, and installing a specialized bronze survey disk marker.

Five one-person crews began GPS observations to first determine the horizontal locations of the monuments. The 26.5-sq mi area was divided into quadrants. Crews started at the outermost corners and worked inward. In addition to taking measurements, crews also would take meteorological readings at the beginning and end of each GPS session to assist post-processing of the GPS data. Woolpert processed, adjusted, and developed a final report to meet or exceed standards for a First-Order horizontal survey.



Geodetic leveling crews from the consultant using quad-runners while running leveling surveys.

Then, the vertical aspect of the control network was conducted. To meet NGS specifications for HM survey methods, minor supplemental geodetic leveling had to be completed. This involved performing precise geodetic leveling to NGS Second-Order, Class I standards and specifications to key (three) geodetic control station monuments in and around the project limits.

The consultant worked to meet the specifications outlined in the Input Formats and Specifications of the National Geodetic Survey Data Base ("blue book" specifications). Upon completion, GPS control point coordinate data and monument descriptions were submitted to the NGS for inclusion in the NSRS. The consultant prepared a detailed final report outlining aspects of the project. Necessary printouts and files necessary for the stations to be "blue booked" were a part of this report. In addition, tables were added containing check measurements, section closures, section comparisons, and field logs.

The city now has consistent geodetic control citywide, and the data are available for public and governmental use via NGS's database on the Internet. Developers now can submit electronic as-builts (records drawings) to the city, and, because of the control network, the city doesn't have to resurvey: the developer information is imported directly into the GIS. The Federal Emergency Management Agency (FEMA) uses the data for updating its floodplain maps. Because of the highly accurate controls, stormwater modeling is now more accurate.

Aerial Survey

LiDAR technology blends the speed of computer-directed lasers and the precision of GPS to create a 3D model of the terrain below. From this data, digital terrain/elevation models (DTMs/DEMs) can be derived, as can elevations for such items as collected utilities. In St. Charles, adding LiDAR to the project meant that utilities captured in 2D via ground-survey methods could be draped over LiDAR DEMs to become 3D without much more cost or time expended. The St. Charles LiDAR project was flown in March 2003 during dry weather. (Although LiDAR may be flown at night or under cloud cover, it cannot be flown in rain, fog, or heavy mist because water vapor can distort the direction of the laser beam and produce an inaccurate reading.)

The project area was more than 20 sq mi. Woolpert flew 15 flights in a north-south direction with a full swath of 3,972 ft at a speed of 125 knots with 30 percent overlap at an average altitude of 6,220 ft above ground level. Using the Leica (www.leica.com) ALS40 LiDAR system mounted on the aircraft, the laser unit emitted a stream of light pulses—up to 40,000 per second—perpendicular to the aircraft's direction of flight. The time it took for each pulse to return to the aircraft was recorded along with the angle off nadir (the perpendicular point) at which each pulse was emitted. Airborne GPS data also were recorded at a rate of 1 Hz for the entire session. Ground stations located onsite identified and corrected errors in the aircraft's position. An Inertial Measurement Unit (IMU) provided altitude data of the aircraft at a rate of 200 Hz for each session.

During post-processing, the slant distance between the aircraft and the ground for each returned pulse was calculated as one-half the time it took for the laser pulse to travel from the aircraft and back, multiplied by the speed of light. Each slant distance was then corrected for atmospheric conditions, and for the altitude, roll, pitch, and yaw of the aircraft, using the IMU data.

GPS data were processed separately and imported into the LiDAR solution; each corrected slant distance was transformed to a ground surface elevation (x,y,z coordinates for each data point). Additional software was used to post-process and study certain aspects of the data, such as calibration parameters, to ensure the tightest and most accurate solutions. Quality control was also performed in the generation of the digital orthophotos, and, for the DEMs, the generation of contours.

For the St. Charles project, LiDAR was used to collect the vertical component of water and stormwater structures at an accuracy level of plus or minus six in. Using the LiDAR data, the consultant would later populate the GIS's water and stormwater point data with the z-elevation (vertical) attribution.

The consultant obtained new black-and-white aerial photography at 1 in. =800 ft scale of the entire city using a Leica RC30 camera system with low-distortion, high-resolution lenses, and forward-motion compensation. The photos were captured in February 2003 and March 2003 to take advantage of optimum visibility (no leaves on the trees; good sun angles).

The consultant performed aerial triangulation with the support of the ground control GPS survey to extend and densify the ground-control network to allow for stereo compilation. Aerial triangulation allowed for the development of a DTM for contour generation.

Using the 3D LiDAR data, the consultant stereo-compiled breaklines to be added to the LiDAR data to support the DTM for use in orthophoto rectification and the generation of contours.

1 in. =100 ft digital planimetric mapping consisted of the following features:

- Hydrology features (rivers, lakes, streams, ponds, large culverts, and headwalls). Rivers and streams more than eight ft were denoted as a double-line stream, and rivers and streams less than eight ft wide were denoted as a single-line stream.
- Directional flow of 3D water features.

The resulting images, with 2-ft contours at a 1 in. = 100 ft scale, were used to create a 3D surface model; later, utility structures captured in the field would be draped over the DTM to establish elevation on the 2D features.

1 in. = 100 ft scale black-and-white orthophotos were produced at 0.5-ft pixel resolution for city-specified areas in a 2,500-ft by 2,500-ft tile format. The tiling system was referenced to the Missouri State Plane Coordinate System. Woolpert performed interactive mosaicking to create, as much as possible, a seamless image dataset.

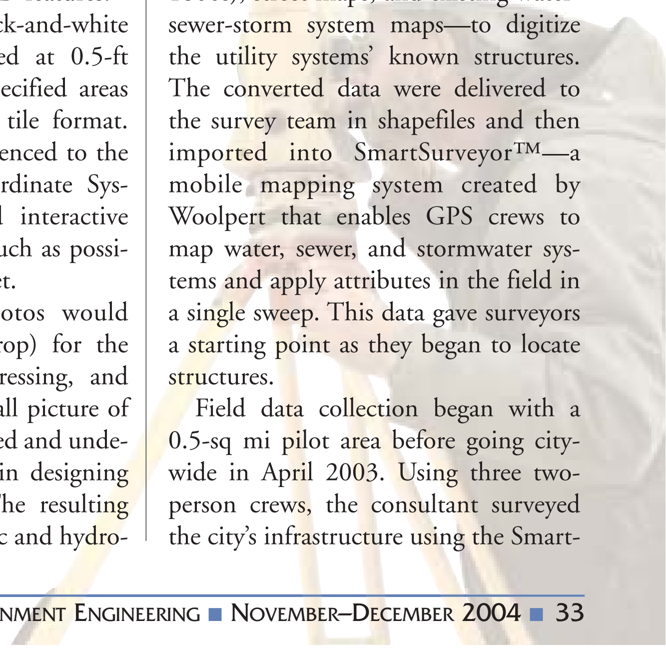
The resulting orthophotos would serve as coverages (backdrop) for the GIS, enabling better addressing, and also provided a better overall picture of the city in terms of developed and undeveloped areas, which aids in designing and planning purposes. The resulting DTMs will enable hydraulic and hydrologic modeling and many other engineering and planning tasks.

Field Survey

Before beginning the field inventory, the consultant developed a Field Collection Procedures Manual that documented the process of collecting location and attribute data for the water, sewer, and stormwater systems. This manual contained the following information:

- Definition of structures collected
- Identification of where and how measurements were taken
- List of attributes collected
- Full procedures for fieldwork, personnel identification, QA/QC, and data management
- Pictures of typical structures and collection methods

A GIS was created to compile a variety of information into a supportive GIS system for schedule analysis and resource management in preparation for field data collection. This supportive GIS environment served as a management tool to track and report project development activities. The effort began with a review of the service areas and applicable source documents. The purpose of this process was to establish a balanced operational schedule and to optimize GPS capabilities.



Before field data collection began, the consultant scanned source material and city-supplied land-base files—including subdivision maps, vintage maps (maps from the original section of town, circa 1800s), street maps, and existing water-sewer-storm system maps—to digitize the utility systems' known structures. The converted data were delivered to the survey team in shapefiles and then imported into SmartSurveyor™—a mobile mapping system created by Woolpert that enables GPS crews to map water, sewer, and stormwater systems and apply attributes in the field in a single sweep. This data gave surveyors a starting point as they began to locate structures.

Field data collection began with a 0.5-sq mi pilot area before going city-wide in April 2003. Using three two-person crews, the consultant surveyed the city's infrastructure using the Smart-

Surveyor software on Fujitsu (www.fujitsu.com) ruggedized pen-based field computers integrated with Trimble's (www.trimble.com) real-time kinematic (RTK) and real-time differential (RTD) GPS technology.

RTD was chosen for the water and stormwater systems because it would provide the x,y (horizontal) coordinates at meter-level accuracy, which was accurate enough for the city's purposes and more cost-effective than the sub-meter-level accuracy of RTK. Additionally, the vertical component for water and stormwater had been obtained via the earlier LiDAR mission. However, Woolpert RTK'd sanitary structures, obtaining x,y,z coordinates at centimeter-level accuracy to achieve highly accurate data. The city intends to use the sanitary system data for an ongoing wastewater study, which will involve hydraulic modeling.

The city determined what attributes to populate in the GIS based on budget. For the full conversion project, the features that were converted included:

Water System. Water main valves' x,y coordinates were collected in the field, however, diameters were populated from paper source documents or assumed from the diameter of the main; the valve type also was populated from paper source documents. Hydrant attributes were collected in the field, including x,y coordinates, inventory status (found/not found), condition comments, rotation (valve open/close direction), age, and manufacturer. The paper source of hydrants (where original information came from, whether map or as-built) was input in the office. Water main features were not field collected; all attribute information originated from paper source documents, including diameter, material, type, source, condition comments, and rotation. Water fittings' location and attribute information came from paper source documents.

Sanitary Sewer System. For the mains, the diameter, material, in depth, out depth, condition comments, and additional notes were field collected. For the structures, the x,y coordinates were field collected, originally with RTD GPS; these points were given to field surveyors, who did a second pass, this time performing RTK GPS to obtain highly accurate x,y, and z coordinates.

Picturesque Mississippi River periodically served as a pleasant backdrop to the massive amount of data collection performed by the consultant.

Stormwater System. Because little paper documentation existed of the stormwater system, crews were starting from scratch to map the system. The area was divided into sub-basins. Crews would start at the low end of each sub-basin and work their way up. As they came across channels and structures, they would "GPS" the locations and collect the applicable connectivity, attribution, and condition assessment information on the pen-based computers. For the mains, stormwater outfalls, and stormwater management structures, the consultant collected the diameter, material, comments, and notes in the field. For the structures, the consultant collected the x, y coordinates, material, structure depth, condition comments, and notes in the field.

During the field survey, crews encountered a number of challenges, including:

Inaccessible structures. Some were paved over or located in areas that could not be reached by field personnel. (A bi-weekly list of these structures was compiled and forwarded to the city for resolution of accessibility issues.)

Lack of access to buried structures. Crews would use a probing rod or a metal detector to verify a buried structure's existence. On occasion, crews would expose structures, but, for the most part, the ground was left undisturbed. Working in SmartSurveyor, crews would code the structure to note that it was buried. This notation also would appear in the GIS.

Blocked GPS signals. For structures located in heavily wooded areas or urbanized areas where the GPS signal was blocked, rendering the RTD GPS inaccurate, locations were made by digitizing the obscured structure into the pen-based field computer using existing mapping as a reference.

Surveyors made daily quality assurance checks to NGS or other established geodetic control stations to verify that accuracy was obtained. In addition, redundant points were checked to ensure that overlap areas were compared geographically. Once data were collected, Woolpert's GIS analysts performed a combination of manual (visual) and programmatic reviews of the field structure locations, attribution, and system connectivity, thus completing the process of building a seamless GIS. GE

Mr. Schrader, PLS, is Group Manager, Survey/GPS, Woolpert LLP, and Mr. Martin is Project Manager, St. Charles, Missouri. Some of the information in this article is from the NOAA/NGS, used with permission.