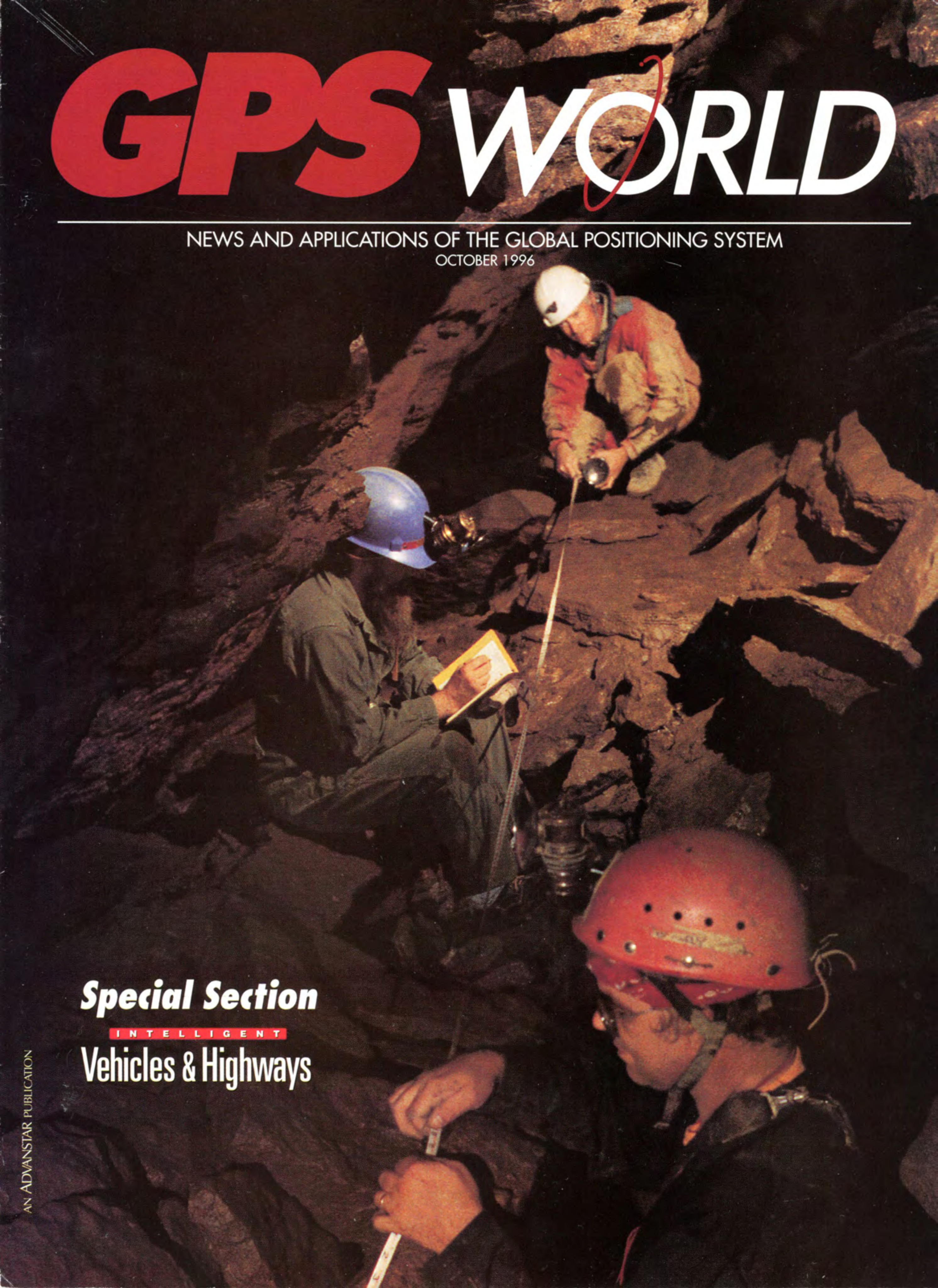
GPS WORLD

NEWS AND APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

OCTOBER 1996



Special Section

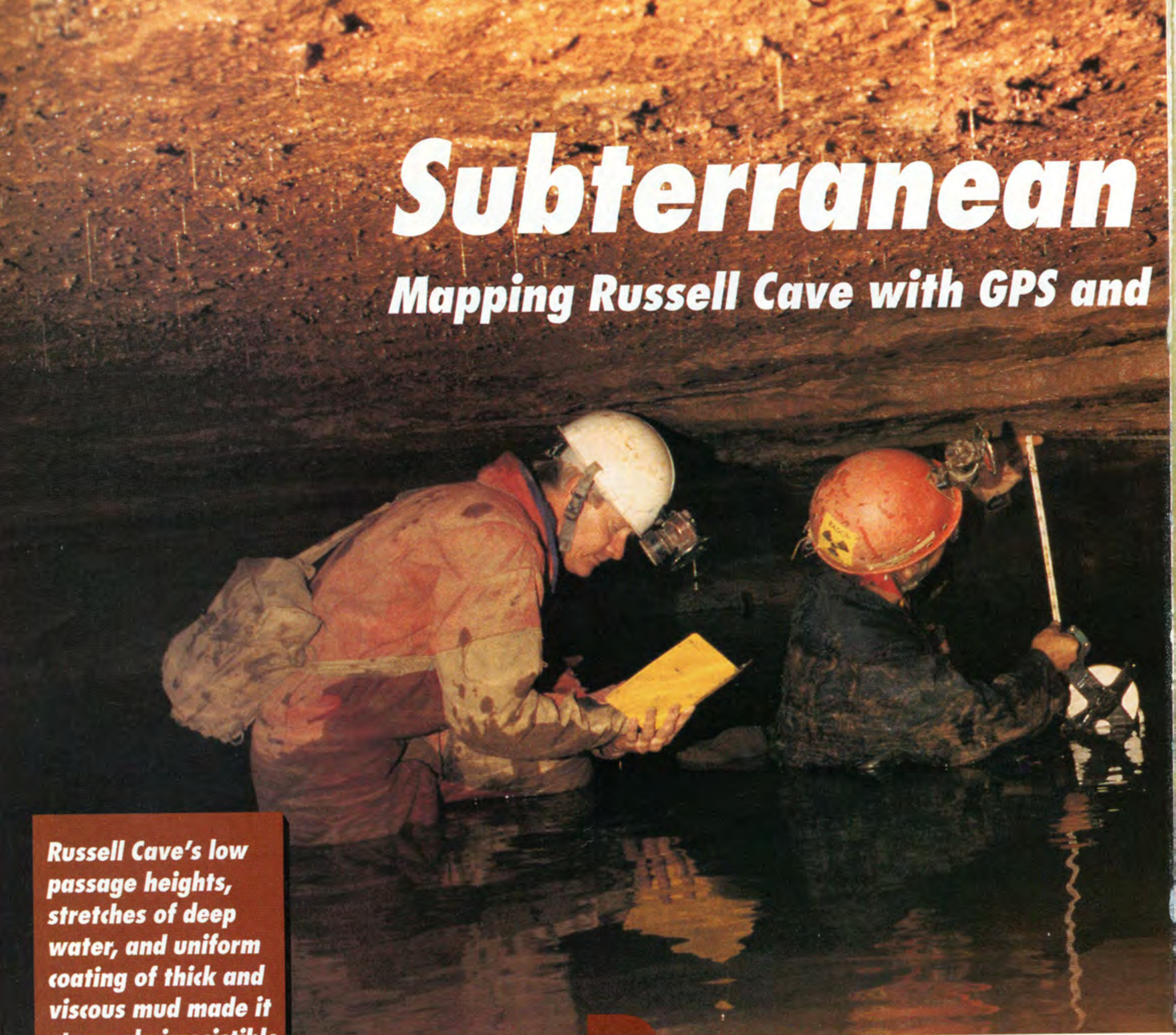
INTELLIGENT

Vehicles & Highways

AN ADVANSTAR PUBLICATION

Subterranean

Mapping Russell Cave with GPS and



Russell Cave's low passage heights, stretches of deep water, and uniform coating of thick and viscous mud made it strangely irresistible to a group of intrepid cavers. Their mission: to test the feasibility of using magnetic induction radio and GPS to transfer to the surface points that were made by survey within the cave. Their rationale: the more difficult the testing environment, the better.

Gary A. O'Dell
Kentucky Division of Water

Ron Householder
MapSync Company

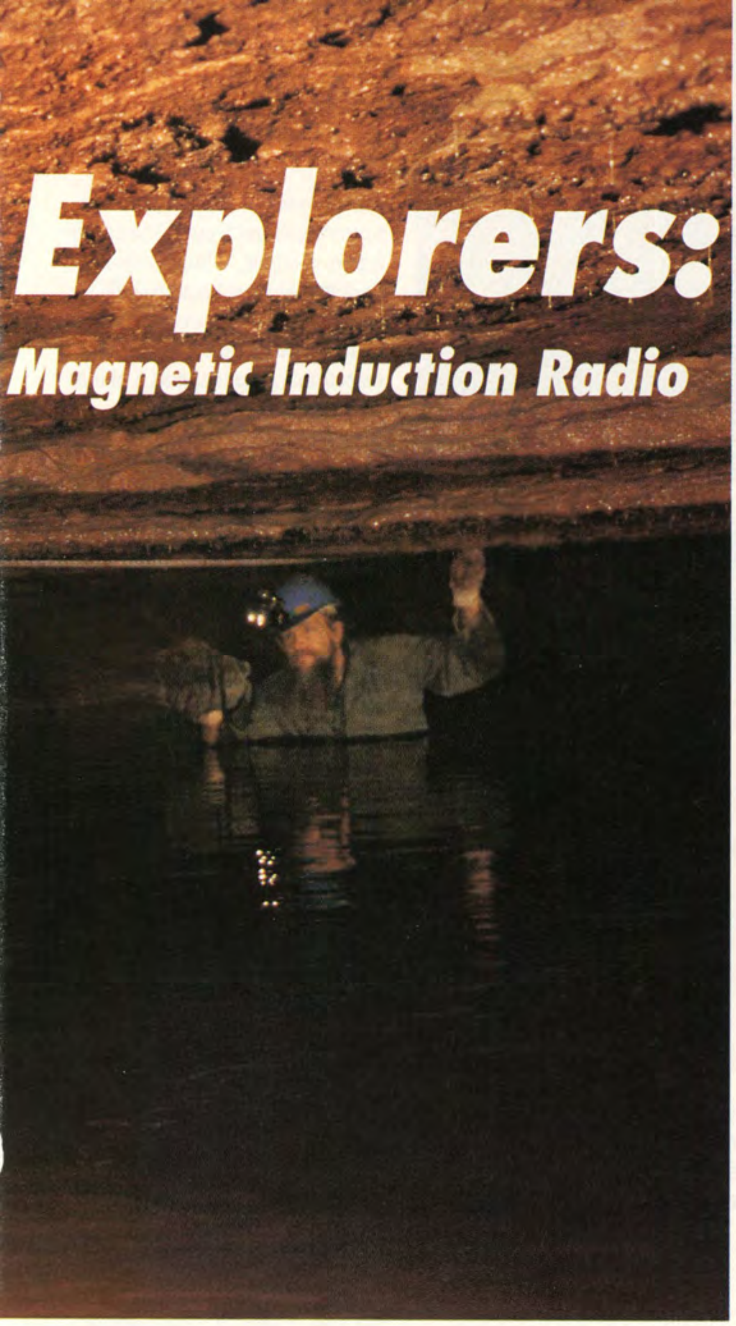
Frank S. Reid
Indiana University

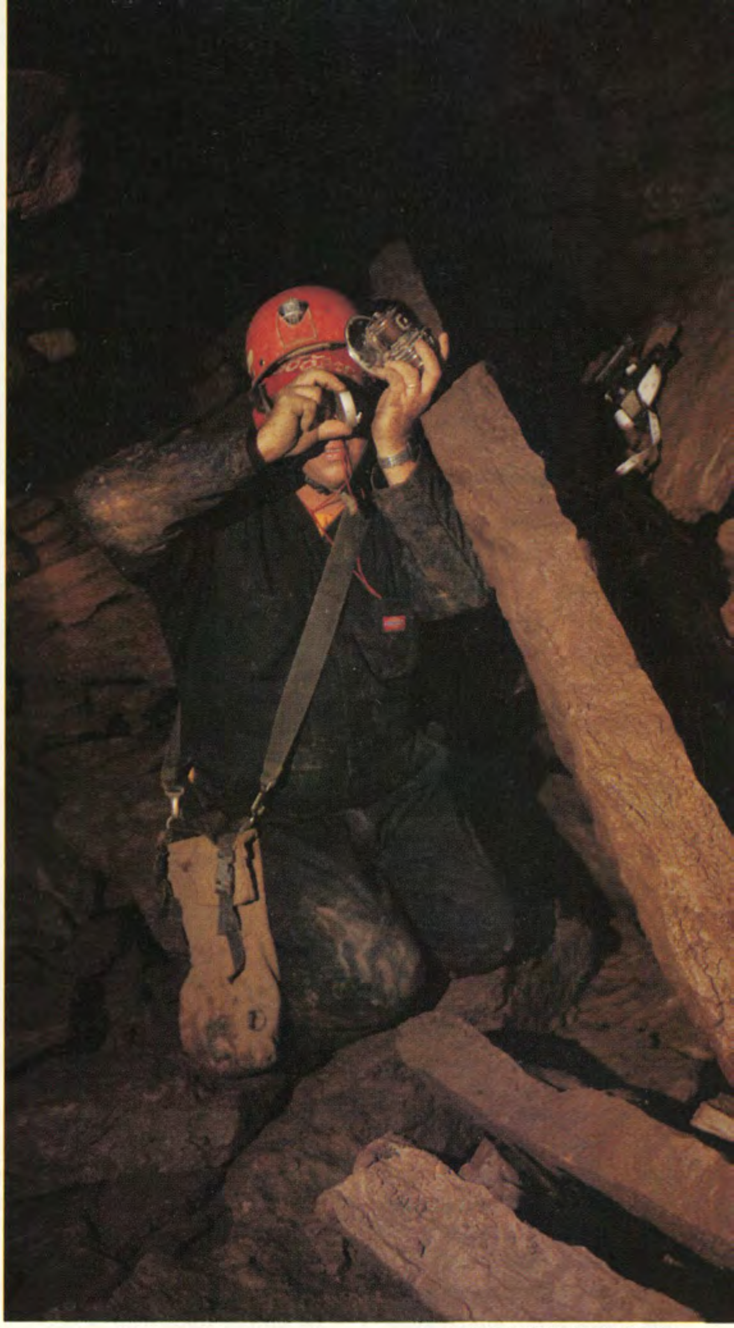
Russell Cave is a historic site located on the well-manicured Mount Brilliant Farm in the heart of the thoroughbred horse district near Lexington, Kentucky. A large plantation-style mansion, built before 1800, sits on the grassy hill above the cave entrance.

An account published in 1820 humorously described a casual venture into Russell Cave by a group of local citizens. With handkerchiefs tied around their heads and candles in hand, the intrepid explorers fortified their courage with a few sips of Madeira and set off into the unknown blackness:

After going about two hundred yards in a circuitous and changing direction, climbing over rude fragments of rock, and squeezing our bodies through narrow straits, we reached a wide portion of the cave with an immense flat surface of limestone above us, and a shallow lake under our feet with a bottom of mud varying from the depth of the knee to that of the whole leg or limb. Walking with our bodies bent double, our heads and backs striking the jagged and dripping roof, our noses nearly in contact with the water and occasionally ploughing its surface, our legs drawn out of the mud at every step with great difficulty, our

Explorers:
Magnetic Induction Radio





BOTH PHOTOS: DAVID L. BLACK

candles in danger of a ducking which would not much increase their usefulness, the possibility that we might meet with some deep hole in the way and suddenly plunge entirely under water at the hazard of drowning, and being at the same time told that we had only sixty yards to traverse in this position, we could not consider as perfectly delightful.

Although the techniques and equipment used in cave exploration have greatly improved during the past two centuries, those who were involved in the recent Russell Cave project (conceived in 1992 and conducted in stages during the next three years) would similarly swear that the wet and muddy cave environment was surely not "perfectly delightful."

The purpose of this project was to test the feasibility of using magnetic induction radio to directly link the subsurface and the surface, with GPS positioning the surface points. Magnetic induction radio has been used to locate points in caves in Kentucky, Florida, Tennessee, and South Dakota for such applications as the installation of water or monitoring wells or to site an artificial entrance. GPS has also been used in other caves, but only to determine the location of cave entrances. But to the participants' knowledge, this was the first time the two technologies had been combined.

The project leaders were Gary O'Dell from Frankfort, Kentucky; Ron Householder from Lexington; and Frank Reid from Bloomington, Indiana. Principal assistants were Reda Smith, Wade Crabb, Marc Cammack, and Pat Hutson, all from central Kentucky.

The concept of linking such antithetical realms as subterranean spaces and orbiting satellites intrigued the participants, many of whom were actively or formerly involved in cave exploration. They anticipated that the two technologies together could be used to determine, with considerable accuracy, the relationships

Russell Cave was one of the worst caves the explorers ever visited. In places, the roof lowers and the stream pools to a depth of nearly 3 feet, leaving precious little air for cavers to breathe. In the large photo, project participants are measuring the distance between survey stations with a cloth tape. From left to right: Marc Cammack, recording data; Gary O'Dell, taking measurements; and Wade Crabb, holding the far end of the tape. In the smaller photo, Gary O'Dell prepares to take a clinometer reading in some cramped quarters.


DAVID L. BLACK

Russell Cave's entrance looks inviting, but the explorer soon finds out that the rest of the cave is wet, muddy, and cool — difficult conditions in which to conduct a survey.

Through Thick and Thin "Skins"

Normally, radio waves are unable to penetrate into the ground or water more than a few feet because of a phenomenon, known as "skin effect," in which radio-frequency currents tend to travel only on the surfaces of conductors. Choosing a lower transmission frequency increases the thickness of the radio wave's "skin" and hence ground penetration. Inductive communication is inherently short range because magnetic dipole field strength decreases as the inverse cube of the distance from the source, unlike radio waves, which obey inverse-square laws. A conductive overburden will absorb some of the signal, but the inverse cube attenuation is so predominant that absorption is rarely noticeable.

directly accessible to humans, such as mines and natural caverns. Point location in such places by conventional means requires a survey transit from a known point on the surface.

Although some underground spaces are mapped routinely, conducting a lengthy and expensive survey in a remote subterranean location is often impractical. In many cases, subsurface conditions render a conventional survey extremely difficult (see sidebar entitled "Trials and Tribulations of Cave Surveying"). Handheld instruments must be used, which are less accurate than tripod-mounted surveying equipment. If the Russell Cave project proved successful, it would mean that GPS/magnetic induction could be used to correct the errors in existing surveys.

RUSSELL CAVE

The 1820 account accurately depicts the conditions still encountered in the first section of the cave today.

The inhospitable environment is the result of a large stream that intermittently inundates the passages. The stream — sometimes only a few inches deep, at other times forming a deep pool — flows through the length of the cave and discharges from the entrance. The frequent flooding ensures that every surface is coated with dark, sticky mud, including any explorers (and their equipment) with sufficient fortitude to explore the cave. With the air temperature at a constant 52 °F, a trip to the end of the cave and back is bone-chilling and exhausting, whether or not additional work such as surveying is conducted.

An explorer entering the cave is forced to wade for 500 feet in a crouched position through water and mud several feet deep. Past this first section is an area of ancient ceiling collapse. Large slabs of rock are piled up nearly to the roof. Beyond this, the passage opens up to a respectable size, 10–20 feet high and wide. In several places along this passage are fissures where small streams join the main flow, sometimes emerging as waterfalls from near the roof.

About 3,000 feet from the entrance is the cave's only significant side passage; situated high above the stream, it is also the only place in Russell Cave that is usually dry. Beyond this intersection, the roof of the main passage lowers and again forces the explorer to stoop. The cave stream pools to nearly 3 feet, with the underlying mud sometimes half again as deep. In many places there is less than 15 inches of airspace above the water.

These conditions persist to the explorable end of the cave, more than 4,500 feet from the entrance. The actual end is not well defined. The roof continues

Trials and Tribulations of Cave Surveying

Conventional land survey instruments of high accuracy may sometimes be used to map caves that have dry and spacious passageways. Such circumstances are rare. The environment within most caves is often harsh or restricted in size, precluding the use of tripod-mounted precision instruments. The potential surveyor may be forced to crawl on hands and knees through mud or water with only artificial lighting as a guide.

By necessity, most cave surveys are conducted with handheld instruments, which are seldom accurate to more than ±0.5 percent. Cave mappers use various techniques to improve the accuracy of surveys. Customarily, higher-quality surveys include precalibration of instruments and multiple sightings both forward and in reverse (backsights). The only practical way to verify the accuracy of cave surveys has been loop closure, either by reconnecting to the surface through a second entrance or by an internal loop. Many cave systems, however, have only a single entrance, and most display a dendritic, or branching, morphology so that long loops are seldom possible. Consequently, the accuracy of a cave survey tends to degrade steadily as the survey progresses farther from surface reference points.

Many cave surveys exceed one mile in total length but few have been accurately related to surface features at the extremities of the survey. Although these surveys can be used to produce maps of the general passage configuration, they do not accurately reflect the relationship between the cave and the surface.

GARY O'DELL

RON HOUSEHOLDER

Top photo, Pat Hutson holds the tape firmly on station during the Phase I underground survey. Bottom, Reda Smith and David Carter duplicate the underground survey on the surface in preparation of Phase II.

to lower gradually and reduce the amount of airspace until the water surface meets the ceiling, and scuba gear would be required for further travel.

EARLIER INVESTIGATIONS

According to the 1820 account, a map of the cave had been made earlier. This report stated that the cave was "accurately surveyed" to a length of nearly three-quarters of a mile. Any such map has since been lost.

Twentieth-century explorations of Russell Cave indicated a length of about 5,000 feet. Until 1993, only a crude sketch map based on the earlier explorations was available.

An Inhospitable Cave. The cave does not initially appear to be suitable for a technological experiment. The groundwater system reacts so quickly to rainfall that the stream inside can become a raging torrent in only a few hours. During the winter and spring, Russell Cave usually remains flooded and inaccessible. Because there is just one entrance, the cave can be safely entered only during periods of dry weather.

After the accidental death of a teenage caver in 1943, the property owners refused permission to would-be explorers for many years. In 1980, the owners granted permission for occasional explorations by experienced cavers, but few have had any desire to do so. Kentucky has thousands of other caves, many of which are much larger and more enjoyable.

A Challenge. So, why was such an unpleasant cave chosen to demonstrate the GPS/magnetic induction linkage? Simply because it was such a hostile, "worst-case" environment. The conditions precluded using conventional land surveying equipment.

Clearly, it is an extreme example, but other factors also favored the selection of Russell Cave. Most importantly, the terrain above the cave is gently rolling pasture with few trees, ideal conditions for receiving GPS transmissions. In addition, during 1990–94, the Lexington-Fayette Urban County Government (LFUCG) locally established a first-order network of GPS surveying monuments. Finally, the cave is adjacent to Lexington, conveniently accessible for most of the project participants.

IN (AND UNDER) THE FIELD

In early spring 1992, Gary O'Dell launched the project. Gary recruited Frank Reid and Ron Householder, once an avid cave explorer and now an expert with GPS equipment and applications. Ron subsequently recruited Reda Smith, David Carter, and Tim Poindexter to assist with the surface survey and GPS operation. Gary presented the proposed project to the Blue Grass Grotto (BGG) of the National Speleological Society in Lexington and found many willing volunteers. Among the most enthusiastic and dedicated were Marc Cammack, Pat Hutson, and Wade Crabb. Ten other volunteers rounded out the exploration/survey team.

Jack Hayden, manager of Mount Brilliant Farm, gave permission for the participants to survey the cave. Gary and Wade made a preliminary scouting trip into Russell Cave in late May 1992, when the water level was unseasonably low. The two encountered no unusual obstacles, although they noted that it was certainly one of the nastiest, muddiest caves they had ever visited. With this accomplished, all involved fully expected to begin the first phase of the project, surveying the passages, during the dry summer months that same year.

Unfortunately, nature decided to make up for its unseasonably low waters with unseasonable highs that continued through summer on to the following spring. With the cave flooded shut, team members gnashed their teeth (figuratively) and waited for the groundwater levels to subside.

Phase I: The Preliminary Survey. A year and a half passed before project teams could again enter the cave. In September 1993, Phase I of the project began — surveying the cave passages and establishing reference stations that would allow the survey to be corrected using magnetic induction and GPS. Gary and BGG volunteers made three successive trips into the cave to map the passages. Consistent with such cave surveys, the volunteers used magnetic azimuths from a handheld compass in conjunction with taped distance measurements and vertical control by way of a clinometer.

Each shot of the survey consisted of sightings both forward and backward. On those occasions when front- and backsights disagreed by more than 1 degree, the cavers took additional readings. During postprocessing, they averaged the readings for a single station. As the survey progressed, the group established semipermanent markers at eight stations approximately 500 feet apart.

Preparing for Phase II: A Random Traverse. With the preliminary cave survey completed, and the raw data processed as an open traverse based on assumed coordinates, the project participants were ready for Phase II — using magnetic induction radio to determine surface locations for the reference stations.

To prepare for this, Ron, Reda, and David conducted a conventional random traverse, using an electronic theodolite and electronic/infrared distance meter. They staked the assumed locations of the eight underground reference stations, as indicated by the cave survey data, on the surface. This would give Frank an approximate starting point for his magnetic induction radio location effort. This step was intended only to save time and was not critical to locating the underground points.

GARY O'DELL

TIM POINDEXTER

Left photo, during Phase II, Marc Cammack carefully travels in the cave's entrance area. In 1943, a young boy was killed by a rockfall in this section. During Phase III, Reda Smith, David Carter, (right photo) and Ron Householder (not pictured) used three GPS units operated in tandem to determine the location of the four surface stations derived from the underground transmissions.

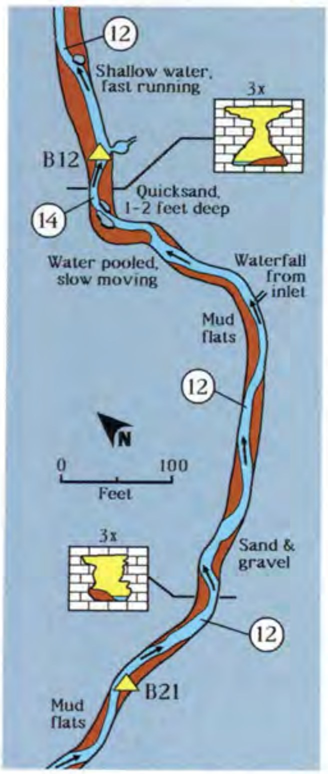


Figure 3. Portion of the Russell Cave map, drafted from corrected survey data and the field notes. Numbers in circles indicate passage height in feet. This is one of the more spacious and least unpleasant areas within the cave. Shown are two of the transmitter sites, stations B12 and B21.

Gary and Ron initially arranged to meet Frank at the cave in mid-October, when he would bring the magnetic induction radio equipment from his lab at Indiana University. October is usually one of the driest months in Kentucky, so the group expected little difficulty with access to the cave. Unfortunately, substantial rains postponed the rendezvous with Frank on this occasion and for two subsequent alternate dates. Russell Cave remained flooded for another entire year, and the participants fervently wished they had chosen another, drier cave for the project.

Phase II Commences: In the Cave. In August 1994, groundwater levels finally subsided enough to again allow access to the cave. Frank traveled from Bloomington to Lexington on the 15th and met Gary, Ron, Reda, and Marc on the hill above the cave entrance. During the preceding weeks, Ron and Reda had reset the stakes for the eight proposed control points, as horses and cattle had obliterated any sign of the previous year's markers.

Frank, Ron, and Reda remained on the surface while Gary and Marc headed into the cave. The most distant reference station in the cave, near the end, would not be used. This station was located in one of the most unpleasant parts of the cave, and the underground team would have been miserable. Instead, the first transmission would be made from reference station B41 located in the dry side passage, three-quarters of the way to the end of the cave.

The intended protocol was simple. The first transmission would begin one hour after Gary and Marc entered the cave and be maintained for 30 minutes. Gary and Marc would then retrace their steps toward the next station, approximately 500 feet closer to the entrance. Ten minutes were allowed for travel, and an additional five minutes to unpack and set up the transmitter. This would be repeated for each station successively. Thus, there would be a 30-minute transmission every 45 minutes.

The underground and surface teams were able to maintain a limited communication capability, thanks to the properties of the magnetic induction equipment. The transmitter's pulsed signal could be heard in Frank's — the receiving operator's — headphones at the surface. The transmitter was equipped with a three-position switch that allowed no transmit, fast pulse, and slow pulse. By prearranged agreement, if Frank received a fast pulse, it was a viable station. If he received a slow pulse, this meant "abort" and move to the next station.

Gary and Marc traveled to the dry side passage without incident and set up the transmitter. After approximately 15 minutes of transmission, they were startled to hear a repeated, deep "thump...thump...thump." It was the sound of Reda driving home a stake on the location determined by Frank's equipment, resonating in the cave through more than 50 feet of soil and bedrock. Apparently, some of the old tales about the cave were not so far-fetched after all: an 1881 county history had noted that explorers sometimes could hear the ring of the anvil at Kearney's blacksmith shop, located near the cave.

This phenomenon occurred at each station. Approximately a quarter-hour after the transmission began came the sound of the stake being driven into the topsoil. For the underground team, it served as an unintended signal to cease transmission and begin packing up the equipment (see Figure 3 for a glimpse of the conditions between stations). In all, the team made transmissions from the four most favorably situated of the eight underground reference stations (designated A2, B12, B21, and B41 during the preliminary survey) and established four corresponding surface points.

Each of the temporary surface stakes driven into the ground by Reda would later be replaced with lengths of 1/2-inch steel rebar and surveyor's identification caps designated NA2, NB12, NB21, and NB41.

The second phase was successfully concluded. With the reference stations now established on the surface, the project was no longer at the mercy of the weather. It remained only for Ron and the above-ground team to determine locations for the surface stations using static GPS and the Lexington GPS network.

Phase III: GPS Locations. The final field phase of the project was conducted on January 27, 1995. Ron, Reda, and Tim Poindexter operated three nine-channel, L1, C/A-code GPS receivers simultaneously in multiple sessions to tie the corrected cave survey to the LFUCG GPS control network.

They could not directly occupy station NA2 as it was located less than one foot from the trunk of a very large tree. Instead, they offset control point (CP) 1001 from NA2 by 57.8

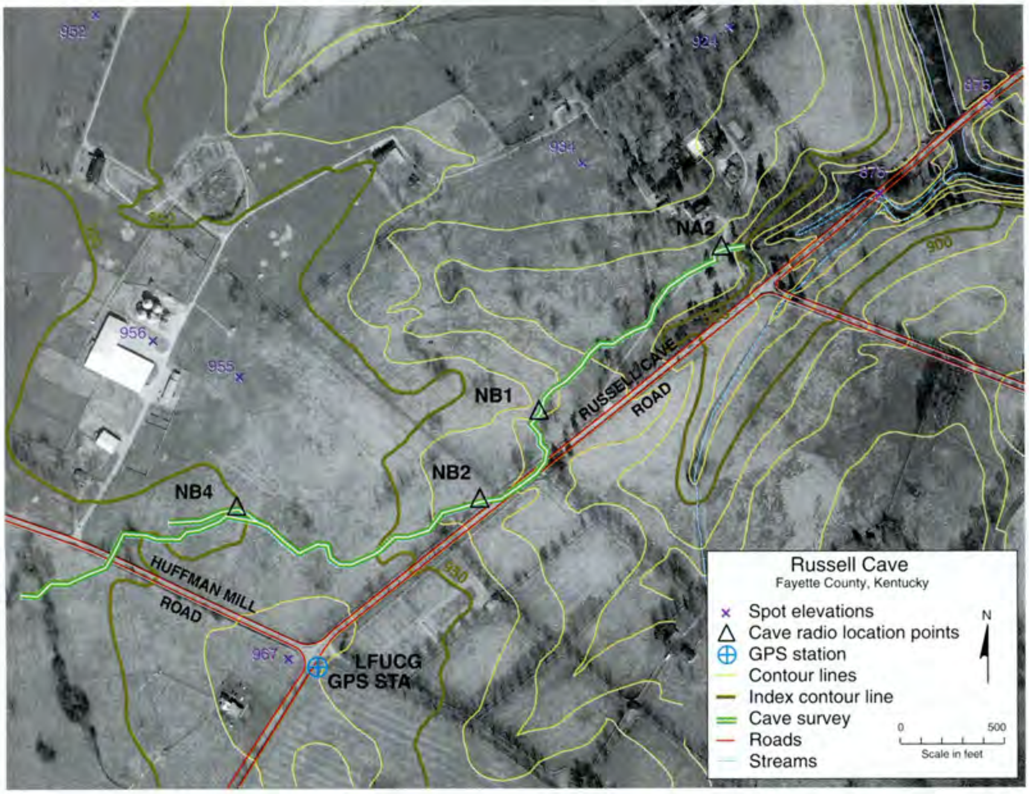


Figure 4. The corrected plot of Russell Cave, overlaid on an aerial photograph of the vicinity. Shown are the cave line plot; the control stations NA2, NB12, NB21, and NB41; LFUCG GPS station 0086; and topographic contour lines.

feet — the distance necessary to allow both elbow room and GPS reception — and subsequently tied the point to NA2 through conventional surveying methods.

They conducted three sessions, each lasting approximately 45 minutes. During the first session, they placed the receivers on LFUCG 0086 (a monument located at the intersection of Russell Cave and Huffman Mill roads), NB12, and CP1001; occupied NB12, NB21, and NB41 during the second session; and occupied LFUCG 0086, NB12, and NB41 in the final session. They chose the points in this order to provide strength of figure to the network of baselines that now connected the project's Russell Cave monuments to those of the LFUCG countywide control network.

The team supplemented and substantiated the GPS elevations with an independent series of level loops. The level survey was carried a short distance into the cave entrance, to station A2, providing both a short reference baseline (100 feet) and a spot-check on the depth determination by magnetic induction. The benchmark for these levels was the published elevation of LFUCG 0086: 958.95 feet above mean sea level. Elevations determined by the two separate methods proved to correspond closely.

DISCUSSION OF RESULTS

Ron and Reda corrected the original cave traverse of 4,629 feet using the control stations whose coordinates were derived from static GPS. They did this using the least-squares method to adjust NA2, NB12, NB21, and NB41 for closure. They first rotated the cave survey to correct for magnetic declination (3.5 degrees west) in effect the year of the survey, 1993. They then adjusted the cave survey in three segments (A2 to B12; B12 to B21; and B21 to B41) to the GPS coordinates of NA2, NB12, NB21, and NB41. This had the effect of localizing errors, rather than distributing them proportionately, throughout the entire length of the survey. The corrected plot is shown in Figure 4.

Previous Research. Research conducted by Charles Bishop and Frank Reid during 1974–75, and published in the *Proceedings of the Eighth International Congress of Speleology* (1981) was used to calculate the accuracy of the Russell Cave survey. These findings demonstrated that points underground can be located to submeter accuracy using magnetic induction radio. At depths of less than 100 feet, errors in horizontal position of less than 6 inches resulted. In vertical position (depth determination) the error was about 1.8 feet (97.6 percent) at 75 feet below the surface.

Error Sources. Sources of error in the preliminary cave survey were of angular and linear types, of which angular differences were the most significant. By comparing the preliminary survey segments with those derived from magnetic induction radio and GPS location, the participants determined that angular error was worst in the first segment, A2 to B12 versus NA2 to NB12. The angular difference between the two segments was 1° 17′ 27″. This was the most difficult area for the in-cave surveyors because of the very low ceiling, deep water, and clinging mud; the relative error decreased for the two succeeding segments. The mean angular difference was 1° 04′ 34″.

Linear error was of a lesser magnitude. Distance measurements by the cave surveyors were surprisingly good, considering the harsh surveying environment. This is indicated by a comparison of unadjusted and adjusted lengths, as measured along the cave survey. For example, the uncorrected length of the survey segment A2 to B12 was 1,134.6 feet, compared with a length of 1,135.2 feet for the adjusted segment NA2 to NB12.

As anticipated, the in-cave survey demonstrated a cumulative horizontal error. The error first became apparent when comparing stations B12 and NB12, 1,235 feet from the entrance, which were displaced horizontally by 22.7 feet. At a distance of 3,105 feet from the starting point, the positional error had increased to 43.1 feet between stations B41 and NB41.

Therefore, inherent horizontal positional error in the uncorrected survey is equivalent to approximately 1.5 percent of the total traverse from the entrance

Table 1. Elevations (in feet) above mean sea level for control stations, derived by different methods

Station number	Elevation of surface station (from GPS)	Elevation from cave survey	Depth from magnetic induction	Elevation from magnetic induction	Difference between survey and magentic induction
A2	912.93 (NA2)	879.1	32.9	880.0	–0.9
B12	925.07 (NB12)	874.7	54.0	871.1	+3.6
B21	931.24 (NB21)	870.5	59.7	871.5	–1.0
B41	939.21 (NB41)	882.7	52.2	887.0	–4.3

Participants

The authors would like to acknowledge the invaluable assistance of the many other persons involved in this project. Without their enthusiastic volunteer participation, often under severely trying conditions, it would not have been possible even to begin, let alone complete, the undertaking. Heartfelt thanks go to the following persons:

- The underground teams: John Barnes, Marc Cammack, Wade Crabb, James C. Currens, Robert Duncan, Barbara Graham, Pat Hutson, Martin Knox, Willie Robertson, Barry Snap, and George Turner.
- The surface teams: David Carter, Bill Glasscock, Timothy C. Poindexter, and Reda Smith.
- Dick Gilbreath (University of Kentucky Center for Cartography and GIS), Kent Anness (Cartographic Section of the Bluegrass Area Development District), and Scott Richards (Kentucky Environmental Quality Commission), for assistance with production of maps and graphics.
- Chester Bojanowski, Kentucky Division of Water (formerly with the U.S. Geological Survey National Mapping Division) for critical review of the manuscript.
- Jack Hayden, manager, for allowing the participants to conduct this project on (and beneath) Mount Brilliant Farm.

to any given point. Using the corrected survey, the inherent error is the same percentage measured instead from the nearest control station; the distance from the entrance becomes irrelevant as the control stations were established independent from any other point of the survey.

According to the corrected survey, the passages of Russell Cave lie very close to the surface. Magnetic induction radio indicated the depth from surface to transmitter for the four control stations ranged from 32.9 to 59.7 feet, with a mean of 49.7 feet. At this depth, based on the 1981 published findings, these would be expected to be approximately 97.6 percent of the true values. Table 1 shows the GPS-derived elevations for the surface control stations located by magnetic induction and compares the elevations derived from the cave survey and from magnetic induction radio for the associated in-cave stations.

Determining Elevations. The participants derived the elevation for Station A2, inside the cave, from the level loop survey and used it as the reference elevation for the other three in-cave stations and also to spot-check the accuracy of the magnetic induction depth determination. Assuming that the depth determination of 32.9 feet for A2 is 97.6 percent of actual, the predicted elevation for A2 would be 879.2 feet above mean sea level, based on the 1981 research. This differs by –0.1 foot from the actual value. The magnetic induction value, in this case, is 97.3 percent of actual. Although this was only a single check, it appears to confirm the published findings.

Excluding station A2, for the remaining three control stations, the mean of the absolute value for the differences between the elevations determined by cave survey with handheld instruments and those determined by magnetic induction radio is 2.97 feet. If the 97.3 percent determination for station A2 is applied to the other control points, the mean difference is reduced slightly, to 2.8 feet.

Vertical and Horizontal Accuracies. In either case, the indication for the Russell Cave survey is that vertical control with a handheld clinometer was more accurate than horizontal position derived from magnetic azimuths. At station B41, the difference between the elevations derived from the cave survey and from magnetic induction radio constitutes a cumulative error of 2.7 feet (using the 97.3 percent correction). As this station is 3,005 linear feet from the known elevation of A2, the cumulative error at this point is 0.09 percent — substantially less than the calculated 1.5 percent horizontal error.

Consequently, the true location of a point 100 feet from a known control station in Russell Cave is contained within an ovoid about 3 feet in diameter and a few inches thick. This assumes that the location derived from magnetic induction radio and GPS is perfectly accurate; in actuality, the error inherent in magnetic induction radio is, at a depth of 50 feet, approximately 6 inches in a horizontal plane and 1.35 feet in the vertical. This uncertainty must also be taken into account.

These results confirmed the project leaders' belief that the accuracy of cave maps do not have to depend on the degraded accuracy common to handheld instruments. Existing surveys can be corrected by using GPS and magnetic induction.

CONCLUSIONS

Though the project was a success, it did have its share of problems. For example, many logistical problems occurred simply because of the difficulties inherent in coordinating the efforts of a project team originating from three different cities in two different states. This was further complicated by the necessity to conduct several stages of the project under specific weather conditions and groundwater flow stages.

If the Russell Cave project is indeed the first application of its type to combine GPS and magnetic induction radio, then its successful results bode well for future cave applications. Conventional cave mapping requires using handheld instruments that produce cumulative angular (horizontal and vertical) and linear errors. By using both magnetic induction radio and GPS, the project participants interrupted the progression of cumulative error; in effect, they reset the traverse to nearly zero error (within the limits of the respective technologies) at each such reference point. The more reconnections that were made, and the more closely spaced, the greater confidence that could be placed in the location of intervening points.

The mapping of caves is, of course, a highly specialized and somewhat esoteric discipline that has only limited practical applications. However, the

GPS/magnetic induction combination can also be applied wherever human activity extends to the subsurface and accurate positions are necessary. Such places include deep mines, tunnels and aqueducts, and underground utilities, as well as natural caverns. In addition to subsurface point location applications, GPS/magnetic induction could be used in marine as well as terrestrial environments, in such applications as underwater archaeology and salvage or rescue operations. In the future, cave surveyors and others who need to locate points or places underground will likely make routine use of these combined technologies. As the Russell Cave explorers discovered, potential applications for GPS combined with other technologies are limited only by the needs and imaginations of the users. ■

__Gary A. O'Dell,__ M.A., a member of the National Speleological Society since 1967, has spent more than a quarter-century engaged in research concerning caves and karst landscapes. He is employed as manager of the groundwater database for the Kentucky Division of Water. O'Dell is pursuing doctoral studies in the Department of Geography at the University of Kentucky, specializing in environmental and natural resource issues.

__Ron Householder__, P.L.S., has been president since June 1994 of MapSync Company, a consulting firm offering a range of GPS, geographic information system, and mapping software development services. He previously owned In-House Solutions, a mapping and consulting firm based in Lexington, Kentucky. Householder is currently a part-time faculty member at Lexington Community College, where he teaches classes in AutoCAD and AutoLISP. He is also a registered land surveyor with 18 years of experience in the surveying and civil engineering fields.

__Frank Reid,__ an electronics engineer with the Electronics Department at Indiana University, began exploring caves in 1961 and joined the National Speleological Society in 1966. He volunteers a great deal of his time as a communications instructor for training conducted by the National Cave Rescue Commission. Reid became interested in magnetic induction radio before 1969 and subsequently developed greatly enhanced equipment. Among his innovations are increased range and resistance to interference. He has applied magnetic induction radio technology to various projects involving cave exploration, location of water wells, and hydrologic and contaminant transport investigations.

MANUFACTURERS

The team used a KB-14 compass and a PMP/360PC clinometer, manufactured by **Suunto Corporation** (Finland), to conduct the underground survey of Russell Cave. The conventional survey, on the surface of Mount Brilliant Farm, was conducted using a CTS-1 Electronic Total Station, from **Topcon America Corp.** (Paramus, New Jersey), and a Nikon automatic level from **Nikon, Inc.** (Melville, New York). The static GPS survey used three nine-channel 4000SE Land Surveyor II GPS receivers from **Trimble Navigation Limited** (Sunnyvale, California). The project participants used Trimble's GPSurvey and Trimnet Plus software to download and process the GPS data. They processed the survey data using SurvCADD from **Carlson Software** (Maysville, Kentucky) and imported the data into AutoCAD Release 12 from **AutoDesk, Inc.** (San Rafael, California) for final drafting.