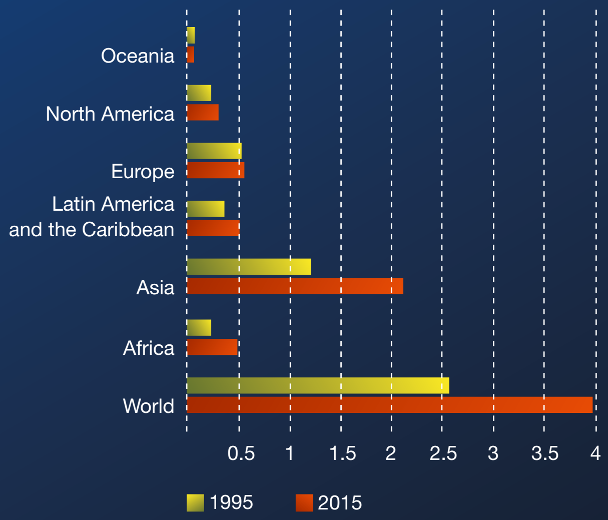
30%

of the urban population

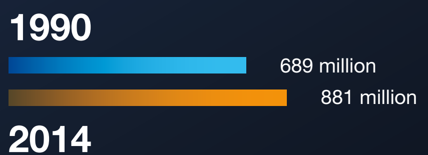
of developing countries reside in slums (2014).

Urban population at mid-year
(1995–2015) in billions

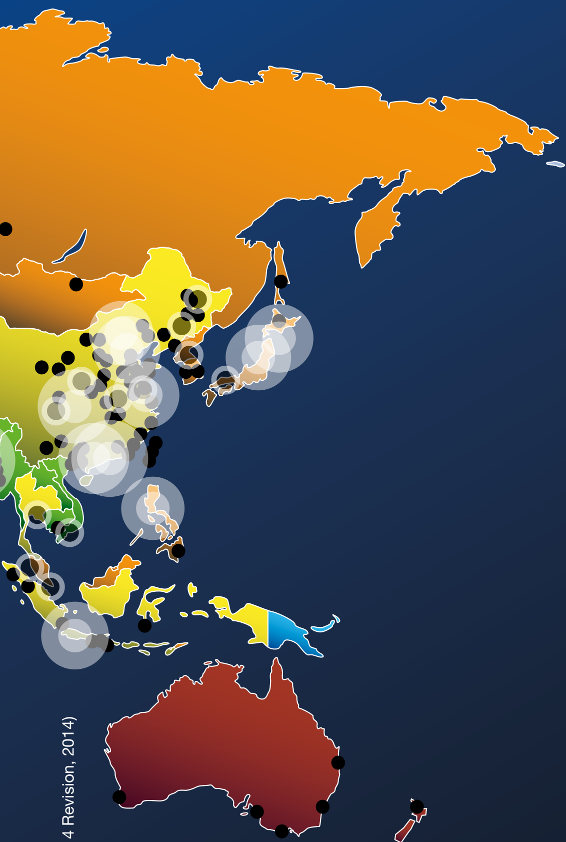


The urban population of the world has grown from 2.6 billion in 1995 to approx. 4 billion in 2015.

Number of urban residents living in slums



UN-Habitat's estimates show that there were 881 million people living in slums in developing country cities in 2014 compared to 689 million in the year 1990.



Global patterns of urbanization, 2014
City population

- 1–5 million
- 5–10 million – large cities
- 10 million or more – megacities

Percentage urban

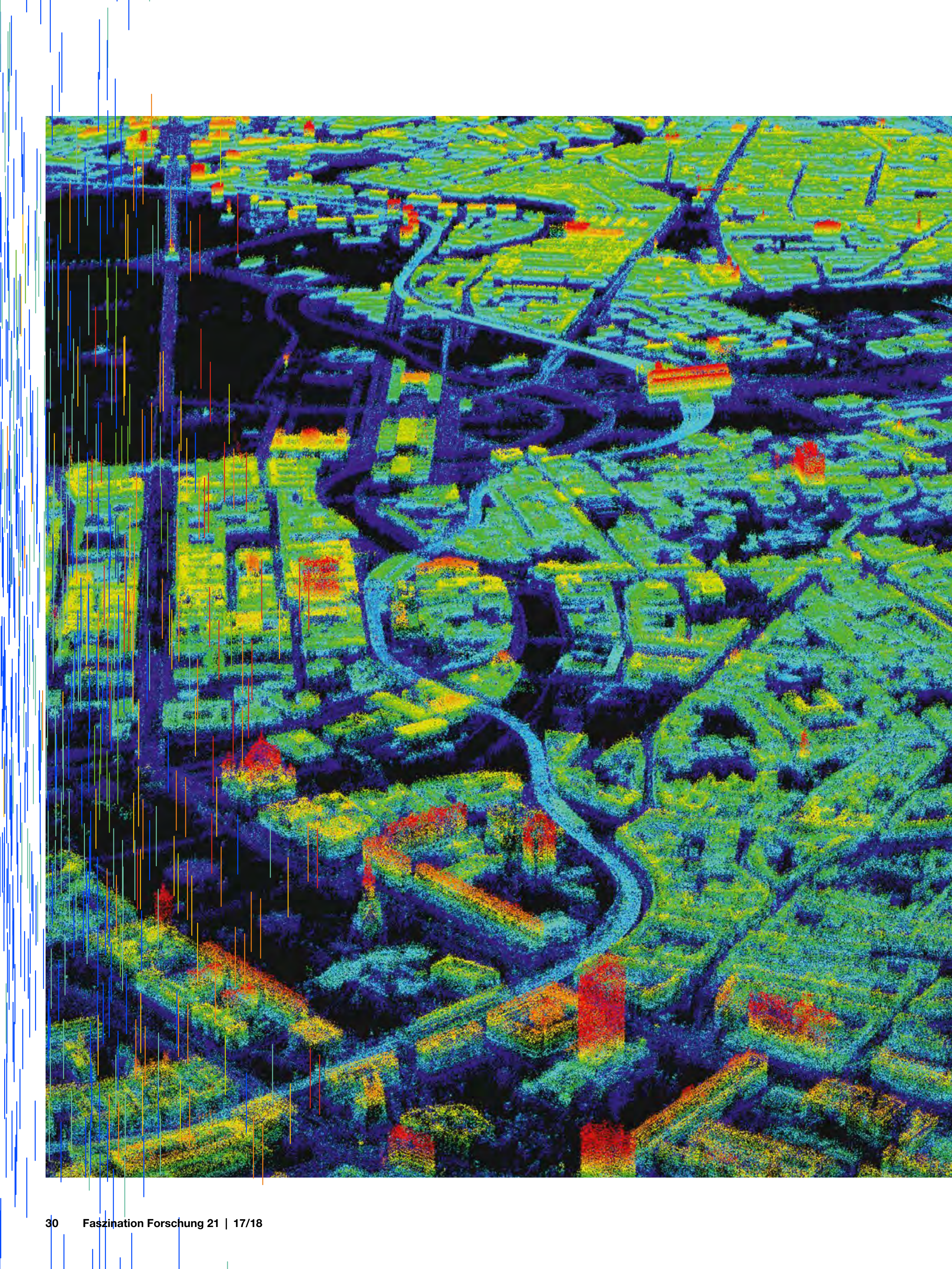
- 0–20%
- 20–40%
- 40–60%
- 60–80%
- 80–100%

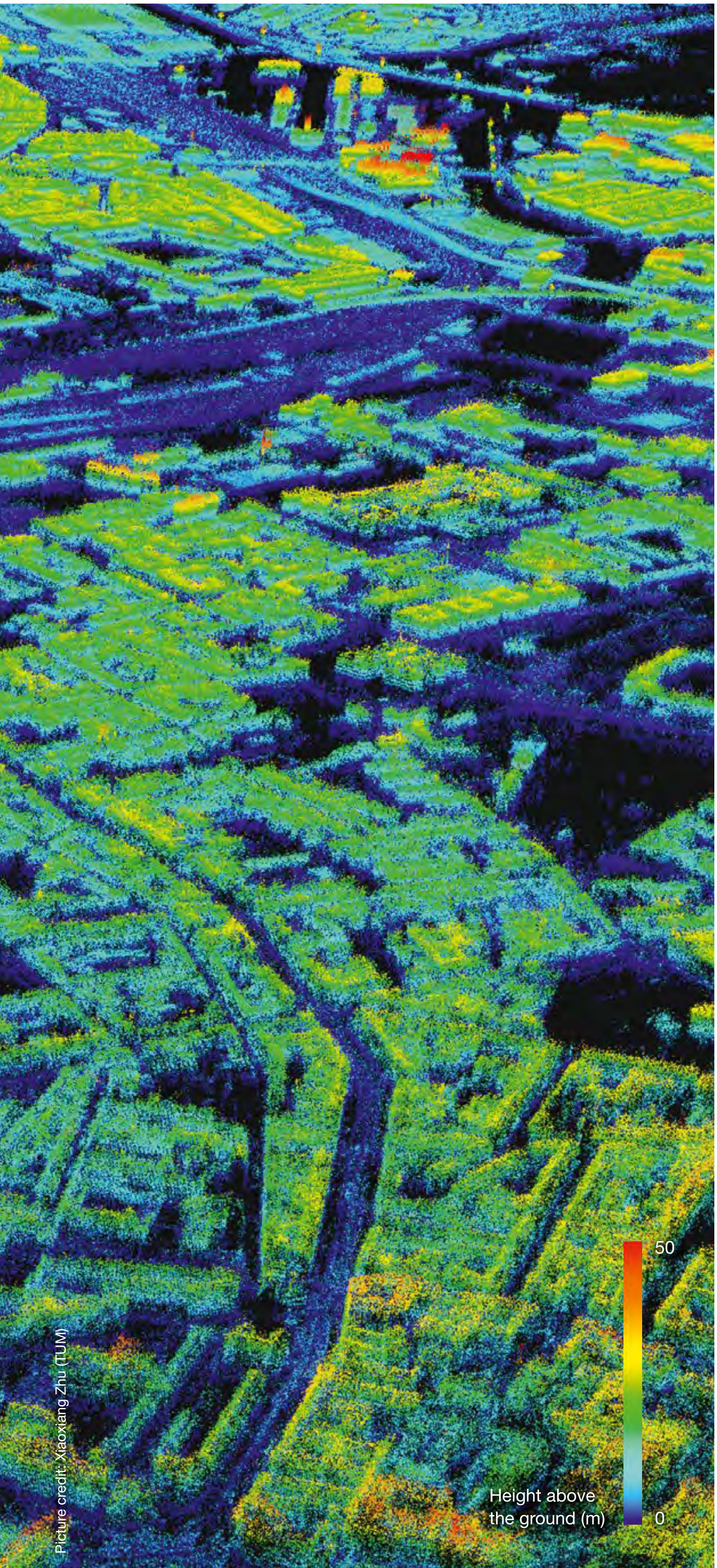
Continued urbanization: In 2014, there were 28 megacities worldwide, home to 453 million people. By 2030, the world is projected to have 41 megacities with 10 million inhabitants or more, according to the United Nations.

Graphics: ediundsepp (source: UN-Habitat: World Cities Report 2016, UN DESA: World Urbanization Prospects: The 2014 Revision, 2014)

Watching **Cities Grow**

Xiaoxiang Zhu has developed new algorithms for analyzing geographical data collected by satellites and is aiming at creating 4D models – including three spatial dimensions and time – of all cities in the world. With this goal in mind, she is combining petabytes of earth observation satellite data and social media data for the first time.





Signal Processing in Earth Observation
www.sipeo.bgu.tum.de

Monika Weiner

Städten beim Wachsen zusehen

Wie Magneten ziehen die Metropolen der Erde die Menschen an. Schon heute lebt nach Schätzungen der Vereinten Nationen mehr als die Hälfte der Weltbevölkerung in Städten. 2050 werden es zwei Drittel sein. Das Wachstum der urbanen Gebiete ist eine gewaltige Herausforderung für Planer, Verwaltungen und Einsatzkräfte. Vielerorts fehlen Informationen über das Wachstum von Stadtteilen und die notwendige Infrastruktur.

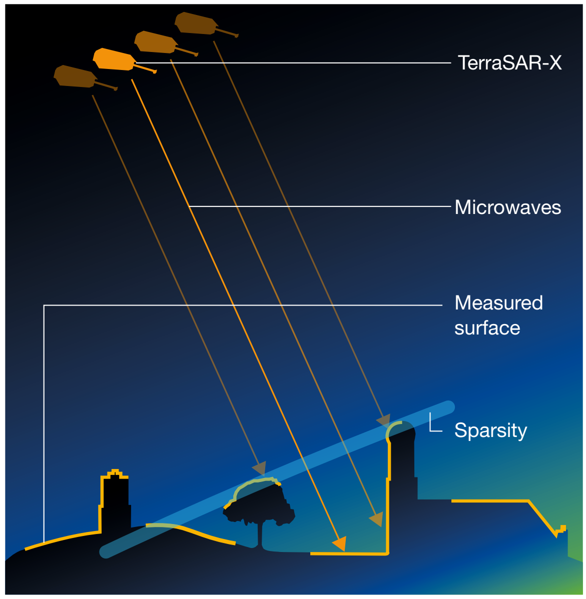
Mit neuen Datenanalyseverfahren will Prof. Xiaoxiang Zhu jetzt diese Wissenslücken schließen. Die 32-jährige Wissenschaftlerin forscht als Professorin für Signalverarbeitung in der Erdbeobachtung an der TUM und leitet eine Helmholtz-Nachwuchsforschungsgruppe am Deutschen Zentrum für Luft- und Raumfahrt (DLR).

Zusammen mit ihrem Team entwickelt Zhu neue Algorithmen für die Auswertung von Satellitendaten. Mit ihren Verfahren ist es ihr gelungen, hochpräzise 3D-Modelle verschiedener Metropolen zu erstellen, aber auch kleinste Veränderungen sichtbar zu machen – und damit eine vierte Dimension hinzuzufügen.

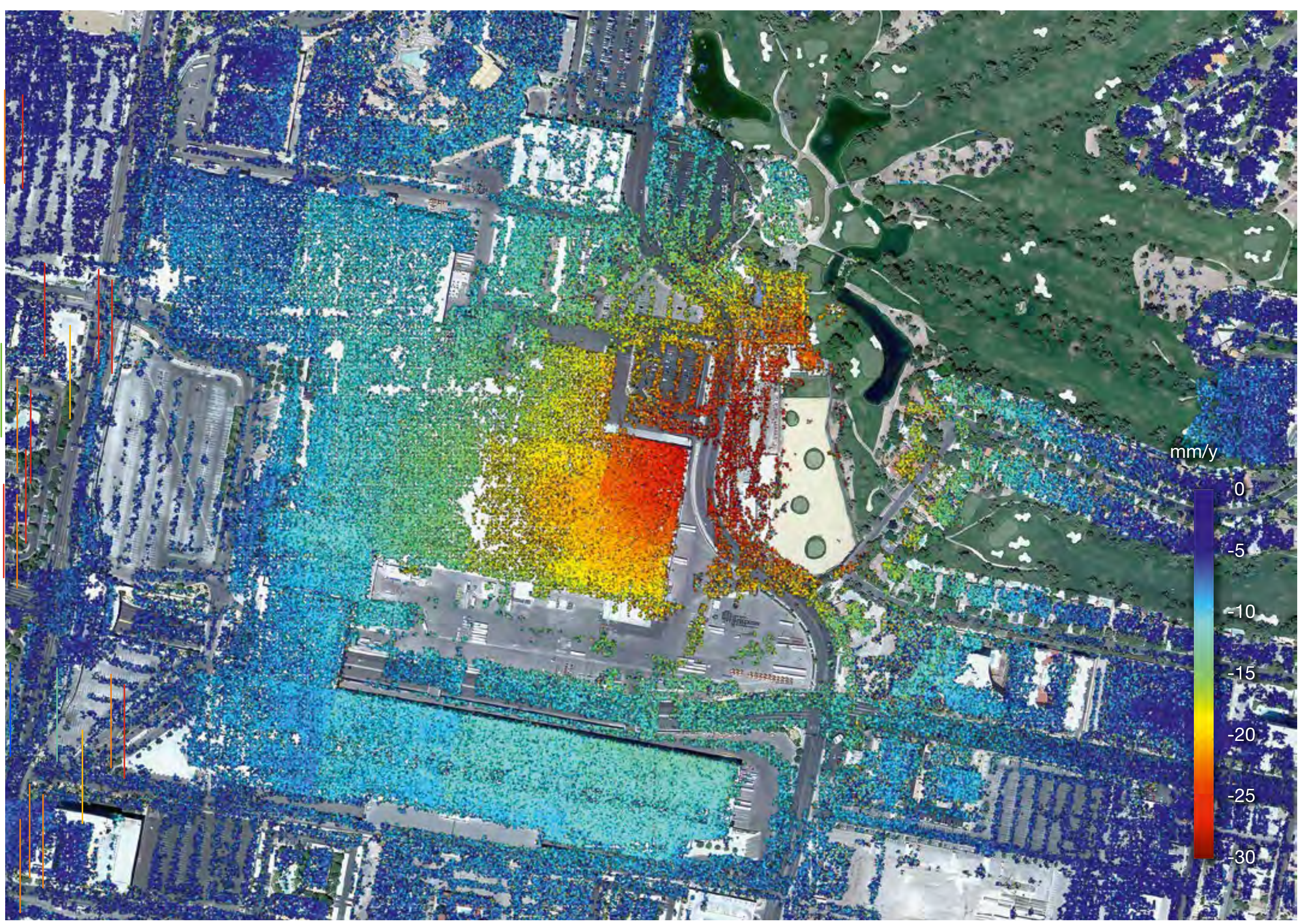
In ihrem aktuellen Forschungsprojekt So2Sat, für das Zhu einen Starting Grant des European Research Council (ERC) erhält, will sie jetzt auch Social-Media-Daten in ihre Auswertung einbinden: Durch Kombination ihrer Modelle mit Open-Source-Kartenmaterial aus dem Internet, aktuellen Fotografien, die Handynutzer ins Netz stellen, und den Tweets, die von einem Standpunkt aus gesendet werden, lassen sich Informationen über Ort und Funktion von Gebäuden sowie die Bevölkerungsdichte gewinnen und in die Modelle integrieren.

Der urbane Fußabdruck, der so entsteht, zeigt, wie sich Stadtgrenzen, Bevölkerungsdichte und Art der Bebauung verändern. Er soll künftig dabei helfen, eine nachhaltige Entwicklung der Städte zu planen und das Leben von Milliarden Stadtbewohnern einfacher und sicherer zu machen. □

A new way of global urban mapping: Using radar measurements from the TerraSAR-X satellite, Xiaoxiang Zhu and her team generate three-dimensional, high-resolution computational models of Berlin (left) and other major cities.



Radar tomography: Orbiting the earth at an altitude of approximately 500 kilometers, the TerraSAR-X radar satellite sends microwave pulses to the earth, in turn measuring the distance between the satellite and the buildings in the area in question. Initially, these measurements are received in a two-dimensional image.
In order to establish 3D or 4D city models, Xiaoxiang Zhu's team uses images taken from slightly different perspectives and at different times. The satellite flies over the same area every 11 days and each time takes an image from a slightly different orbit position. Comparable to a computed tomography of the earth, the method allows the localization of all reflecting points, which are sparse – a three-dimensional surface in the full three-dimensional space.



High resolution: Since the satellite images are taken at different times, the researchers are able to look for deformation patterns by noting even the tiniest changes (the 4th dimension) in a building's distance from the satellite. The 4D model shows a ground subsidence of up to three centimeters per year around the Las Vegas Convention Center, indicated by the red zone (center). This deformation is probably due to ground water being pumped up.

The United Nations estimate that city dwellers already account for half the global population. By 2050 that proportion may increase to two thirds. In particular, around a billion people live in slum conditions, their absolute number continuing to grow. Global urbanization, especially the uncontrolled kind, places enormous challenges in the path of urban planners, local administrators, utilities and emergency services. Basic data is often lacking: How many inhabitants live in a square kilometer? How quickly are urban areas growing? Where are people at risk in case of floods, earthquakes or tornadoes? Are there enough roads for an emergency evacuation? Where are hospitals located? How about schools? "All of this information is essential if we want to improve the planning of urban growth, develop security concepts and provide adequate infrastructure," explains Xiaoxiang Zhu. The 32-year-old scientist is a professor of Signal Processing in Earth Observation at TUM and the German Aerospace Center (DLR).

Virtual city tour

With the methods she has developed for analyzing earth observation data, Zhu can watch cities grow without leaving her office. With one mouse click, a 3D image of Berlin is displayed on one of the two monitors mounted on her desk. Another click and Paris appears, followed by Las Vegas. "There we can see, using data from the radar satellite TerraSAR-X, that the golf course has sunk by three centimeters within a year – probably because ground water is being pumped up to water it," reports the researcher. The next stop on the virtual city tour: Mumbai. An animation shows the steady spread of slums within just a few years, with the accompanying rise in population density indicated by a dark red shading of the areas.

So far this extremely detailed view of urban areas throws a spotlight on just a few of the world's cities. To date Zhu has examined around a dozen metropolises. "The examples show that the use of large quantities of earth observation data can reveal changes triggered by urbanization – both in 3D and over time. In other words, in the fourth dimension."

Pioneering work in data mining

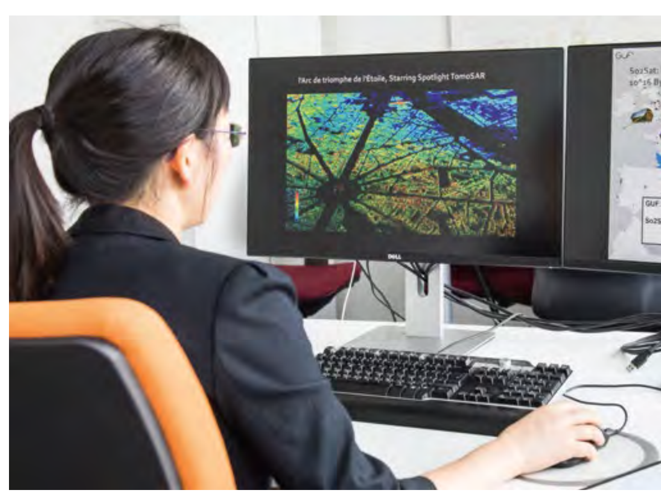
The actual challenge is in the sheer quantity of data to be processed. It's "Big Data" in every sense of the word. The German earth observation satellites TerraSAR-X and TanDEM-X and the Sentinel-1 and Sentinel-2 satellites of the EU Copernicus program alone transmitted to date already 10 petabytes of data to the ground stations. In the DLR Earth Observation Center, a room as big as a gymnasium, barely 200 meters from Zhu's office in Oberpfaffenhofen, the information is catalogued and stored on magnetic tapes and discs. Scientists studying changes in urban areas can access this resource with a mouse click whenever they need it.

How can the information relevant to the global development of cities be filtered out of this enormous mountain of data? "It's true that nobody would live long enough to complete this task by hand. Not even the 20 million core hours of computing time that the Leibniz Supercomputing Center allocated to me as a TUM professor would be long enough," acknowledges Zhu. "Analysis can succeed only with special machine learning and artificial intelligence algorithms." Developing these mathematical rules that enable computers to solve complex problems one step at a time is Zhu's field of specialization.

From the second to the fourth dimension

Xiaoxiang Zhu was already writing algorithms that used images from the then newly launched TerraSAR-X for urban mapping purposes in her doctoral thesis. The radar satellite bounces microwave signals off the earth and receives the echo. These images are of limited information value, however, the reflections of different objects equally distant from the satellite overlap in the final image. This effect reduces the three-dimensional world to two dimensions.

But the images can be expanded into three or even four dimensions if tens of satellite measurements taken at slightly different positions and different times are included in the calculations: If the satellite flies over every region of the earth at 11-day intervals, its position is not always exactly the same. These orbital variations can be utilized to calculate the spatial locations of objects such as buildings from varying angles – similar to computed tomography, where multiple measurements are used to create an image of the human body. In addition to this third dimension, Zhu was able to derive a fourth dimension from the satellite data – showing the development of cities over time. ▷



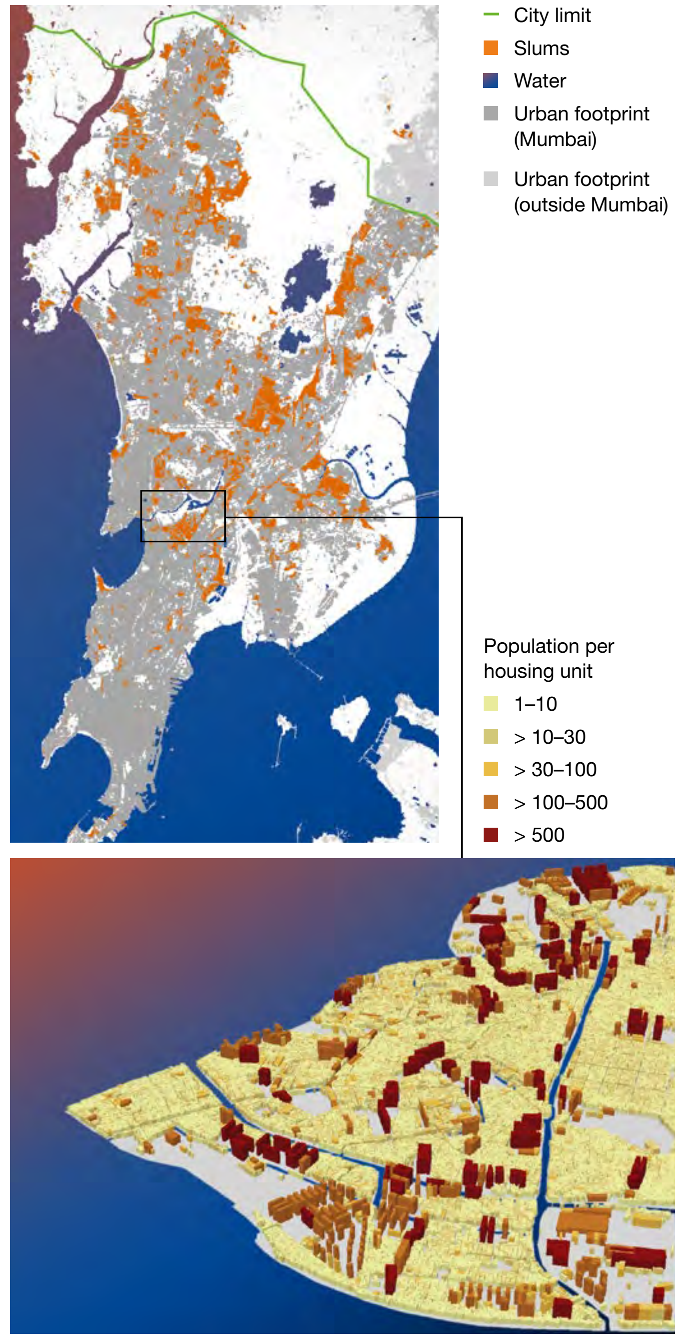
Paris on the one hand – Mumbai on the other: Xiaoxiang Zhu's methods are suitable for all types of cities and settlements. Her aim is to create thematic footprints of all cities in the world.

Graphics: ediundsepp (source: TUM); Picture credits: Xiaoxiang Zhu, ediundsepp

In the recently completed 4D-City project, she worked with her team to generate high-resolution models of Las Vegas, Paris and Berlin, setting a new world record in this technology: The system reconstructed three million measurement points per square kilometer.
More importantly, the analysis recognizes deformations of buildings or soil subsidence of just one millimeter. “We demonstrated that this technology is suitable for detecting danger points, for example impending damage to bridges, dams or tracks,” reports the scientist.

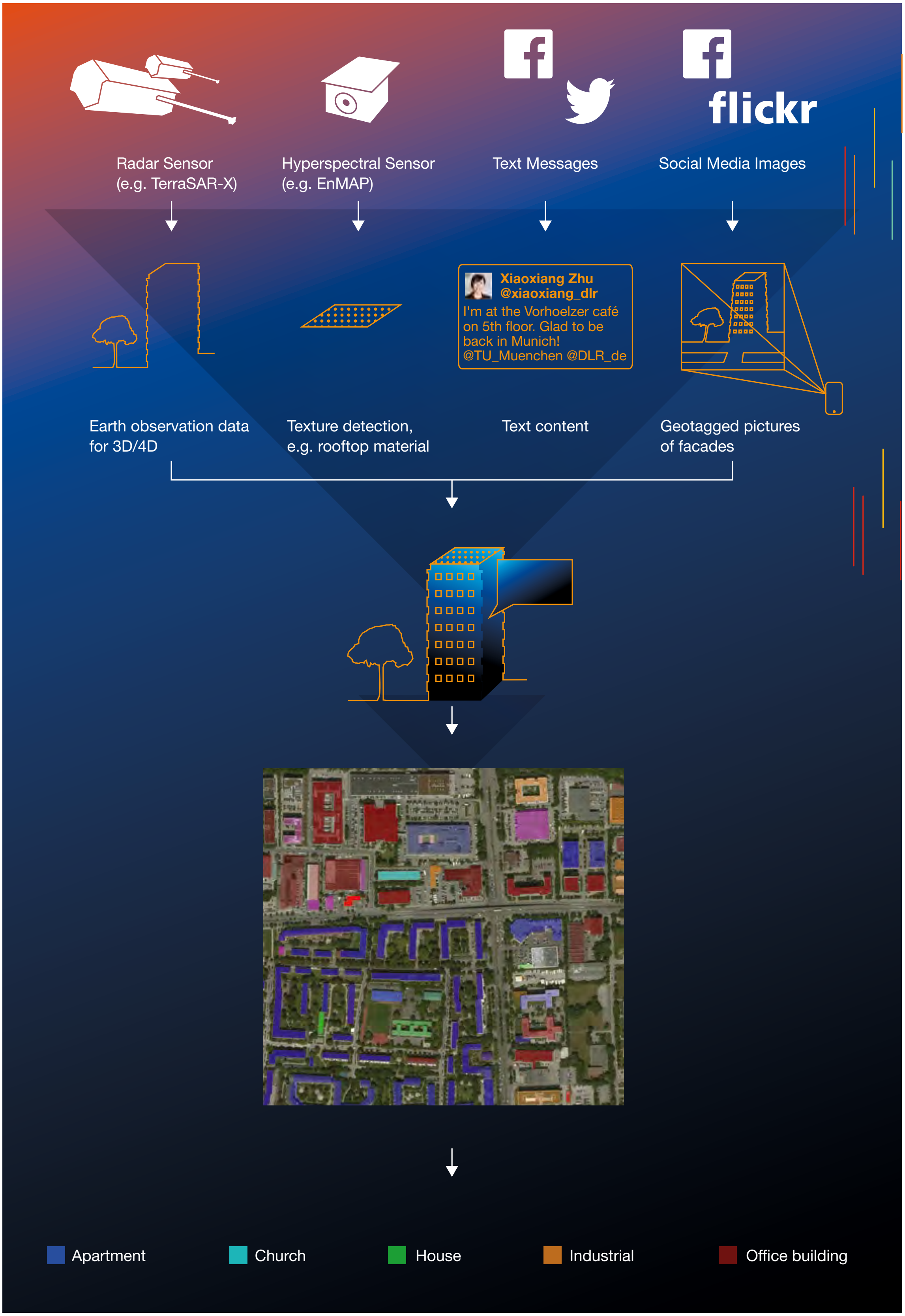
Deep learning for earth observation

Her experience in dealing with mountains of data now pays off when faced with even more massive quantities of information: The satellite fleet of the European Copernicus program has been in orbit for a few years. These Sentinel satellites, as they are called, are the world’s first large source of free and open earth observation data. In addition, the German EnMAP satellite, scheduled for launch in 2020, will transmit information to earth around the clock in an entirely new form: The sensors will detect 242 wavelengths for every pixel in various ranges of the spectrum, from short wave infrared to blue. This high spectral resolution allows the material to be identified and thus conclusions to be drawn on the properties of the mapped objects – differentiating for example tiled roofs typical of residential buildings from metal roofs typical of industrial zones. “This will give us an innovative and powerful earth observation technology that we want to be ready for,” says Zhu. With her colleagues she is now developing algorithms to enhance the resolution of the images and filter out signal noise. “At the same time, we have to explore new paths to convert the wealth of measurements into usable information quickly.” That will not be possible with traditional computational methods.
In her research project “Big Data for 4D Global Urban Mapping – 10^{16} Bytes from Social Media to EO Satellites” – “So2Sat” for short – the scientist is therefore exploiting the ability of computers to learn: Instead of analyzing every image pixel by pixel, the information will be compared against known patterns. This process will utilize deep learning, a technology based on artificial neural networks.
Deep learning is characterized by neural networks involving many layers, for this reason, they are called deep. As their shallow counterpart, deep neural networks exploit feature representations learned exclusively from data, instead of hand-crafting features that are mostly designed based on domain-specific knowledge. From massive labeled data they learn to recognize structures such as houses, churches or trees. Based on these structures, building settlement types are classified, displayed and verified by the researchers. In particular, with transfer learning techniques — one possible way to handle the challenge of limited annotated data — deep learning helps the analysis of images from all cities across the globe, with labeled data from only tens of cities. “This technology ▷



The 3D model of the Dharavi district in Mumbai showing changes in population density, is an exception. For the vast majority of slums, information on location, extent and morphology is lacking. Xiaoxiang Zhu and her colleague Dr. Hannes Taubenböck at DLR want to change that.

Picture credits: Taubenböck H, Wurm M, Esch T & Dech S (Hrsg.) (2015): Globale Urbanisierung – Perspektive aus dem All. Berlin Heidelberg, SpringerSpektrum. p. 297.



Data fusion: With the help of deep learning techniques, Xiaoxiang Zhu can "teach" algorithms to automatically classify houses, churches or industrial buildings, as shown here for a mixed urban area of Munich: Building instance footprints based on GIS maps are merged with geotagged street view images of facades as well as with text messages referring to the function of the building.

Graphics: ediundsepp (source: TUM); Picture credits: Xiaoxiang Zhu allows us to significantly reduce the manpower required for preparing labeling data of a large number of cities. We teach the machine to label data, in a sense," says Zhu.

New data source: social media

For Prof. Zhu, however, the final objective goes beyond that. "For comprehensive mapping and analysis of the urban footprint, we need more than just 4D models. We also want to know what the buildings look like, how they are used and how many people live in them. And the best way of collecting this information is through social media: from images uploaded to Instagram and Facebook, the number of text messages and tweets sent from a location at certain times of day or night, and open-source map materials such as Open Street Map," Zhu explains. In 2017 she was awarded a 1.5 million euro Starting Grant by the European Research Council (ERC) for her project.

Pictures, tweets and text messages – the fact that social media usage has generated billions of new data records to be analyzed leaves Zhu unfazed. On the contrary: "The ability of algorithms to learn improves with the quantity of data. The only problem is that the complexity of that learning also increases. We are therefore developing new algorithms that permit compressed assessment and analysis," she says.

Pilot applications have shown that the team is on the right track: They succeeded in combining the 3D model of Munich, generated using satellite data, with photos uploaded by smartphone users. The researchers also digitally combined the city map of Mumbai with data from messages and tweets to visualize the population density in the slums.

Xiaoxiang Zhu's hope is that, "Merging earth observation data with social media will make entirely new applications possible in the future. In case of a disaster such as a flood, city models can be updated using smartphone images and tweets for an immediate damage assessment without having to wait for a satellite to pass overhead."

A goldmine for science

As the next step, Zhu and her colleagues want to optimize the new processes to the point where a thematic urban footprint can be created for every major city in the world: This will include information on the expansion of urban boundaries, the population density in various areas and the type and function of buildings – with everything in 3D and precise to the meter.

"The possibility of comprehensive mapping will help planners and architects as well as security experts to take steps towards sustainable development", Zhu concludes. "This will help to make the lives of billions of urban residents easier and safer."

Monika Weiner

Prof. Xiaoxiang Zhu

Aiming high

Looking at the sky has fascinated Xiaoxiang Zhu since the age of five, when she happened to see a book with pictures of space. After completing High School in Changsha, China, she studied aeronautics at the university there.

At TUM, the young researcher then specialized in the analysis of earth observation data. She completed her doctorate and established a Helmholtz junior research group at the German Aerospace Center (DLR) and TUM. This was followed by numerous stints as a visiting researcher in China, Japan, Italy and the USA. At the age of 30, in 2015, she was appointed as a professor of Signal Processing in Earth Observation at TUM as a joint appointment together with DLR.

Zhu has not regretted leaving aeronautical engineering behind to enter the field of earth observation for even a minute. "It was not so much an interruption as a development," the researcher says. "In our team we have specialists from engineering sciences, physics, mathematics and computer science. Without that interdisciplinary dimension, we could never tackle projects like the global mapping of urban development."

Xiaoxiang Zhu has already received many grants and awards, including an ERC Starting Grant (2016), a renowned Helmholtz Excellent W3 Professorship (2017), and the Heinz Maier-Leibnitz Prize of the German Research Foundation (DFG), the highest honor granted to young scientists in Germany.

“Only with the help of specialists from different disciplines can we tackle the global mapping of urban development.”

Xiaoxiang Zhu

At her office at the German Aerospace Center (DLR) in Oberpfaffenhofen, Xiaoxiang Zhu has access to several petabytes of earth observation data. With a double appointment, she works as a professor at TUM and as a group leader at DLR.

Picture credits: ediundsepp