CHRISTIAN ZIEGLER

The internet of animals

Martin Wikelski has spent 17 years getting an antenna into space to track animals around the world. That's the first step in his plan to revolutionize biology.

BY ANDREW CURRY

On a Wednesday afternoon in August, biologist Martin Wikelski watched helplessly as 17 years of his professional life was about to go to waste — because of a cable mix-up.

Some 400 kilometres above Earth, cosmonaut Oleg Artemyev was fumbling with an electrical connection while Wikelski monitored the operation from a command centre in Moscow. The cosmonaut was floating outside the International Space Station (ISS) and trying to manoeuvre the thick, stiff gloves of his spacesuit to join two unmatched cables — something that was never going to succeed. As the ISS hurtled through space at more than 27,000 kilometres per hour, the cosmonaut made no headway with his task.

Wikelski, the director of the Max Planck Institute for Ornithology in Radolfzell, Germany, was in Moscow to witness the culmination of a quest that had absorbed much of his career — and had threatened to derail it at times. Artemyev was installing a three-metre-long antenna on the outside of the space station as part of a system designed to track wildlife on Earth. This project would enable scientists to spy on animals from space for the first time, including ones so tiny that they can't carry current satellite-tracking devices.

In the long run, Wikelski hopes the system will connect so many individuals — from elephants and warblers to baby sea turtles — that it could create an 'internet of animals'. It could use the movements and habits of wild creatures to reveal patterns in much the same way that mobile-phone apps pinpoint traffic and illuminate people's social networks. But first, the cosmonaut had to plug in the antenna on the ISS.

The 15 August spacewalk had been agonizing to watch from the

Martin Wikelski studies a bat in Zambia as part of a tagging expedition.

start. In an auxiliary room at the Moscow command centre, Wikelski winced as he saw Artemyev grapple with the 120-kilogram antenna and manhandle it out of the station's airlock, knocking the fragile receiver into the exterior of the spacecraft. Hours went by as Artemyev and his fellow cosmonaut Sergei Prokopyev crawled across the ISS, painstakingly stringing cables around its cluttered exterior.

Finally, as the Russians struggled to connect the antenna to a power source, Wikelski was plagued with doubts. Had his team somehow made a horrible mistake with the wiring that was causing problems for the cosmonauts? Was all this work destined to fail?

He huddled with a small team of engineers from the German Space Agency and his own institute, watching Artemyev attempt again and again to make the connection, while checking the blueprints to make sure he hadn't let the wrong cable somehow slip through. Wikelski knew the long-delayed project wouldn't get another chance.

Finally, after minutes that seemed like hours, Artemyev located the right cable end and plugged the antenna into the station's power supply. Engineers in Moscow flicked on the antenna's computers. One by one, its systems came online. As the last line on the screen moved from red to green, Wikelski could finally relax.

Days later, back at the Max Planck institute he's led for the past decade, the 53-year-old researcher stood up in front of his gathered staff. "Nominal operation should start in early November," Wikelski announced exuberantly, raising a glass in a toast. "Now we are spacemen!"

FLYING HIGH

Over the past few decades, tracking wildlife using radio collars and GPS (Global Positioning System) transmitters has changed the way that researchers understand the behaviour of the animal kingdom. Using tags that communicate through satellite, mobile-phone and radio technology, scientists can follow everything from whales in the open ocean to jaguars beneath deep jungle cover.

But the long-range movements of most of the world's species remain invisible to researchers. Animals that weigh less than 100 grams can't safely carry the smallest available satellite tags. That puts 75% of all bird and mammal species — and all insects — off limits to this kind of tracking. And the tags themselves cost thousands of dollars apiece, making wide-scale deployment a pricey proposition.

Wikelski hopes to change all that with his project, called ICARUS (International Cooperation for Animal Research Using Space), which goes well beyond the single ISS antenna. Within ten years, he foresees a network of satellites devoted to following hundreds of thousands of animals in real time.

"If you don't understand what they're doing in the wild, you don't understand biology."

The internet of animals envisioned by Wikelski would be able to answer questions that researchers didn't even know they had. ICARUS could, he says, illuminate why migratory bird and bat species are disappearing, and map the spread of pathogens such as bird flu and Ebola. It could even provide early warnings of pest outbreaks and, possibly, earthquakes. "By elevating our viewpoint into space and looking down on the globe, it changes the approach to ecology," he says.

It has taken Wikelski a large part of his career to get ICARUS aloft. He came up with the idea of a radio receiver mounted on the ISS back in 2001. Ever since, he has been pitching it to funders and other biologists, while waiting for the technology — and everyone else — to catch up with his vision.

It hasn't been easy. NASA officials at the Johnson Space Center, where ISS mission operations are based, laughed him out of Houston. He eventually won a spot for ICARUS on the Russian ISS module, but spent years worrying that international political strife would sink that chance. He focused so much of his effort on ICARUS that, at one point, his position at the Max Planck Institute for Ornithology was at risk. Even after he'd grown ICARUS into a project involving dozens of people, partners in five countries and eight major funding institutions, Wikelski told colleagues in January that he was on the verge of giving up, unwilling to lose more years of his research career to a quixotic dream.

But he didn't, or couldn't, let it go. "Mere mortals would not have achieved this," says ornithologist David Winkler at Cornell University in Ithaca, New York. "He deserves a ton of credit for putting so much of his life into this. It's been a tremendous investment."

And the real work, it turns out, could just be getting started.

UP IN THE AIR

As a boy, Wikelski spent hours staring up at swallows and house martins sheltering under the eaves of his family's barn in the Bavarian countryside. When a teacher told him that the tiny birds roamed as far as South Africa each year, it sparked his imagination. In his teens, he photographed birds and trained as a bird bander, fixing tiny strips of metal to fledgling swallows and marvelling when they returned years later — sometimes to the same nests. "When you band an animal and it comes back after a global journey, it's really incredible," he says.

The discovery began a lifelong quest to get as close as possible to migrating animals. During his mandatory military service in the early 1980s, Wikelski volunteered for early shifts as a transport driver, waking at 5 a.m. to finish his working day by early afternoon. As soon as he was off-duty, Wikelski headed for the heights of the Bavarian Alps, hang-glider in tow. "I had the chance to hang-glide every day for a year," he says.

Suspended high above the ground, he was able to feel the air currents that carried birds and bats aloft. "It was transformative," Wikelski says. "I wanted to understand what birds were doing, and you can't understand if you don't do it yourself."

Wikelski earned a behavioural ecology PhD in Germany, then headed for a postdoc in the United States and quickly on to the Smithsonian Tropical Research Institute in Panama, before taking a position at the University of Illinois in Urbana-Champaign. On the flat plains of the US Midwest, he traded his hang-glider for a beaten-up Oldsmobile with purple velour seats and an antenna protruding from the roof. His graduate students referred to the contraption as the Batmobile.

It might not have looked like much, but when it came to understanding migrating birds, the Batmobile was state-of-the-art. Researchers had used similar set-ups since the 1960s, when pioneering US biologist William Cochran used tiny radio tags to track migrating songbirds such as the Swainson's thrush (*Catharus ustulatus*). The transmitters were light enough for the small songbirds to carry, but the trade-off was a short range: Cochran, and later Wikelski, had to follow within a few kilometres of the birds to pick up the radio signals.

Because Swainson's thrushes fly at night and can move at up to 112 kilometres per hour when the winds are right, tracking the birds takes the skills of a rally-car driver and the endurance of a marathon runner. "The thing takes off anywhere between [dusk] and 2 a.m., and as soon as that beep changes you start driving like crazy because you don't want to lose that bird," Wikelski says. The Batmobile offered the necessary acceleration. Speeding along at 3 a.m., the unusual car with its peculiar antenna would get stopped by local police two or three times each night.

In 2004, Wikelski and Cochran teamed up with biologist Henrik Mouritsen to work out how the thrushes navigate after dark. They placed captive birds in magnetized cages to artificially reorient them, then released them. Racing behind them night after night — including a 1,100-kilometre odyssey across the US Great Plains to chase a bird smaller than a clenched fist — they were able to show that the birds

In a marathon spacewalk in August 2018, cosmonauts attached the ICARUS antenna to the International Space Station.

used a combination of magnetic sensing and light cues to calibrate their flight path[1].

Wikelski has since adapted the technique to track ever-smaller creatures. He has successfully mounted radio tags to cicadas, dragonflies and even bumblebees, and continues to follow radio-tagged birds and bats across Europe. He's learnt that long-distance migration is much more common than was thought, and that some insects fly for kilometres to find food. The work shows that migration is much cheaper for animals in terms of energy output than researchers ever imagined: bats and birds float on updraughts, butterflies 'swim' in the airstream, and some birds have the same heart rates during flight as they do while sitting, says Wikelski.

The work cemented his belief that tracking the natural movements of animals is key to unlocking their behaviour. "If you don't understand what they're doing in the wild, you don't understand biology," Wikelski says.

But it was apparent that chasing after animals on the ground one at a time was always going to yield limited results. "If you really want to understand the world, you have to do it from above," Wikelski says.

An internet of animals could answer questions that researchers didn't even know they had.

TRACKING IN THE JUNGLE

Wikelski first tried tracking animals from above in the late 1990s, on a 16-square-kilometre island off the coast of Panama called Barro Colorado. He and biologist Roland Kays, now at North Carolina State University in Raleigh, wanted to follow jungle creatures such as jaguars, agoutis and sloths as they moved through the thick forest. But GPS was in its early days, and the forest's thick canopy thwarted tags equipped with the technology.

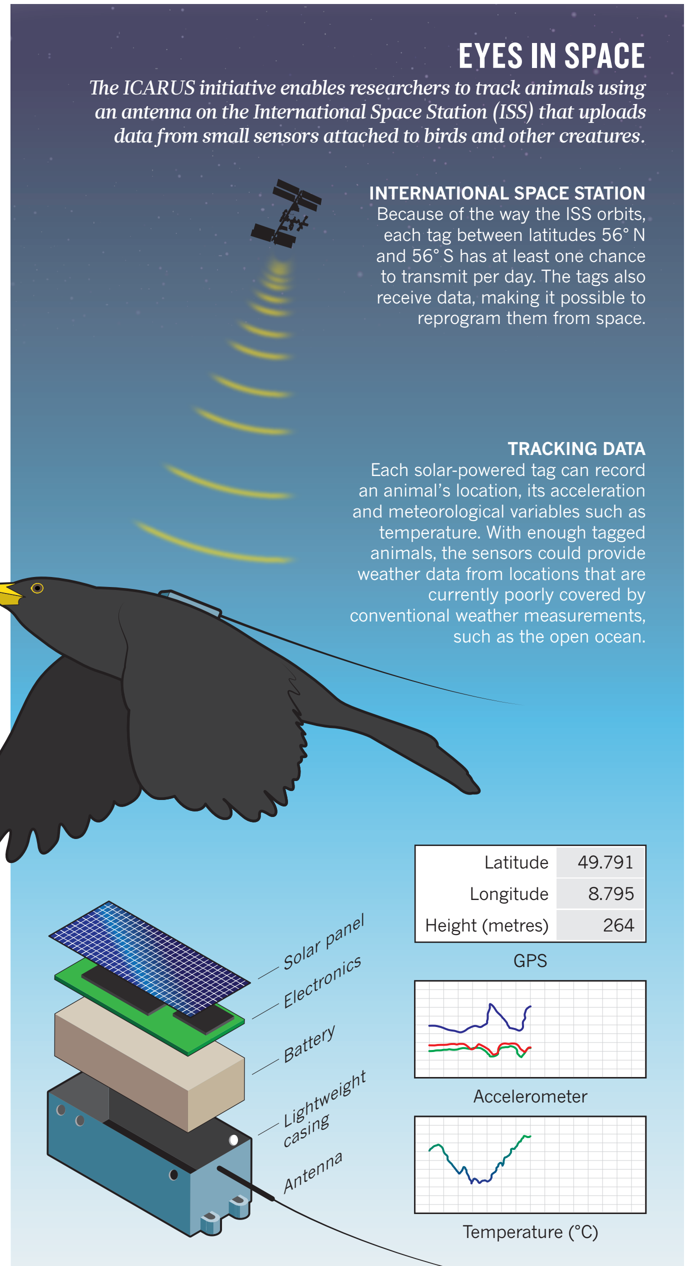
Instead, Wikelski and Kays adapted radio tags and built a network of 7 radio towers, each more than 40 metres tall, to triangulate signals from animals on the move. The software they devised to process and store their data became the basis for a system called Movebank, which lets biologists around the world analyse and share movement-tracking data. The system was launched in 2007 and collected its billionth data point in September, providing the basis for hundreds of scientific publications. Some of its information on animal movements is also accessible to the public through a mobile-phone app called Animal Tracker.

By linking ICARUS and Movebank, Wikelski hopes to create a powerful tool that both researchers and the public can use. Standing in the shadow of the Radolfzell castle near his office, Wikelski pulls out his smartphone and taps on the Animal Tracker app. He calls up a type of duck called a Eurasian wigeon (*Anas penelope*) that researchers had nicknamed Guillaume. The duck wears a tracking tag that connects with mobile-phone networks, which shows he's been bobbing on a pond in Kazakhstan for the past two weeks.

A button on the app lets users easily scroll back in time. Wikelski traces Guillaume's zigzagging trail back across Europe to the outskirts of Amsterdam, where the duck was captured and tagged six months earlier. In an age in which people watch live streams of eagle's nests and obsess over individual animals while thousands more disappear unnoticed, Wikelski thinks such tracking data are a way to personalize conservation. "Finally we have a way to live with a wild pet. We can finally understand how difficult and dangerous it is. You can see that duck on your local pond just got back from Russia," he says. For a moment, the boy who watched swallows set off for South Africa shines through.

Tracking animals, Wikelski argues, is a way to "Cecilize" conservation. Cecil was a charismatic male African lion (*Panthera leo*) and was one of the most photographed — and beloved — animals in Hwange National Park in Zimbabwe. In 2015, Cecil was hunted and killed by a US dentist outside the park, but data from the lion's tracking collar revealed he was lured outside the protected area. Cecil's death sparked an international uproar and triggered calls for a ban on trophy hunting.

Wikelski sees opportunities to capture the same kind of interest about other wildlife problems, such as the rapid decline in European songbird



SOURCE: MAX PLANCK SOCIETY

populations. He would like to raise awareness by tracking what happens to them. "We're missing 420 million songbirds, and no one cares," he says. "One Cecil the shrike changes everything."

Wikelski's experience tracking animals in Panama and the United States prompted him to wonder about a better method. Why bother with radio towers or chasing birds in a car or aeroplane when you could put your receiver in space, where it would be able to pick up signals from around the world, regardless of geography?

The idea seemed so powerful and obvious that, when he first proposed it in 2001, he assumed it would be an easy sell. "I thought, 'In three years we'll have it on the space station,'" he says. Instead, it took years for Wikelski, by then an assistant professor at Princeton University in New Jersey, to even get an appointment at NASA. When he went to the agency's Houston space centre in 2004, the earnest young German biologist was shuffled from office to office with no success. Birds and bats, he quickly learnt, weren't on NASA's radar.

Wikelski refused to let the idea go. "After NASA said, 'It's never going to fly,' I called it ICARUS," after the doomed character from Greek mythology who plummeted into the sea after flying too close to the Sun. He began reaching out to colleagues around the world, gathering interest and examples of how lighter, cheaper satellite tags could make a huge difference in everything from large-mammal conservation to sea-turtle research.

The result was a 2008 white paper that listed 32 possible applications of the technology and carried signatures from dozens of prominent biologists worldwide[2]. Within the field, the idea of lighter, cheaper satellite tags was a hit. "The challenge was convincing the space people it was worth it," says Kays, one of the project's founding partners. "What he's been doing for the past ten years is talking to the space people."

Around the time he released the white paper, Wikelski was offered one of the most coveted positions in science: a Max Planck directorship. In 2008, he took over the Max Planck Institute for Ornithology, moving from Princeton to the institute, which was housed in a countryside castle near Konstanz.

The transition, he says, was rocky. Wikelski shut down the institute's bird-banding operation — the same one through which he had first learnt to band birds as a teenager — earning him the enmity of many traditional bird-watchers in Germany. And even Wikelski's renowned endurance was tested as he struggled to run an institute, teach at the nearby University of Konstanz and continue pressing forward with ICARUS.

A few years after he took over, Wikelski says, external reviewers gave him a failing grade as a director, citing ICARUS and Movebank as distractions. He was at risk of funding cuts or of losing his directorship. Herbert Jaeckle, the vice-president of the Max Planck Society at the time, says Wikelski persuaded the society to trust him and his ICARUS plans. "He was almost fanatical with respect to this idea," Jaeckle says. "We were convinced he was going to do it, and we were right."

ICARUS started to gain momentum after the head of the German Space Agency (DLR) heard a pitch from Wikelski and told him to apply for funding. The DLR was more enthusiastic than NASA had been, but still struggled to work out where an animal-tracking project might fit into a space agency's priorities, says Johannes Weppler, the project manager at the DLR who is now in charge of the ICARUS programme.

Eventually, in 2012, the DLR agreed to fund ICARUS as a technical experiment, and spent more than €27 million (then US$35 million) to develop, test and build the ICARUS antenna now on the ISS. Russia, the project's other national partner, provided the room on the station, the crew to install it and the rocket to carry it up to space. The launch was tentatively scheduled for 2015.

As relations between Russia and the West grew rocky, the launch was delayed again and again. "At a certain point, I wondered if it would be cheaper to just give up," Wikelski says. By the beginning of 2018, he vowed: "If the antenna's not going up in February, another few months and we quit."

Suddenly, things began to move. In February, Wikelski was at the Russian space centre in Baikonur, Kazakhstan, to watch ICARUS's antenna array leave Earth. And in mid-August, he watched from Moscow as the system sent its first signals back to Earth.

IN FLIGHT

Just a few days later, Wikelski drives his convertible Fiat 500 onto a dirt airstrip on the edge of Konstanz. Bounding up the steps of the two-storey control tower, he greets the lone air-traffic controller on duty with a hug. Wikelski spends a lot of time here — he's at the controls of the institute's Cessna aeroplane for at least 200 hours each year.

Pulling open a hangar door, Wikelski pushes the small red-and-white prop plane outside. After a pre-flight check and a bumpy take-off over a rutted grass field, he banks north above the blue waters of Lake Constance. As Wikelski heads for the forested hills to the north, he turns on an antenna mounted on one of the wing struts and balances a tablet computer on his lap. "We're simulating the ISS, basically," he says.

Somewhere down below, he explains over the roar of the engine, are five blackbirds wearing some of the first ICARUS tags deployed in the wild. The 5-gram tags each contain a thermometer, accelerometer and GPS receiver, plus a transmitter that can send a signal into space and a solar-charged battery to power it all (see 'Eyes in space').

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Biologist Martin Wikelski frequently pilots his institute's Cessna aeroplane to track tagged animals.

The device's small size, Wikelski says, makes a huge difference. Tags that weigh more than 3% of an animal's body weight have the potential to alter its behaviour and threaten its survival. That's why the vast majority of animals are off limits to standard tags that use mobile-phone or satellite technology. Once the ICARUS system is fully operational later this autumn, the tags will transmit 220-byte strings of data at a time up to the ISS. That's the equivalent of 20 GPS positions, enough to provide a sketch of an animal's movements on any given day.

Thanks to a solar-powered battery, ICARUS tags can theoretically last as long as the animal that's carrying them — and can be retrieved and reused. The tags also include a memory chip that can store up to 500 megabytes of data — enough to record an animal's travels, movement and energy expenditure over a lifetime.

For faster data transmission, researchers can download information from the tag using a handheld radio device if they can get close enough — anywhere from a few hundred metres to 15 kilometres, depending on geography and vegetation. "That's very exciting," says Emily Shepard, a specialist in bird energetics at Swansea University, UK.

As the plane flies 1,000 metres above the wooded hills around the Radolfzell institute, information begins to appear on Wikelski's tablet: the location of the blackbird tags, how much battery power is left and when they last communicated with the receiver. Each byte sent skyward provides details about the birds' habits.

Colleagues say that the array of sensors on the tags offers researchers the opportunity to answer thorny but crucial questions about animal behaviour. They could, for example, explore why birds choose certain flyways, by combining accelerometer data on the number of times they flap their wings, and their GPS positions, with wind speed and precipitation records. Scientists could use all of that to compare how much energy it would cost for a bird to take one route instead of another[3].

Monitoring bird migrations is only the beginning. To sell the idea of a €27-million animal-tracking antenna to policymakers, Wikelski leant heavily on its potential benefits for humankind. Tracking the airspeed and temperature of thousands of birds, he argues, amounts to creating a low-cost, distributed weather-monitoring system across the globe[4].

"In the future, we'll use every animal that flies as a meteorological drone," he says. "To measure the temperature in the middle of the Pacific at 20-metres altitude is impossible, but birds do it all the time."

He doesn't plan to stop with the weather. One of Wikelski's most daring ideas depends on deploying ICARUS tags in areas that are prone to seismic activity. Folktales are full of animals that can predict seismic events. So Wikelski thought it might be possible to create an earthquake early-warning system by putting tags with accelerometers on animals in seismically active areas.

To test the idea, in 2012 Wikelski tagged semi-feral goats that roam the slopes of Mount Etna, an active volcano in Sicily, Italy, with data-logger tags that let him analyse their movements after he recovered the tags. Over the course of several years, he observed the goats moving around much more during the 4 to 6 hours before major eruptions than after the events. "If you have a distributed network of goats on the mountain and they all go crazy on some nights, it's pretty simple," Wikelski says.

For all the potential of an internet of animals, Wikelski recognizes that colleagues still have reservations about creating such a system. If it is deployed on the scale Wikelski imagines, unretrieved tags might amount to high-tech litter in some of the world's least-accessible places. And no matter how light the tags might be, catching creatures and placing trackers on them subjects the animals to increased risk. "We need to be asking, just because we can tag something, should we?" says Shepard. "As the cost decreases and the access increases, it's going to be something important to keep in mind."

All this depends on deploying lots of ICARUS tags, which cost about $500 for the first generation but could become cheaper and smaller in the next few years, says Wikelski. It will also require expanding the system from a lone antenna on the ISS to a network of satellites that would enable real-time read-outs and monitoring. He estimates that a three-satellite system would cost between $80 million and $100 million, and will require a lot of buy-in. "We have to show there's some value in global decision-making based on animal behaviour or movement," he says.

He also has to get ICARUS up and running. By mid-October, the Russians still had not switched ICARUS on for public use because of a snag in discussions between that nation and the DLR about the antenna's operation. Wikelski hopes those talks will be resolved soon and the system will come online. Then he needs biologists around the world to adopt it en masse — and soon. The ISS's Russian module is scheduled to operate for just six more years, although it could continue past that. The DLR, meanwhile, has plans to fund the mission only until 2024. "What comes after that is a big question," Weppler says.

That gives Wikelski and his collaborators a decade, at most, to convince the research community and space agencies that ICARUS is worth expanding into a global satellite network.

Days after his flight over Lake Constance, Wikelski was on a plane again — this time to Vancouver in Canada, where he announced the launch of ICARUS to the World Ornithological Congress. Over the next year, Wikelski will be travelling the globe to get ICARUS off the ground, helping to tag bears in Kamchatka in eastern Russia, condors in Bhutan, flying foxes in Zambia and migratory birds in the Congo Basin. "We have to go global," he says insistently. "We have to go wild. We have to go." ■

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