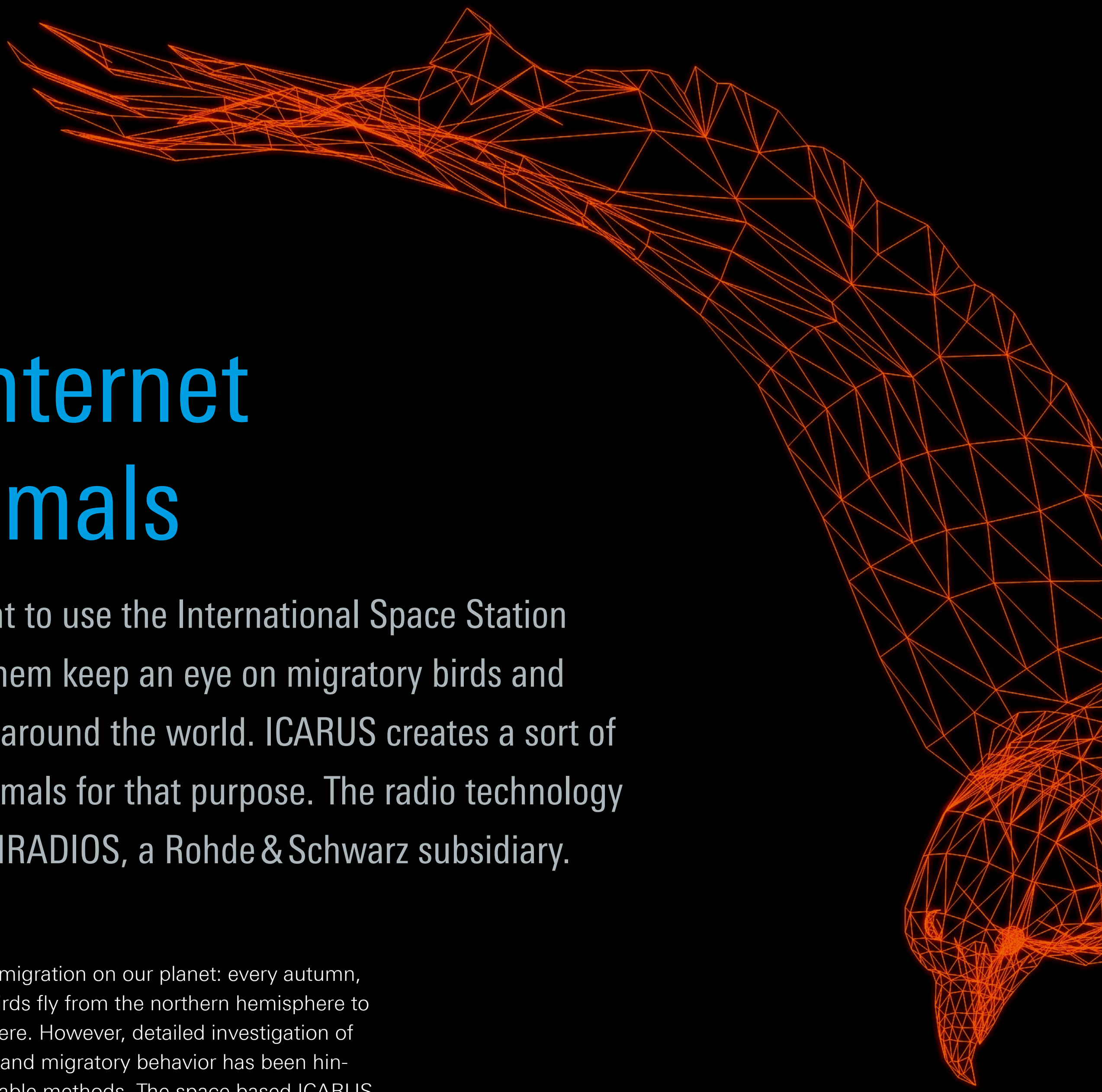

The Internet of animals

Scientists want to use the International Space Station (ISS) to help them keep an eye on migratory birds and other animals around the world. ICARUS creates a sort of Internet of animals for that purpose. The radio technology comes from INRADIOS, a Rohde & Schwarz subsidiary.

The project

It is the biggest mass migration on our planet: every autumn, billions of migratory birds fly from the northern hemisphere to the southern hemisphere. However, detailed investigation of their migration routes and migratory behavior has been hindered by a lack of suitable methods. The space based ICARUS observation system will change that. It allows the routes of individual animals to be followed with GPS precision. And that's not all. Information about the energy consumption and acceleration of the animals can be used to draw conclusions about their life history, their behavior and their community.

ICARUS is a joint project of the Max Planck Society, the German Aerospace Center (DLR) and the Russian aerospace agency Roscosmos. It was initiated and is directed by the Max Planck Institute for Ornithology (MPIO) in Radolfzell (Germany).

The MPIO calls this a new era of behavioral research. Along with birds, this big-data project will observe the behavior of bats, turtles and many other species, so it is of interest not only to ornithologists. It is intended to create a global network – a sort of Internet of animals. The potential applications are manifold and include protection of endangered wild animals as well as prevention of locust plagues. It is even possible for animal behavior to warn of impending natural disasters. The data from the animals (equipped with miniature transmitters) will be processed in a computer on board the International Space Station (ISS)[1] and transmitted to Earth over a radio link[2]. The signals can also be received directly on the ground using mobile or stationary receivers.

ICARUS will be the world's first satellite based IoT system. The technology opens up new paths for the remote monitoring of sensors in remote areas. The Dresden based Rohde & Schwarz subsidiary INRADIOS is handling realization of the radio concept, implementation of the firmware for the onboard computer and development of the transmitters for the animals. Rohde & Schwarz is also responsible for developing the ground radios and is producing all components.

The ICARUS onboard equipment was carried to the ISS by two supply missions in October 2017 and February 2018. Along with the FPGA board, the system consists of three receiving antennas and one transmit antenna. The antennas, which are scheduled to be installed in August 2018, will be arranged to cover a transmission area on the Earth that is oriented forward in the flight direction (with a small rearward extension) and a narrow receiving area oriented slightly to the rear (see Fig. 4).

The ISS travels in a virtually circular orbit at an altitude of 350 km to 460 km (the altitude only varies within this range in the long term) at an angle of 51.6° to the equator. It circles the Earth 16 times each day. The trajectory of the space station moves 2500 km to the left each time it circles the Earth. In a 24-hour period, the receiving area of the ICARUS onboard antennas covers over 90 % of the Earth's surface between 58 degrees northern and southern latitude.

The components

Bidirectional satcom radio system for sensor data transfer

INRADIOS developed the radio method for data transmission from the animal transmitters (called tags) to the ISS in cooperation with SpaceTech GmbH. They chose CDMA as the channel access method, together with several PSK modulation modes. The biggest challenge was the very low signal power, which the receivers on board the ISS must be able to process. In light of the low data rate (about 1800 bit/s in the uplink), an efficient error correction method had to be developed to make the best use of the available capacity. The expertise of DLR's Institute for Communications and Navigation (ICN) came in helpful.

The signals from the individual animals (transmitted simultaneously) are kept apart by CDMA coding. The receivers can separate up to 120 simultaneous incoming signals. Since the duration of each transmission is only about three seconds, there is potential for data transmission from even more animals in the instantaneous overflight reception area, which is only about 100 km wide. However, to make this possible it must be ensured that they do not all start sending data at the same time (the tags know down to the second when the ISS is accessible). This is done by a

ICARUS at a glance

How does ICARUS work?

- Acquisition of movement data of individual animals by miniaturized data processing sensor and radio modules (tags).
- Individually accessible every day
- Preliminary data processing on the tag, including data compression and transmission management
- Transmission of small data packets to the ISS or to a LEO satellite during each overhead pass (timeslot for this only about 15 s per orbit)
- Supports orbit altitudes from 350 km to 600 km
- Type and quantity of sensor data as well as frequency of its transmission individually configurable on each tag
- Tag energy management with adaptive sleep mode
- Alternative transmission to ground receiving station
- Simultaneous reception in the orbital station of signals from 120 animal transmitters
- Bundled transmission of all new data from the orbital station to the main ground station during overhead pass
- Transmission of data from the ground station to the user data center operated for the project by I-GOS, a company founded by the MPIO
- Data access for scientific users via www.movebank.org
- Advance warning of natural disasters (floods, volcanic eruptions, earthquakes) from unusual group behavior

Tasks and benefits of ICARUS

From the behavior of animal populations, it is possible e.g. to draw conclusions about environmental conditions and changes to those conditions:

- Discovery of unknown migratory movements
- Monitoring of environmental changes (habitat shifts, desertification, ice melting)
- Enhanced understanding of ecosystems (pollination, pest control)
- Infectious disease control (avian influenza, hoof and mouth disease, Ebola)
- Protection of endangered species by constant monitoring of individual animals

Transmission technology

- Uplink
  Frequency range: 401 MHz to 406 MHz
  (licensed for ICARUS)
  Bandwidth: 1.5 MHz
  Net data rate: 520 bit/s
  Transmitted data volume per overhead pass: 1784 bits
  Simultaneously receivable coverage area:
  approx. 100 km (in flight direction) × 1200 km
- Downlink
  Frequency range: 467.5 MHz to 469.5 MHz
  (licensed for ICARUS)
  Bandwidth: 50 kHz
  Net data rate: 656 bit/s
  Simultaneously addressable coverage area:
  1200 km × 1300 km
- Channel access: CDMA
- Modulation: various PSK modes

Animal transmitter (tag)

- Weight: < 5 g
- Volume: approx. 2 cm^3
- Antenna length: approx. 150 mm
- Sensors: GPS, magnetic field (compass), acceleration, temperature, humidity, pressure, electrical conductivity (for salinity measurements)
- Data storage: microSD (4 Gbit)
- Processor: microcontroller with hardware-level programming
- Battery capacity: 70 mAh
- Solar cell area: approx. 2 cm^2
- Transmit power: approx. 6 mW

randomizer that allocates transmit times within the reception timeslot.

The ISS onboard computer sends commands to individual tags in the downlink. All tags can be uniquely identified and addressed by their ID codes. This allows ICARUS users to send individual behavior patterns to the tags (for example, the type and frequency of sensor data recording) and to merge animals into groups. The net downlink data rate of 656 bit/s is very low for an advanced transmission system. That is due to the narrow licensed bandwidth, but it is sufficient for the needs of ICARUS. Changes to tag configurations occur only rarely and are not time-critical, so it does not matter if the data can only be provided in one of the following overhead passes.

Signal processing board for the space station computer

The FPGA board for signal processing is installed in the Russian module of the ISS. All algorithms for digital signal processing were implemented by INRADIOS on a Xilinx FPGA platform, which essentially consists of two Virtex 5 FPGAs. The radio channel between the ISS and a tag is similar to a conventional wireless channel. It transports direct line-of-sight signal components as well as diffusely scattered components (non-line-of-sight), which combine to form a time-varying (fast fading) signal level as shown in Fig. 1. The demodulators in the ISS on-board computer and the tags equalize the channel situation of each tag individually and adaptively to enable reception even over radio channels with strong dynamic behavior.

Animal transmitters

The animal transmitters/receivers developed by INRADIOS are produced in the Rohde & Schwarz Memmingen plant – a very ambitious undertaking at the limit of current production technology because the total weight of the tag with the antenna, enclosure, processor, memory, radio module, sensors, solar cell, battery and potting compound must not exceed five grams (Figs. 2 and 3). Even relatively small birds such as blackbirds can carry this weight without it hindering them or impacting their behavior.

To prevent the tags from expending their limited resources unnecessarily, data transmission to the ISS takes place in narrow timeslots when the station is

Fig. 1: The radio link between the tag and the ISS is subject to fading, which must be taken into account in signal processing.

ICARUS transmission channel to ISS

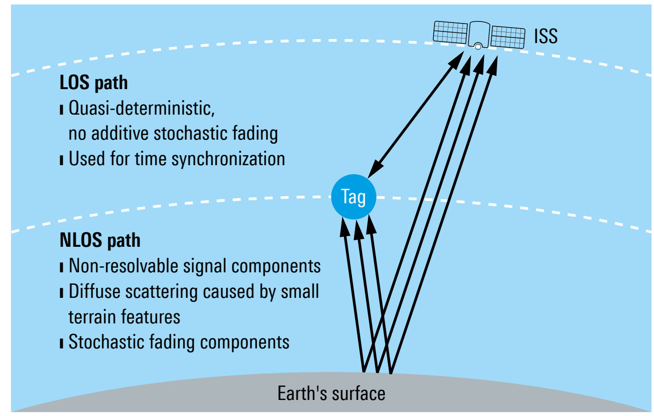

Fig. 2: Blackbirds and larger birds will be able to carry the tags without any hindrance to their daily activities. The final version of the tag (Fig. 3) is even smaller than this early prototype.

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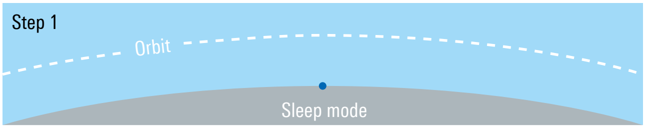
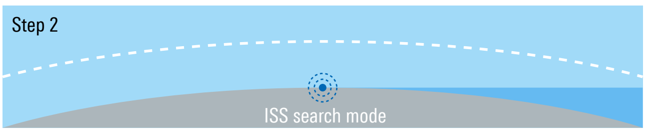
Fig. 3: The ICARUS tag (a virtually series-ready prototype is shown here in actual size) was developed jointly by the Max Planck Institute for Ornithology and I-GOS. It is an autonomously operating multisensor device with a radio module (see the overview box on the left for the sensors). The tag communicates with the ISS and with terrestrial base stations.

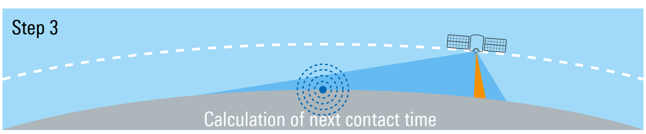
ISS orbit update



The tag is in power-saving sleep mode and waiting for the internal timer to wake it at the expected ISS overhead pass time.

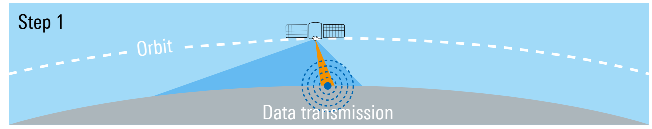


After waking up, the tag checks at short time intervals whether the ISS download signal is being received.

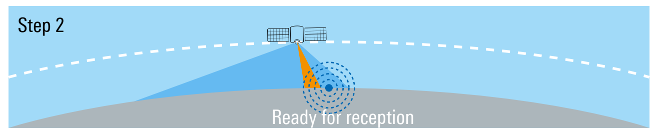


When the signal is received, the tag extracts the current ephemeris data and uses it together with its own GPS position to calculate the time of the next transmission slot. Then it returns to sleep mode if no data logging is pending.

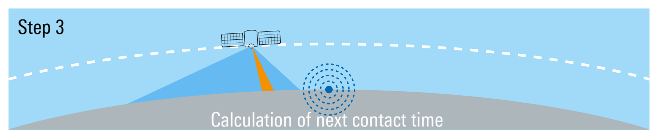
Transmission of sensor data



When the time slot for a possible transmission to the ISS nears, the tag awakens from sleep mode. The upload, which takes approx. 3 s, is started randomly within the short approx. 15 s open transmission slot so that not all adjacent tags are sent simultaneously.



After the data upload, the tag briefly enters receive mode in case there are any subsequent control commands for the tag. The ISS only sends these to a tag when it knows from a recently received upload that the tag is within range.



Before the tag goes back into sleep mode, it calculates the next contact time. The timer is one of the key components of the tag. It wakes the tag only when there is something to be done, which means either logging sensor data or getting ready for a transmission.

Fig. 4: Data is transmitted between the ISS and the tags in narrow timeslots.

passing over the tags. The tags independently compute these times from the ISS orbit data, which is sent to them at regular intervals (Fig. 4).

The tags are water-resistant and have an operating temperature range from –10 °C to +50 °C. Comparable existing tags for terrestrial animal observation weigh 15 to 20 grams, use the mobile network for data transmission and lack the multiple sensors of the ICARUS tags. Animals that leave the network coverage are irretrievably lost to observation. In addition, mobile networks are not always suitable for monitoring wild animals.

The ICARUS tags therefore fill several capability gaps.

- **Weight:** With a weight of just five grams and very compact dimensions, now even small animal species are available for observation.
- **Accessibility:** The tags can be addressed worldwide via the ISS link, and in the other direction the tags can upload their collected data to the observation network every day via the ISS. In addition, a terrestrial ICARUS infrastructure can be used to establish local acquisition networks with high data rates.
- **Multisensor technology:** ICARUS tags enable access to their GPS coordinates and to various environmental variables (temperature, orientation/compass, acceleration, Earth's magnetic field, humidity, pressure).

Terrestrial infrastructure as an alternative transmission path

Besides the ISS link, ICARUS offers the possibility to read tags through a terrestrial infrastructure. This considerably increases the readout frequency and transmission data rate. The achievable terrestrial data rate is 1 Mbit/s, about 1000 times greater than with the orbit uplink.

The terrestrial infrastructure can be implemented with either handheld mobile devices or stationary base stations. Both types of equipment are developed and produced by Rohde & Schwarz. The tags automatically detect which transmission paths are available and then choose the corresponding default settings for one of these paths (usually the terrestrial connection). With terrestrial readout, an app is used to upload the data to the central database at www.movebank.org.

Dr. Marco Krondorf

1) ICARUS is intended to be used with low Earth orbit (LEO) satellite systems. The ISS is serving as the initial test platform. It is fundamentally conceivable to operate a LEO satellite fleet with ICARUS at a later point in time in order to increase availability or shorten the overhead pass intervals.
2) The ground station will be operated by Roscosmos, the space organization of the Russian Federation. From there the data will be sent over the Internet to the company I-GOS, which will take care of uploading it to www.movebank.org.

A new era in biology: Earth observation by animals

Guest article by Prof. Dr. Martin Wikelski, Director of the Max Planck Institute for Ornithology in Radolfzell, Department of Animal Migration and Immune Ecology; Professor at the University of Constance; Head of the ICARUS project

Scientists have been working on this ambitious project for more than 15 years. The objective of the ICARUS (International Cooperation for Animal Research Using Space initiative) is to explore the global network of the most intelligent sensors available to humanity: wild animals. Animals have a "sixth sense" for events on the Earth. The latest research shows that mutual interactions of animals – often referred to as swarm intelligence – form the basis for incredible sensory performance. Some examples of this are advance warning of natural disasters or the ability of storks to find migrating locust swarms in the deserts of Africa. Locusts are still acting as a sort of Biblical plague that robs one-tenth of the world's population of their basic nutrition.

Now, with the aid of ICARUS technology, we can utilize the information from our animal "sniffer dogs" to launch a new era in Earth observation. At the same time, it makes wild animals so important as information sources for humans that we will want to protect them even better.

The author with a straw-colored fruit bat in Zambia. Fruit bats are useful carriers for ICARUS tags because they perform ecosystem services (seed distribution) and can act as "sniffer dogs" to track down sources of Ebola infection.

In today's internationally networked world, global data on animal movements and animal behavior is indispensable for understanding how we can safeguard human livelihood while protecting the animal world at the same time. Up to now, scientists have not been able to track small and very small animals on their long journeys. Billions of songbirds migrate from one continent to another every year. Many bat species and countless insect species also cover large distances, possibly crossing continental boundaries as well. We do not have accurate knowledge of this.

However, this knowledge is important, for example for understanding how disease organisms are spread by their hosts, maintaining the ecosystem services of animals or using the distributed intelligent sensory systems of animals to predict natural disasters. To remedy this worldwide lack of knowledge about the distribution and individual migratory behavior of small and extremely small animals, the ICARUS project has been initiated by an international consortium of scientists.

The onboard computer for the ICARUS experimental system was transported to the Russian module of the International Space Station (ISS) by a Soyuz rocket in October 2017, followed by the large ICARUS antenna module on a Soyuz mission in February 2018. This was done in cooperation with the Space Travel Management section of the German Aerospace Center (DLR) and the Russian aerospace agency Roscosmos. The computer was put into operation in April 2018. Startup of the overall ICARUS system will also require a spacewalk lasting about five hours, which is scheduled for August 8, 2018, and will be carried out by two Russian cosmonauts.

The data generated by ICARUS holds the promise of revolutionary insights into the life, behavior and death of animals on our planet. For example, the data collected worldwide will enable us to draw conclusions about the propagation of diseases (zoonoses), climate change and disaster prediction. The anticipated research results will be of invaluable importance to humanity and ultimately for all life on Earth.

ICARUS Global Observation System (I-GOS, www.i-gos.de), a company founded by the Max Planck Institute for Ornithology in Radolfzell on Lake Constance, has been collaborating for many years with the Dresden based Rohde & Schwarz subsidiary INRADIOS to jointly develop the best and least intrusive ways to attach transmitters to various types of animals. Songbirds will carry the tags on their backs like miniature knapsacks, secured by skin-friendly elastic bands. Larger birds, such as storks, cranes and eagles, have been fitted with ankle rings for 100 years, and now these rings will be equipped with advanced ICARUS electronics to transform the birds into in situ Earth observers that will also collect data for weather services from the remotest parts of the world. Mammals such as bears, tigers, zebras, rhinoceroses and elephants can be fitted with small ICARUS ear tags and wear them all their lives virtually unaware of them. The main goal here is animal protection. The large African bats that we hope to use to find the host of the Ebola virus will carry their tags as delicate collars. Eels, whose migrations to their breeding areas in the middle of the Atlantic or Pacific ocean are still largely unknown, will swim with pop-up ICARUS dorsal tags and measure ocean temperatures, currents and salinity, even at great depths. After a predetermined time, the tag will detach from the eel and float up to the ocean surface, where it will establish contact with the ISS and start transmitting the eel's behavior data logged over the course of time. At the same time, the tag will serve as a measurement buoy for surface currents, temperature and salinity. In the future, ICARUS tags will be used to protect fish populations, for example tuna and salmon. The tags will also be attached worldwide to newly hatched sea turtles in order to learn about the "lost years", i.e. the unknown migratory years of young turtles.

ICARUS tags can be regarded as a sort of biodata treasure, which can also be collected with the aid of interested members of the general public (citizen scientists). Via the Animal Tracker app, they will be informed of all places where tags can be found, for example when tag carriers die. Then these interested persons can find the treasure, in the same way as a geocaching treasure hunt, and send it to a participating institution. The stored data can be read like a diary that documents the entire lifetime of the individual animal.

If you want to observe animals yourself, you can download the free *Animal Tracker* app from the Max Planck Institute. This app is not only used by professional scientists, but is also part of a citizen science project. If you contribute photos or observations of animals whose movement data is recorded at movebank.org, you will enliven the data and help the scientists interpret the data.