Homing In with GPS

Putting GPS on a small bird requires sophisticated technologies and perseverance. To better understand how homing pigeons navigate, researchers developed a GPS flight recorder small enough to fit between the wings of a pigeon.

As the victor in the decathlon event of the first Olympic games (circa 776 B.C.) in ancient Greece stood on the championship podium, a flurry of wings broke the sky. Homing pigeons raced from the Olympic stadium, taking word of the games' results to villages all around ancient Greece, including the home village of the victorious athlete.

News of victories and events in the 2000 Olympics in Sydney, Australia, will travel the world much faster, through modern communications networks. Despite the fact that we no longer depend on homing pigeons for communication, their innate ability to fly home from places where they have never been continues to fascinate hobbyists as well as biologists. We still only partly understand the navigation mechanism used by these birds.

Homing pigeons navigate to find their destination using a combination of map and compass mechanisms. To determine their position relative to home, pigeons use a map of physical factors that may include smell, magnetic field intensity, infrasound, polarised light, and possibly landmarks. The physical factors are thought to form a grid. Homing pigeons learn the values of their home loft and then compare them to the values they encounter on their trips or experimental flights. Although the nature of the physical factors forming the map is still unclear, probably several of these factors are used together and form a redundant system.

During the past decade, researchers have found that pigeons also use two types of navigation compasses: a sun compass and a magnetic inclination compass. Pigeons rely on the compasses to localise the bearing toward home in reference to their flying direction. The sun's azimuth (horizontal position) and the intensity of the magnetic field function as the sun and magnetic inclination compass. The pigeons, using an internal clock, can compensate for the sun's changing horizontal position during the day and direct themselves home.

Traditionally, observers study pigeons' orientation behaviour by watching them with binoculars and determining the direction in which they disappear, also known as the vanishing bearing. With this method, only the first few miles of a pigeon's flight path can be observed, and although biologists established the existence of the two compasses, we gained little insight into the nature of the map.

KAREN VON HÜNERBEIN University of Frankfurt am Main and ECKHARD RÜTER Rüter EPV-Systeme GmbH

Recording a pigeon's complete flight path from release to the home loft and correlating the data with the area's topographical structure and other possible factors in their navigation would help us better understand how pigeons navigate home over such large distances. Only then would it be possible to answer questions such as, at what point in their flight do pigeons correct initial deviations from the homing direction? And, what factors do they use to determine where they are, compared to where they need to go? GPS technology offers a way to track pigeons' flight paths and gather the information needed to answer these questions.

As a member of the Institute of Zoology at the University of Frankfurt working with Professor Wolfgang Wiltschko, I began in 1995 to develop a GPS flight recorder for homing pigeons. One year later, Eckhard Rüter of Rüter EPV Systeme GmbH, a company developing transponder systems for homing pigeons, joined the project. When we first started, all we had was a dream and a vision — and many obstacles to overcome. Finding the right technical system to suit our unique requirements and making it small enough to fit on the light bodies of pigeons seemed unattainable objectives in 1995. However, in the intervening years, our design efforts, aided by advances in GPS electronics, have made our vision a reality. Today we are tracking homing pigeons with GPS, and our data promises to add much to our knowledge about how the birds navigate.

Observers, using a traditional method of watching pigeons as they fly toward home, use binoculars to view the birds and determine their vanishing bearings.

Why We Chose GPS

We began our work by investigating traditional navigation technologies used for measuring and recording flight paths. We considered inertial navigation; LORAN-C; a Doppler-measuring satellite receiver system called ARGOS; conventional radio tracking; following the pigeons in an airplane; and a route recorder containing a strong magnetic compass that measured flight direction. However, none of these methods met our needs. They offered, for example, low-precision results, limited range, high cost, and the potential that the equipment would influence the pigeons' navigation method.

Compared with the alternatives, GPS provided several advantages, including worldwide availability, high-precision results, a choice of sampling rates, and unlimited range. Having compared the technologies available, we decided to try to develop our own GPS receiver capable of fitting between a pigeon's wings.

Unique Requirements

To build a flight recorder meeting the requirements for a homing pigeon, we needed to take several factors into consideration.

Weight. Homing pigeons weigh 300–500 grams. To fly freely, the birds should not be burdened with more than 10 percent of their body weight. In fact, many bird researchers say the ideal amount should be closer to five percent. We wanted the recorders to be as light as possible to allow the birds to behave normally on their flights home.

Drag. A backpack disturbs the aerodynamic flow around a bird and thus creates additional drag, making flight more difficult. Our GPS unit would have to have a compact design and a low profile.

Sampling Rate. Pigeons' average flight speed is 70 kilometres per hour. At that speed, a sampling rate of one value per minute would provide data points more than a kilometre apart — adequate for many applications but too far apart for our needs. Sampling one position once every 1–5 seconds would be ideal.

Operation Time. Orientation experiments with pigeons are usually performed within a range of 10–200 kilometres, with the birds returning home between three and 24 hours after release. So our device's battery would have to last at least several hours, yet be extremely light.

Other Factors. Our device would have to be constructed in such a way that the surrounding magnetic field would be as little as possible so as not to affect the pigeons' navigational abilities. And, of course, the cost needed to be low enough to allow us to build enough devices to track a large number of pigeons.

The Bottom Line. With these constraints in mind, we set out to design a flight recorder with the following specifications: ability to record position with an accuracy of 100–300 meters; overall size no larger than 70 × 40 × 30 millimetres; weight no greater than 30 grams including antenna and power supply; a sampling rate between 5 seconds and 5 minutes; an operation time of 3–12 hours; no deterioration of position fix accuracy with time and distance; and no loss of data in case of power failure.

A Reality Check

When we began inquiring about small GPS receivers in early 1996, we found that the smallest unit weighed 36.4 grams — too heavy for the birds. At the same time, the smallest available GPS antenna was a passive patch antenna, with a side length of about 2.5 centimetres and a heavy ceramic layer in the middle. The antenna length could fit a pigeon's back, but the ceramic layer would add too much weight for the bird to handle.

At that point, we almost gave up because solving the GPS miniaturisation problem seemed impossible. Even the manufacturers of the GPS hybrid board, the only device we could find until 1999 that was small and light enough for this application, did not believe that GPS would be suitable for pigeons when I discussed the application with them in December 1997. Eckhard Rüter was one of very few engineers who shared the vision and the enthusiasm of putting a technology like GPS on a pigeon's back. Most other engineers thought it was a laughable idea. However, they offered valuable information to help me find new ideas. For example, a German antenna manufacturer gave me a passive patch antenna out of its laboratory. Weighing just 13 grams, the unit was lighter than any other device I had discovered during all my research. It renewed my hope, and I was convinced that eventually a lightweight antenna design would be developed and pigeons could be tracked with GPS. To me, the most fascinating aspect of this particular project was that it resided on the limits of contemporary technology.

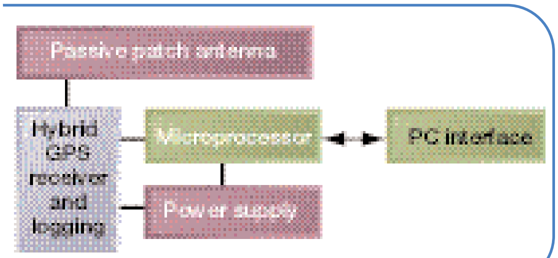


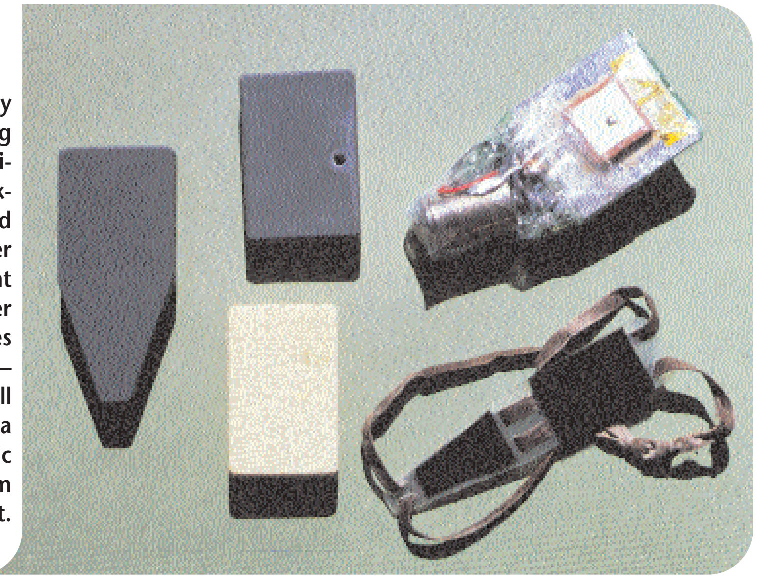
Figure 1 is a diagram of the GPS flight recorder, previously published by the Royal Institute of Navigation, United Kingdom, in *GNSS 2000.*

Building the Flight Recorder

By 1997 technology had finally advanced to allow us to build a GPS flight recorder. In early 1998, we were ready to begin building. We first developed a prototype that weighed 100 grams. We tested it for nine months before identifying mistakes and making improvements. For example, in 25 percent of the tests, our passive patch antenna without a preamplifier failed to get good enough signal reception for the GPS receiver to make a position fix. And the external datalogger sometimes did not record more than one value, which required programming entirely new software based on an unfamiliar programming language. At this point, I again almost gave up on the project.

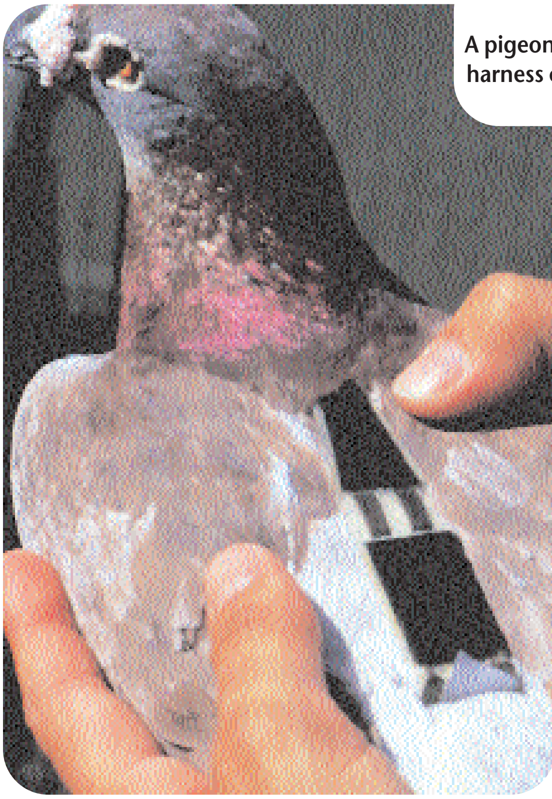
Then, in the spring of 1999, new GPS technology became available that saved us the trouble of fixing the first GPS prototype. The second prototype — our final design — gave us a fresh start. Eckhard Rüter and Michael Riechmann of Rüter EPV Systeme GmbH created the device and made it functional. Clemens Bürgi and Stefan Werffeli, ETH Zürich, greatly contributed to the antenna part of the device.

The new recorder comprises a GPS hybrid board, an onboard datalogger, a power converter, a small patch antenna, a lithium battery, and an additional microprocessor that controls the GPS according to user-defined parameters. A casing of thin plastic foil covers the components. The device measures 8.5 × 4 × 1.5 centimetres and weighs 33 grams, plus an additional 5 grams for the harness. It can store approximately 90,000 positions and operates for three hours, recording one position per second. Figure 1 shows the relationships among the components.



Five items carried by the pigeon during training and experiments: a harness backplate with Velcro and Teflon ribbon (lower right), GPS flight recorder (upper right), and three types of training weights — a 7.5-gram small wooden weight, a 25-gram small plastic weight, and 35-gram long plastic weight.

Our GPS recorder measures the pigeon's positions during its flight and records these positions in internal memory. At the end of the pigeon's flight, the position data are downloaded to a computer. Then the flight paths, or parts of it, can be calculated or displayed on a map. In case of power failure, data is protected because the positions are stored on a flash RAM. Data can be downloaded in NMEA, in a binary format, or as ASCII text. A Visual Basic program converts NMEA data to standard formats that can be processed by PCs.



A pigeon with a 5-gram harness on its back.

A pigeon in a flying cage, wearing a GPS flight recorder.

Taking GPS into the Air

Before actually flying pigeons with our GPS recorder, we first needed to let the birds become accustomed to wearing the unwieldy device.

Training the Pigeons. We used adult pigeons experienced with orientation experiments. We gave the pigeons three months to become familiar with carrying the harness and the weights. We tried to put 25 grams on one pigeon right away, but the pigeon acted very disturbed. So we removed the 25-gram weight immediately and gave the pigeons time to adjust more slowly, starting with eight grams and eventually adding as much as 35 grams.

In the first hours of their training, the pigeons sat on the floor or on their wooden bars, sometimes in a strange position, and looked dumfounded, with a puzzled expression that seemed to say, "What is going on here?" After a while, they began to behave normally but, not surprisingly, kept picking at the harness, weight, and knots.

Once the pigeons were accustomed to wearing the harnesses in their cages, we released them from increasing distances and different directions to allow the pigeons time to adjust to flying with both the harness and the additional weight. During these first flights the weight of the harness was still eight grams. The harness has since been improved to five grams.

Test Flights. After short test flights in Minden and Frankfurt, Germany, in early September 1999, we conducted the flight experiments on 27–28 September, 1999, choosing a release site at Obermörlen, Germany, approximately 30 kilometres north of Frankfurt, used by homing pigeon researchers throughout the past 22 years. During our tests, nine different pigeons carried GPS flight recorders, and one of them flew twice, so we had 10 pigeons flying with GPS flight recorders. In addition, we equipped eight pigeons with weights and released 11 pigeons without weights of any kind to help determine any differences between pigeons carrying the GPS recorders and pigeons carrying nothing, which we called controls.

During these first field experiments, we sought to answer questions such as: Does the flight recorder work? Do pigeons fly well with it? Do they come home? What do the flight paths look like? How many of the flight recorders will fail in operation? And are there any differences in homing time, vanishing bearings, or vanishing times between control pigeons, pigeons carrying a harness and a 35-gram weight, and pigeons carrying a harness and a GPS flight recorder?

The Release Site. We chose the Obermörlen site because, in addition to being used previously during pigeon experiments, the site was a moderate distance — within the range of 10–200 kilometres — from the home site, providing us with just enough distance to demonstrate whether the GPS flight recorders worked adequately.

The site also provided what is called a *release site bias*, meaning that the mean values of direction of several groups of pigeons are shifted several degrees away from the actual home direction and that this shift shows a systematic tendency even when the experiments are repeated several times. At the Obermörlen site, pigeons often have shown considerable deviations to the east of the home site. Mean direc-

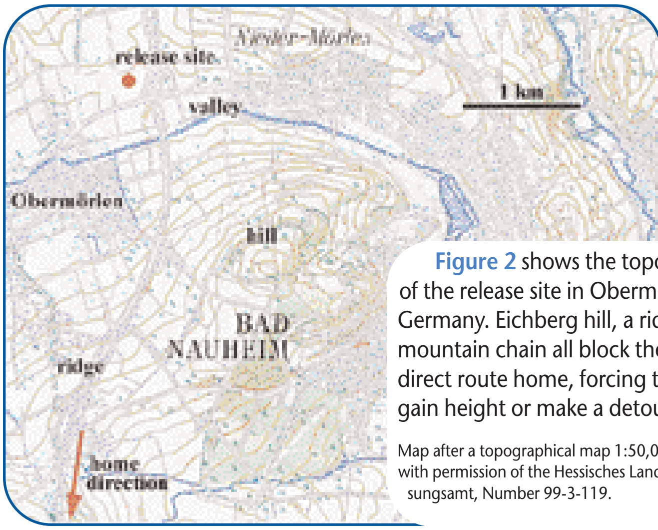


Figure 2 shows the topography of the release site in Obermörlen, Germany. Eichberg hill, a ridge, and a mountain chain all block the pigeons' direct route home, forcing the birds to gain height or make a detour.

Map after a topographical map 1:50,000, reprinted with permission of the Hessisches Landesvermessungsamt, Number 99-3-119.

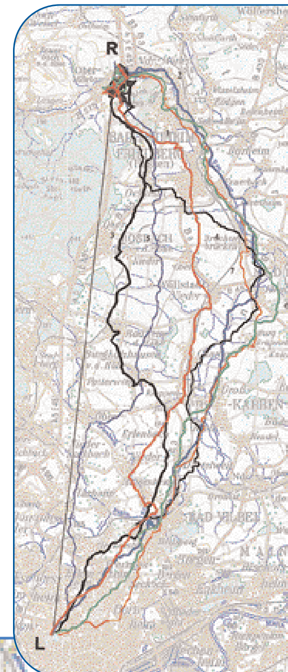


Figure 3 shows seven complete flight paths of homing pigeons wearing GPS flight recorders. The straight black line depicts the most direct route between the release site in Obermörlen and the home loft in Frankfurt, Germany.

Map copyright at Bundesamt für Kartografie und Geodäsie, Frankfurt am Main, Permission Nr. 22/00 of 14 July 2000.

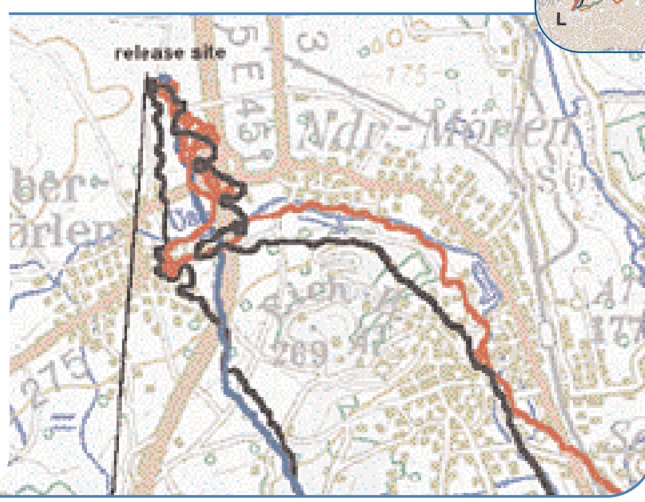


Figure 4 shows four examples of the pigeons' initial flight paths at the release site in Obermörlen, Germany. Two pigeons' flight tracks can be seen circumnavigating 90 degrees to the east of Eichberg hill.

Map copyright at Bundesamt für Kartografie und Geodäsie, Frankfurt am Main, Permission Nr. 22/00 of 14 July 2000.

tions of control pigeons carrying nothing varied from 114–184 degrees in the years before 1993 and from 157–172 degrees in the spring of 2000. This differs from the correct home compass bearing of 185 degrees, which would take the pigeons straight home.

The site's release bias was important to our research because one of the strong motivations for making a flight recorder was our question of where pigeons correct for their seemingly wrong course at sites where a release site bias exists. So one of the questions in releasing pigeons with a flight recorder in Obermörlen was, Can an equivalent of the eastward release site bias also be seen in flight tracks recorded with a flight recorder?

Also, in previous experiments, pigeons had returned home from Obermörlen at a high rate, and we wanted to choose a site that gave us a return of as many pigeons as possible. This GPS flight recorder is an expensive device, and whether the experiments worked or not, we wanted to have it back. In addition, the site's topography is interesting, see figure 2, with a hill, a ridge, and a mountain chain that all block the direct way home, forcing pigeons to choose to gain height and use additional effort or to detour and avoid the ascent.

Getting the Results

Before the actual flight, we switched on the GPS flight recorders to allow acquisition of satellites before take-off, to acquire a first fix, and to check whether the GPS recorder operated. Then, we released the pigeons.

When conducting the first experiments in Obermörlen, we trembled wondering if the pigeons would return. The autumn weather varied greatly on these last September days. When I saw the last pigeon returning home the second day, I was extremely relieved and grateful just to have the animals and the devices return.

Of the 10 pigeons released with flight recorders, we successfully measured nine flight paths, with one recorder failure. Every recorded track contained approximately 10,000 recorded positions. Homing times could be measured from all 10 pigeons.

Seven of our nine measured flight paths were complete or nearly complete, see figure 3, with flight tracks recorded from the release site all the way to the home loft. In the other two cases, we found that the pigeons took such long breaks that the batteries ran down and the device stopped operating.

The Flight Paths. Plotting was not as easy as we had planned. Converting the data took time. Finally we succeeded in plotting four initial parts of the flight paths on a topographic map, see Figure 4. Every move, turn, and loop the pigeons had flown could be seen. The flight paths came out exactly as we had wanted them through the entire project. An idea had turned into reality.

During the tests, we carefully observed the pigeons to determine whether differences existed between pigeons carrying the GPS recorders and the control pigeons not carrying anything. Generally, the pigeons flew well with the GPS recorder, but they tended to fly lower, and their wing beat frequency seemed to be higher. People who frequently work with pigeons observed them and noted differences they saw, but the pigeons' flight appeared unhindered: they were not faltering, they did not have trouble taking off from the ground, and they flew as pigeons normally do.

Furthermore, some birds carrying recorders disappeared behind obstacles such as trees, houses, or churches before giving a normal vanishing bearing, which in standard experiments represents the group behaviour and indicates whether that pigeon group was oriented and whether the orientation was toward home or another goal during the initial stage of the flight.

Most pigeons flew extensive loops immediately after starting their flight over the village or in the home direction, which is a common observation, see Figure 4. Surprisingly, all the flight path positions beyond a few hundred meters south of Obermörlen village are situated east of the direct line between the release site and the loft. Pigeons deviated as much as 9.3 kilometres to the east of the direct route, as shown in Figure 3, which depicts seven complete flight paths. *R* is the release site or start of the flight, *L* is the loft (the pigeon's home), and the thin, straight line is the direct route between the release site and the loft.

Two mountains connected by a ridge are almost perpendicular to the direct route home, presenting an obstacle on the first few kilometres of the homing flight. The ridge is 70 meters higher than the release site and 80 meters higher than the valley. In three tracks, pigeons can be seen flying 90 degrees eastward at the very beginning of their flight, circumnavigating the mountain, shown in Figure 3. Then they change course to the southeast and seem to follow a river valley and human settlements. The southwest correction of the heading is made only several kilometres later. The other five chose to climb and to fly over the ridge. But even some of them turned eastward after crossing the ridge.

Other GPS Data. Our GPS recorder also measures speed, which allows us to determine where and when a pigeon stopped flying. Most pigeons took several breaks during their flight home, ranging from one minute to three hours, as shown in figure 5.

Immediately after the GPS recorders were switched on, two out of nine measured flight paths exhibited major errors in position. Some initial positions deviated by as much as 2.9–5.6 kilometres from the true position for several seconds. These errors occurred because the GPS receiver had not yet acquired all satellites in view. We had observed this type of switch on error during the GPS recorder development.

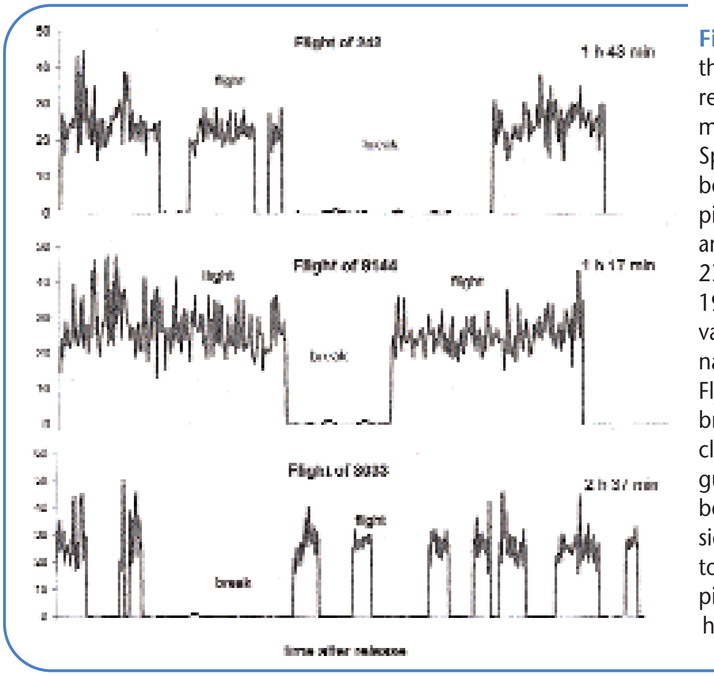


Figure 5 shows the GPS fight recorder also measures speed. Speed profiles can be seen of homing pigeon 242, 8144, and 8033 flying 27–28 September 1999. Every tenth value of the original data is plotted. Flying periods and breaks can be clearly distinguished. The numbers on the right side represent the total time the pigeon took to get home.

Therefore, we took care during the experiments to switch on the GPS recorders at least seven minutes before the animals were released. During the actual test flights, we saw no sudden position jumps.

Several pigeons landed for more than 15 minutes during the flight tests, giving us an opportunity to check whether the errors were caused by selective availability (SA), which would have caused the records to show a significant shift in the pigeons' positions, even though we could tell by our speed data that they were sitting still. For example, we determined from the speed data that one pigeon sat for three hours, and during that time all of the position points were within 110 meters, as plotted by mapping software. In 14 of 16 long breaks we observed, we found that the maximum difference in positions was 100 meters. From now on, this precision should be even better (10–30 meters) because the U.S. government switched off SA 1 May 2000.

The one-value-per-second high sampling rate results in a realistic resolution of the loops flown in the tracks, as in Figure 5. A sampling rate of one value every 30 seconds distorts the loops. At this lower resolution, not shown in any of the accompanying figures, it is still possible to see that the flight path deviates from a straight course, but the exact loops are not identifiable.

Pigeons carrying GPS took significantly longer to return home than did two out of three groups of controls of previous experiments. The GPS pigeons' median value was 133 minutes, compared to 52, 91, and 56 minutes of three controls. In our experiments, the fastest pigeon carrying GPS flew without a break and took 52 minutes to reach home. The slowest pigeon took a very long break lasting at least three hours and came home after six hours and 40 minutes. One of the control pigeons also took six hours and 1 minute on the same day. Much of the increase in homing times in GPS pigeons is due to long breaks in this case. By subtracting the time spent in breaks from the overall time to return, we found that the mean time GPS pigeons spent in flight was around 60 minutes.

Future Improvements

We have now achieved our aim of developing a GPS device sufficiently miniaturised to attach to homing pigeons, having them fly with it, and obtaining accurately measured flight paths. But two grave limitations of the GPS device regarding homing pigeons persist: weight and a residual magnetic field.

The physical size of the device suits the pigeons well. Except for its weight, we are satisfied with the harness. The Teflon ribbon and harness have caused no damage to feathers and skin, but continued work is still necessary because damage was caused by this year's lighter version of the harness. The devices also stuck to the back plate and never fell off in the first experiments.

Compared to our initial requirements, two GPS recorder features are far better than we expected: the sampling rate is even higher (one value per second) than our minimum value of one per five seconds, and the number of positions that can be stored also is higher than the minimum of 1,000 we targeted in the beginning. Now, we can store 10,000 positions, and we would be able to store about 90,000 if the battery lasted longer. The three-hour operation time is the minimum time we wanted. At the moment only one battery on the market has the required combination of low weight, high capacity, and high output, so those three hours are currently the best that can be achieved.

The flight recorder weight is 33 grams with an additional seven grams for the harness. We cannot reduce the weight any further with state-of-the-art components. This past winter, we reduced the seven grams of the harness to 5 grams by omitting the breastplate and reducing the size of the back plate. Thirty-eight grams total is still a lot for a pigeon to carry, representing about ten percent of its body weight. The pigeons' flying behaviour is influenced as seen in the long homing times and in our observations of pigeons that lost their ease of flight and flapped their wings with a higher frequency. The pigeons' long breaks also indicate that the GPS recorder caused them additional effort. An earlier study showed that pigeons can be influenced very much by transmitter loads with a weight of 2.5 to 5 percent of body weight. The birds slow down by 15–28 percent on 90-kilometre flights, and their carbon dioxide production increases by 41–50 percent.

Nevertheless, we think that the device weight is within the acceptable range because it is about the same as the weight of food that pigeons carry after feeding, and because all of our birds returned from the homing flight on the day of the release, implying that the impairment is not too great. The fact that the flight recorder weight causes the pigeons additional effort in flight does not necessarily imply that the orientation was influenced or that the flight path was significantly altered.

The device also produces a residual static magnetic field. Previous work has

Pigeons through the Ages

The first known domestication of the rock pigeon occurred during the ancient civilisation of Mesopotamia in the Western part of the Near East. The best known archeological finds of pigeons are terracotta clay pigeon figurines discovered in Babylonia and Assyria from approximately 5000 B.C. Pigeons were also listed as cuisine on an Egyptian restaurant menu that dates back to 2700 B.C.

Pigeons were first bred in the area of the Euphrates and Tigris Rivers and only much later spread to the Near East, and then to Europe during the Greek and Roman Empire. In the Roman Empire, pigeon breeding was already widespread as reported by Roman writers such as Varro (116–79 B.C.) and Plinius (79–23 B.C.).

Throughout human history, pigeons have held symbolic value for various cultures. In the Orient, pigeons have represented fertility and purity. During the Greek Empire, pigeons were dedicated to the gods as the oldest domesticated animal and represented beauty and love.

During the Roman Empire, pigeons were called *columba* and were the favourite animals of the Roman emperors. The Jews used pigeons for religious sacrifices. At this time, not only the wild rock pigeon, but also many other types of pigeons were already known, such as: the white domesticated pigeon, homing pigeon, and ancestors of today's Roman pigeon.

Pigeons have been used to carry messages for centuries. One marked advantage of transmitting messages by way of pigeons is that they are difficult to catch, unlike other modern forms of communication that can be easily intercepted by an enemy. During the first Olympic games in 776 B.C. pigeons carried messages to inform other Greek cities about victories. Later, between A.D. 1000–1500, the caliph of Baghdad and the sultan of Egypt organised a complete mailing system based on pigeons. By A.D. 1288 approximately 2000 pigeons lived at the post office of Cairo, Egypt. The Romans, Turks, and Arabs also frequently used pigeons during times of war to deliver messages. European knights came into contact with messenger pigeons during the Crusades, and, finding them useful, took the birds with them. Pigeons also were relied on to transfer messages until World War II.

Today's homing pigeons mostly stem from a special breed that was produced in the late 1700s in Belgium. Pigeon racing originated in Belgium and continues to be a national sport in that country today. The Belgian people consider pigeon racing a serious sport; it is estimated that one out of every thirty adults in Belgium actively participates in raising and racing homing pigeons.

Differences in Pigeons?

Pigeons hopping around the plaza or cooing on a building ledge all originate from the wild rock pigeon (*Columba livia*), which still lives on steep rocky cliffs of the Atlantic and the Mediterranean Sea coast, in the mountains of North Africa; Asia; Dalmatia, Yugoslavia; as well as at the coast of Scotland and some British islands. Rock pigeons were domesticated and bred by humans throughout time for many different purposes.

City pigeons are actually domesticated pigeons (*Columba livia domestica*) run wild. They are the same species as homing pigeons. The similarities are visible in their habits. They both have gathering places, feeding spots, breeding sites, and sleeping spaces all within a small area. Pigeons are social birds and seek each other's company. Both search for food on the ground, enjoy flying together, and maintain a social pecking order.

City pigeons tend to stay near where they were born, but are capable of going on foraging trips of several kilometres. They can breed six times a year and raise up to 12 offspring. The general lifestyle of city pigeons resembles the domesticated or even the originating rock pigeon. For example, breeding and sleeping places are eaves, niches in walls, towers, churches, and ruins because they represent good equivalents to the original rocks that the rock pigeons used as breeding sites. Domesticated pigeons live in lofts made mostly of wood, built especially for them, containing little boxes where they can sit and breed. Gathering places for city pigeons can be train stations, public buildings, squares, and school yards.

So, a reflection of the wild rock pigeon can be seen in the habits of even the most metropolitan city pigeons. The main distinguishing characteristic that sets the homing pigeons apart from the rock, domesticated, or city breeds is the homing pigeon's finely tuned ability to locate their route from long distances and navigate home.

shown that field intensity differences of about 0.2 percent of the field's strength can make a difference in pigeons' initial orientation. Further investigations into the strength and source of this residual field will help us to decrease it.

Questions Still to Answer

The GPS recorder greatly extends the possibilities of measuring flight paths on birds, such as falcons, albatrosses, and geese. The GPS recorder has now made it possible to accurately measure, record, and plot flight path details with a high temporal and spatial resolution, a range of measurement limited only by the power of the battery, and a comparative ease of experimental procedure requiring little human power. The flight recorder success represents a significant advance in developing technology for animals, with the possibility that many more animal species may be tracked with GPS technology.

In our own work, now that we have shown that GPS can adequately record the flight paths of pigeons, we can begin to conduct more experiments aimed toward finding more about how homing pigeons navigate their direction home. Thorough flight recorder data analysis, we hope, will help us further investigate the biological mechanisms behind homing pigeons' navigation. Because humans have for centuries relied on homing pigeons for communication, and now use them for sport, a great accomplishment would be to finally, fully understand how these small birds find their way through the world to reach home.

Acknowledgements

This project has been financially supported by the Deutsche Forschungsgemeinschaft DFG (grant to Wolfgang Wiltschko) and the German Society of Telemetry (Arbeitskreis Telemetrie, grant to Karen von Hünerbein). We thank our partners for building and testing equipment hardware and software: Frank Jöst and Dr. Stefan Wolff, University of Darmstadt, Germany; Hajo Hamann, Rainer Hartmann, Professor Klinke, Ralf D. Müller, B. Klauer, University of Frankfurt, Germany; Stefan Werffeli and Clemens Bürgi, ETH Zürich, Switzerland; and Michael Riechmann, Rüter EPV-Systeme GmbH, Minden, Germany. For assisting with pigeon field trials: Harald Schuka, Minden, Germany. For practical help with measuring data: Gisela Schmiedeskamp, Olaf Henseler, and Ralf Hohmann, University of Frankfurt. For supplying component samples at no cost and for being very helpful with information, we thank the following companies: WiSi, Rockwell (now Conexant), Murata, Bosch, Varta, Eagle Picher, and JRC. For encouragement and support: God; Erhard Salow, Germany; Professor Joe Riley, UK; Kirsten Märkel, Germany; and Dr. Anthony Woakes and Dr. Sandra Wolley, UK. ⊕

Manufacturers

The GPS flight recorder was conceived and developed by Karen Von Hünerbein and developed and manufactured by **Rüter EPV-Systeme GmbH** (Minden, Germany) based on a **μ-blox** (Zürich, Switzerland) hybrid board. Data conversion software was developed using **Microsoft** *Visual Basic* (Redmond, Washington, USA), and pigeons' tracks were plotted with the **Northport System** mapping software *Fugawi* (Toronto, Canada) and **Daimler Benz Aerospace & Dornier** *Top 50* (Stuttgart, Germany).

Authors

Karen von Hünerbein, *born in 1963, acquired two high school degrees, one from the United States in 1981 (Cum Laude) and the other from Germany in 1983. She studied biology in Aachen, Germany between 1983 and 1990, with a major in animal physiology and also studied computer science. For five years, she held various computer jobs before becoming interested in achieving a PhD. In 1995 she attended the Institute of Zoology at the University of Frankfurt, Germany, and began the project, "Development of a Flight Recorder for Homing Pigeons," combining both her biology and computer skills.*

Eckhard Rüter *is an electronics engineer who worked at Alcatel SEL, Stuttgart, Germany, for several years gathering experience with GPS. He then started his own company developing and producing the transponder system TauRIS for precise timing in pigeon races.*