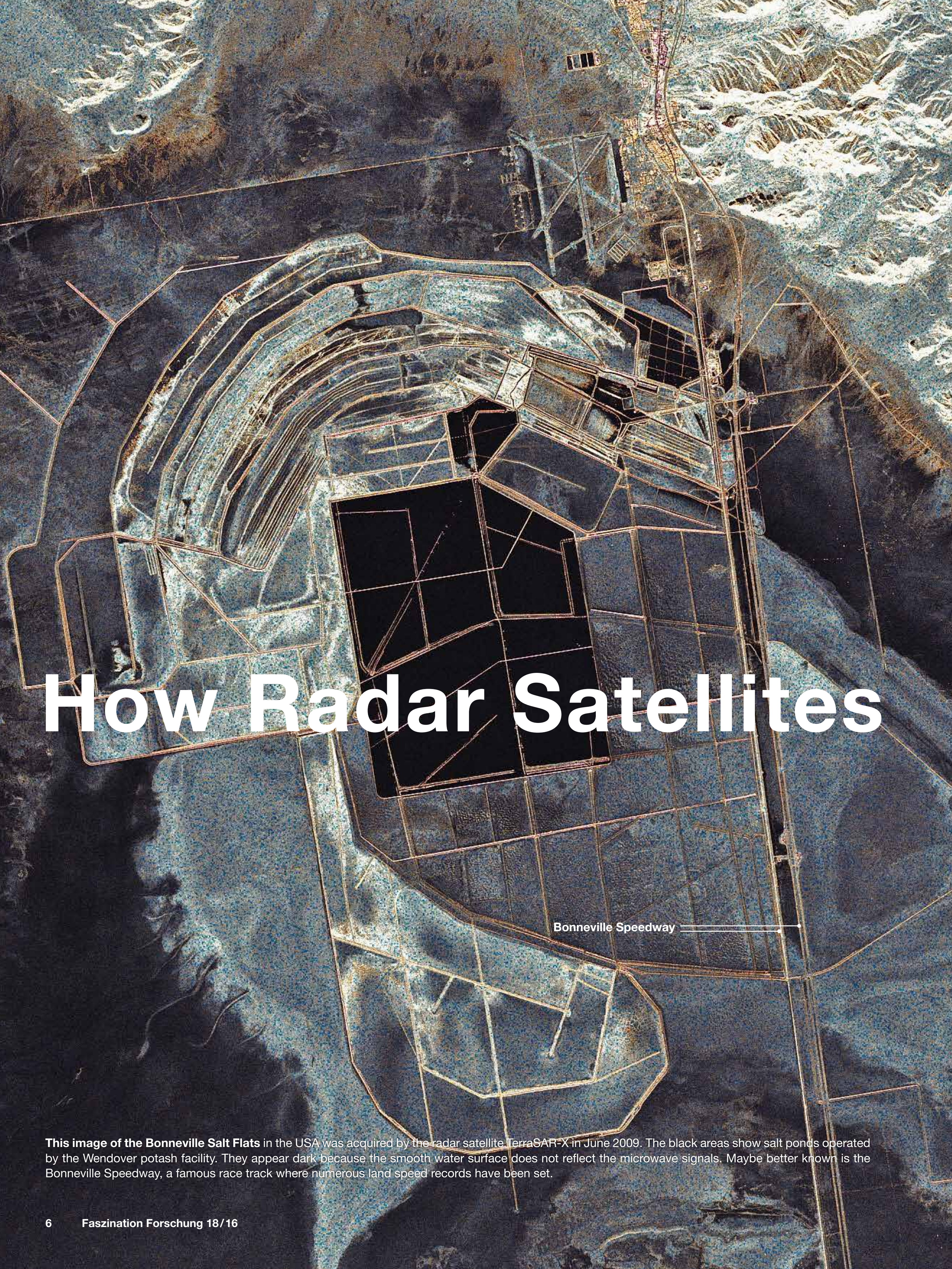
How Radar Satellites



This image of the Bonneville Salt Flats in the USA was acquired by the radar satellite TerraSAR-X in June 2009. The black areas show salt ponds operated by the Wendover potash facility. They appear dark because the smooth water surface does not reflect the microwave signals. Maybe better known is the Bonneville Speedway, a famous race track where numerous land speed records have been set.

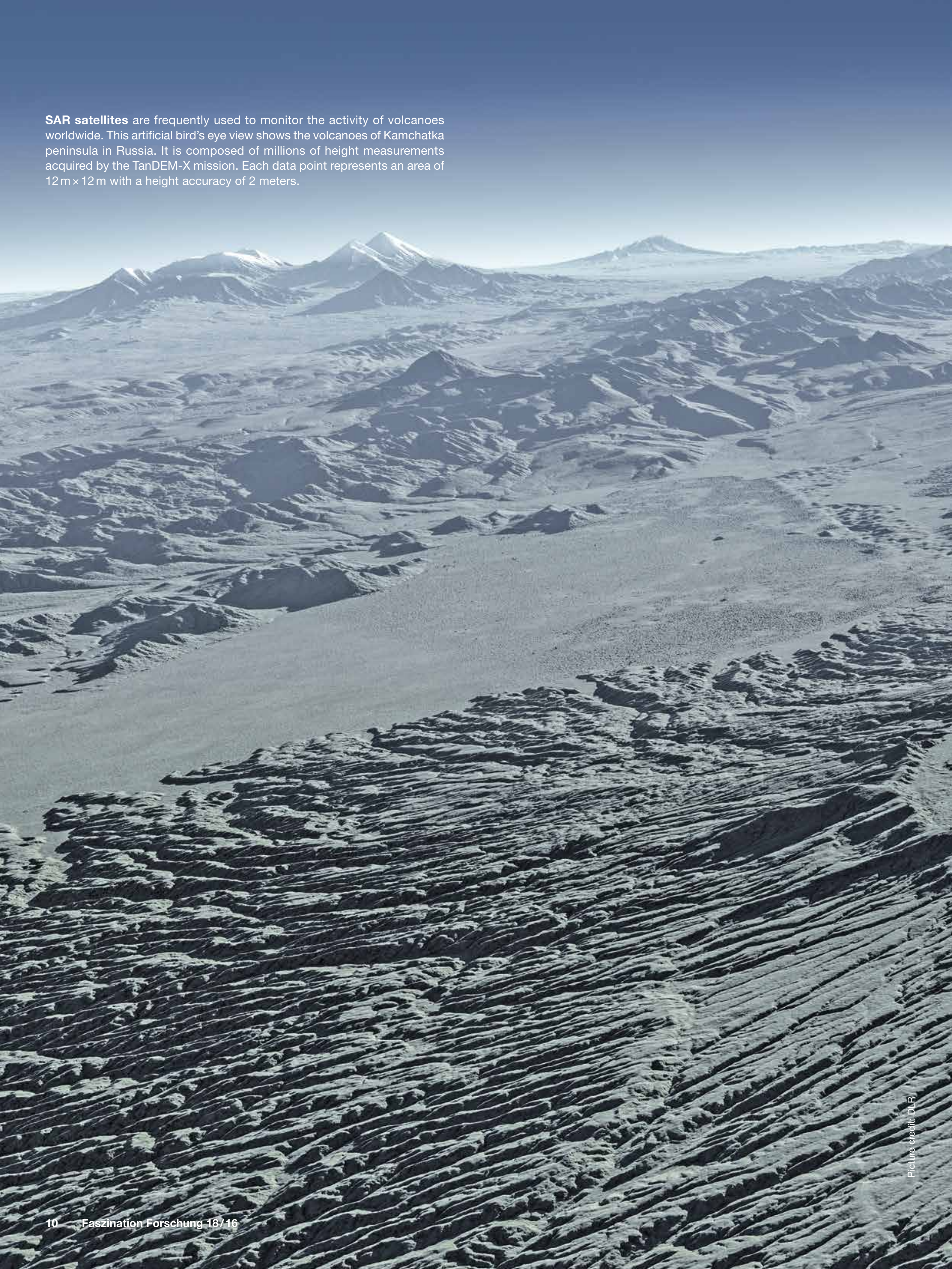
See the World

Space missions deliver global 3-D topography mapping and more.

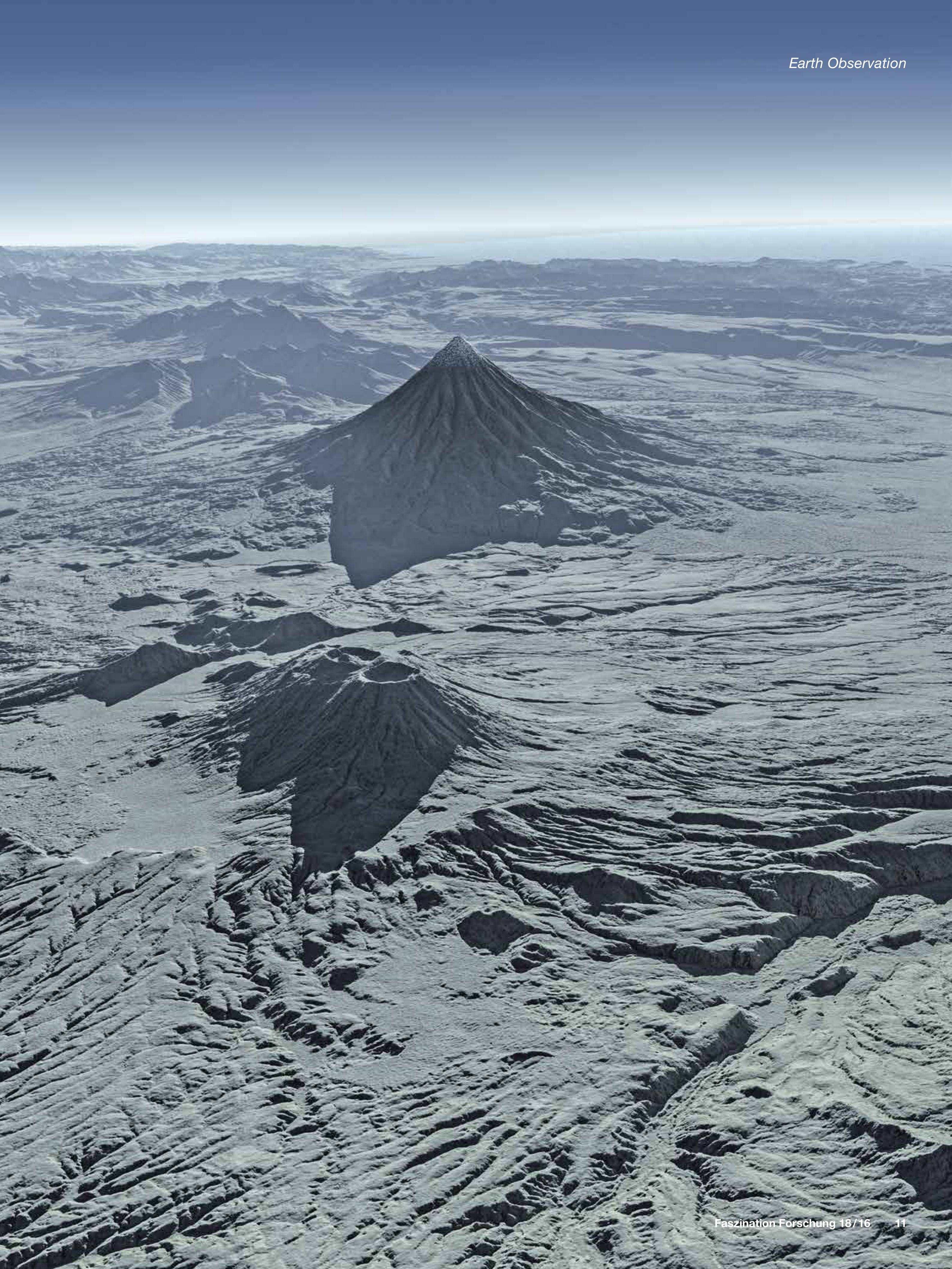
Picture credit: DLR

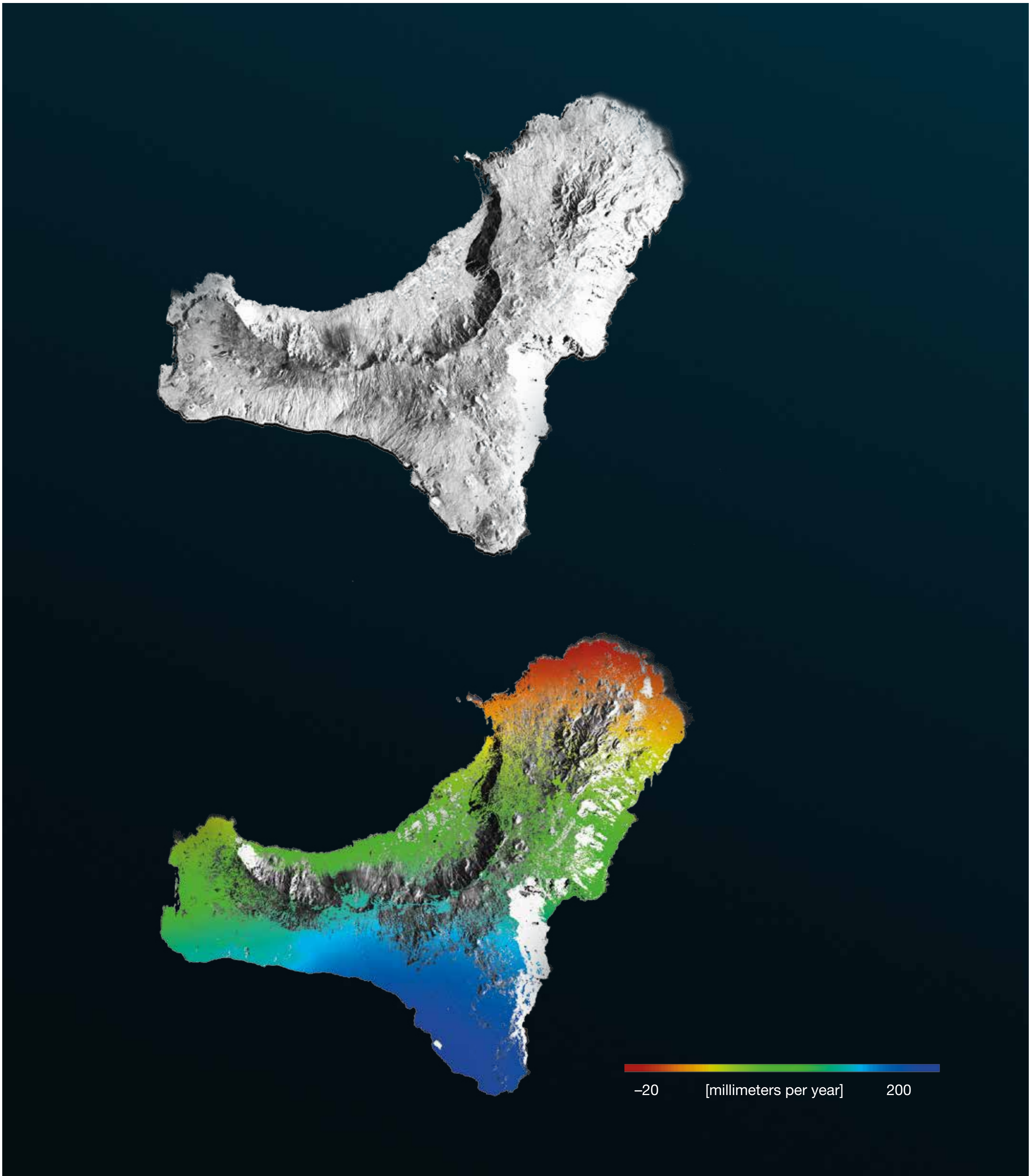
Picture credit: DLR

Radar Art: Image of Manhattan Island, New York with a ship cruising the Hudson River in the foreground. Due to the high resolution of TerraSAR-X, ships, docks and bridges, and even individual windows of high-rise buildings cause strong radar reflections. For esthetic reasons, the grey values are inverted – water appears white and windows appear dark. The image is presented in such a way that the geometric radar distortions – a common phenomenon in radar imaging – appear like a perspective view of the city.



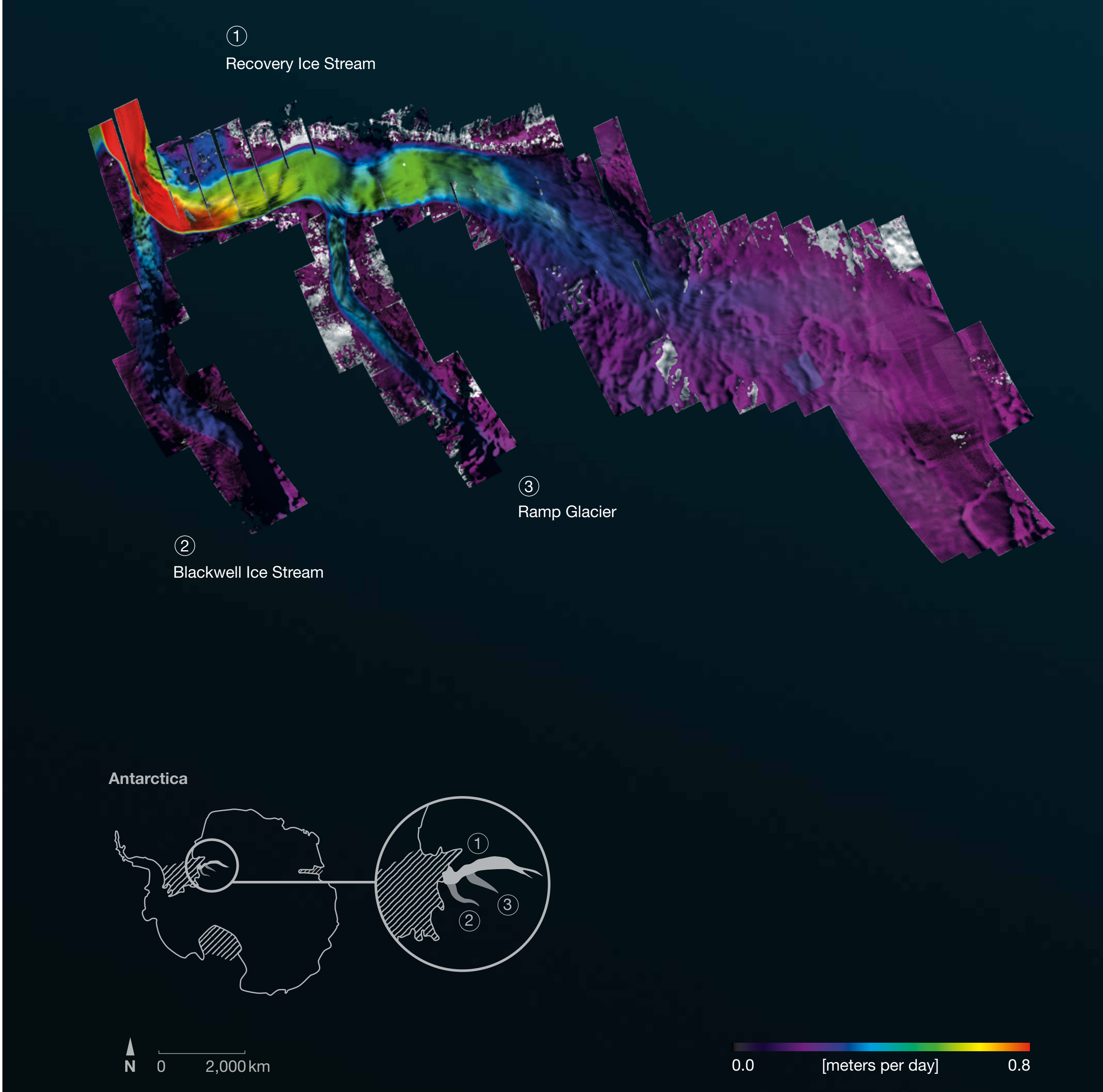
SAR satellites are frequently used to monitor the activity of volcanoes worldwide. This artificial bird's eye view shows the volcanoes of Kamchatka peninsula in Russia. It is composed of millions of height measurements acquired by the TanDEM-X mission. Each data point represents an area of 12 m × 12 m with a height accuracy of 2 meters.





Volcanoes sometimes announce their activity or eruption days or weeks before by a small deformation of their surface, which is caused by pressure changes inside the magma chamber. Such small signals can be measured from space with radar interferometry. The top image shows a TerraSAR-X view of the Canary Island El Hierro. The bottom image shows several centimeters deformation (blue: uplift, red: subsidence) on the El Hierro volcano between 2011 and 2013 derived from 50 TerraSAR-X data sets. The actual eruption occurred underwater in the bottom left area of the image.

Picture credits: DLR, Graphics: ediundsepp (source: DLR)



Measuring the speed of the Recovery Ice Stream flowing into the Filchner-Ronne Ice Shelf in Antarctica. The ice mass transported to the ocean by Antarctic glaciers is an important climate indicator and contributes to sea-level rise. Ground-based measurements of the glaciers' velocity are demanding, time-consuming, and "point-wise." Radar satellites record the velocity patterns of whole ice streams with high resolution and thus can deliver much more complete data for climate research — any time of year, not only during the Antarctic summer.


IMAGING
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DLR scientists and TUM professors Richard Bamler (right) and Michael Eineder are leading the data analysis work for the TerraSAR-X and TanDEM-X missions.

Picture credit: ediundsepp

Link
www.dlr.de/eoc

Patrick S. Regan

Wie Radarsatelliten die Welt sehen

Blickt man von einem Punkt einer polaren Umlaufbahn schräg nach unten, ist infolge der Erdrotation jeder einzelne Fleck unseres Planeten in regelmäßigen Abständen zu sehen. Wird nun die Szene mittels Radar im Mikrowellenfrequenzbereich ausgeleuchtet, lassen sich Objekte unabhängig von den Wetter- und Lichtverhältnissen sichtbar machen. Für das „Radar-Auge“ der computergestützten SAR (Synthetic Aperture Radar)-Technologie, bei der aufgezeichnete Wellenfelder in gestochen scharfe Bilder umgewandelt werden, treten selbst kleinste Details so deutlich hervor wie in einer Großaufnahme. Verfügt man gar über zwei solcher Augen, lässt sich damit eine Entsprechung zum stereoskopischen, dreidimensionalen Sehen erreichen.

Damit ist im Kern beschrieben, was die Radarsatelliten TerraSAR-X und TanDEM-X in Verbindung mit einer ausgeklügelten Datenverarbeitung am Boden leisten. Wichtigstes Ergebnis ist ein digitales Höhenmodell (DHM) des gesamten Planeten, das für jeden beliebigen Punkt eine Höhenangabe liefert und 3D-Ansichten erlaubt. Diese Daten bzw. das DHM werden zum Beispiel für Kartographie, Hydrologie, Erdsystemforschung, Katastrophenschutz, aber auch für kommerzielle Anwendungen wie die Planung und das Management von baulicher Infrastruktur benötigt. In enger Kooperation mit Industriepartnern arbeitet das Deutsche Zentrum für Luft- und Raumfahrt (DLR) daran, entsprechende Missionen an den Start zu bringen. Die TUM ist dabei einer der wichtigsten Wissenschaftspartner, insbesondere in den Bereichen Algorithmenentwicklung, Datenverarbeitung und experimentelle Anwendungen. Geleitet werden die Arbeiten von Prof. Richard Bamler und Prof. Michael Eineder, die sowohl an der TUM als auch beim DLR tätig sind.

Wie die Ergebnisse belegen, liefert TanDEM-X nicht nur das umfassendste und konsistenteste Höhenmodell, das es gibt, sondern ist darüber hinaus 30-mal genauer als das beste bislang verfügbare DHM. Die Wissenschaftler des DLR planen bereits eine weitere Satellitenmission namens Tandem-L, die an die bisherigen Erfolge anknüpfen soll. Technologie und Einsatzpläne sind hier dahingehend weiterentwickelt, dass sich Veränderungsprozesse auf der Erdoberfläche bzw. in der Bio-, Geo-, Kryo- und Hydrosphäre kontinuierlich beobachten lassen. □

The twin satellites TerraSAR-X and TanDEM-X orbiting Earth at an altitude of around 500 kilometers. The TanDEM-X mission will survey all 150 million square kilometres of Earth's land surface several times over during its three-year mission, delivering a global elevation model that is homogeneous in quality and unprecedented in accuracy. It produces 3 petabytes of data and one trillion data points, each representing an area of 12 m^2 at a height accuracy of 2 meters.

Picture credits: DLR, ediundsepp


EARTH
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You can see a lot, looking back at the Earth from space. From a vantage point in orbit, on a path that crosses the poles, every square meter of the surface comes regularly into view as the planet turns on its axis. Illuminating the scene in microwave frequencies, radar makes objects visible day or night, regardless of the weather. Better still, with an "eye" of synthetic aperture radar or SAR – a computer-enabled technology that transforms long-distance measurements into sharp images – details become as clear as in a close-up. And with a pair of such eyes, you get the equivalent of stereo vision and three-dimensional sight, with extremely high resolution and global coverage.

This is essentially what the radar satellites TerraSAR-X and TanDEM-X, coupled with sophisticated data processing on the ground, are delivering. The main product is a digital elevation model (DEM) covering the entire planet, to be completed in the fall of 2016 and then further enhanced for selected regions. It will give a height for every point and enable 3-D views. Virtually all commercial and scientific activities that involve mapping depend in some way on digital elevation models. Applications run the gamut from navigation services and infrastructure engineering to Earth systems monitoring, hydrology, and disaster recovery. Results to date already confirm that this model – besides being the most complete and consistent – is more than 30 times more accurate than the best previously available.

The German Aerospace Center DLR has worked closely with industry partners – EADS Astrium and Infoterra, now both units of Airbus Defence & Space – to get these missions off the ground and to get data products into the hands of commercial users. TUM is one of the primary scientific partners, particularly in connection with algorithm development, data processing, and experimental applications. The circle of scientists using mission data – for studies ranging from land use to climate change impacts – is large and growing, with more than 200 researchers attending the latest user group meetings. A follow-on mission has already been proposed, building on this success and opening up new possibilities.

From 1-D measurements to 3-D images

The names alone, TerraSAR-X and TanDEM-X, tell part of the story: Terra emphasizes that Earth is the object of this remote sensing program, SAR highlights synthetic aperture radar, and X identifies a specific band of electromagnetic radiation, centered on a wavelength of around 3 cm, which partly determines what the radar can see in detail. TanDEM-X stands for "TerraSAR-X add-on for Digital Elevation Measurements." But the names can refer either to the individual satellites or to the missions as a whole, and TanDEM-X employs both satellites. To avoid confusion, let's call the satellites TSX and TDX respectively, reserving the full names for the overall missions.

The satellites are nearly identical twins, although TSX was launched three years earlier than TDX. Since 2010, they have been orbiting together in a tight, helical formation that allows them to fly safely – at around 25,000 kilometers per hour – as close to each other as 100 to 500 meters. To better understand why, consider how space-based radar measurements are transformed into images, models, and maps.

Radar, stripped to its essentials, is a technology for measuring distances. Transmit a short radio-frequency pulse, wait for the reflection that comes back from an object in its path, and the time interval provides the basis for determining the distance. In reality, that reflected pulse is more like a "wave package" that will have different peaks at different times, corresponding to multiple objects. Record the entire complex reflection, and the data could yield an image, not just a distance between two points. The next logical step might be flying the radar system on an airplane or a satellite to scan the land as it moves along, but physics presents a problem (the first of many): One of the limits to how sharply a radar system can resolve an image is the size of its transmitting and receiving antenna; looking down from an orbital height of around 500 kilometers, achieving even meter-scale resolution would require an antenna several kilometers long.

> The radar satellite mission TanDEM-X yields a global digital elevation model over 30 times more accurate than the best previously available.

This is where SAR comes in. The distance a radar satellite flies during the time it illuminates a point on the ground with its actual antenna becomes, in essence, the size of a virtual antenna: an appropriately large "synthetic aperture." Now the orbiting radar can scan the ground – at an inclined angle, to distinguish objects at different distances – recording many complete reflections together with precise temporal and spatial details. Such data, downlinked to a ground station and transferred to a computer center, will be the primary input for the intensive signal processing needed to produce two-dimensional images and bring out features including surface roughness. The synthetic aperture is like a lens that can only be brought into focus by algorithms running inside the computer. But with very good algorithms, that virtual lens can be focused with almost arbitrary resolution. This is a key strength of TerraSAR-X and TanDEM-X, according to TUM Professor Richard Bamler, who also heads the Remote Sensing Technology Institute at DLR: “Every bit of the raw data from these satellites runs through algorithms developed here by DLR and TUM scientists, because we want to make sure the quality of the images is optimal and quality controlled. No one else in the world has developed such a processing chain.”

After processing, data captured by TSX during the three years it orbited alone showed just how good one such eye in the sky can be. Resolution can be comparable to the best optical satellite imagery, with advantages including independence from weather conditions, global coverage every 11 days, and consistent quality. TerraSAR-X demonstrated resolution as high as 0.25 m × 0.5 m, together with geometric location accuracy as high as 1 to 2 cm, which is comparable to the best GPS technology.

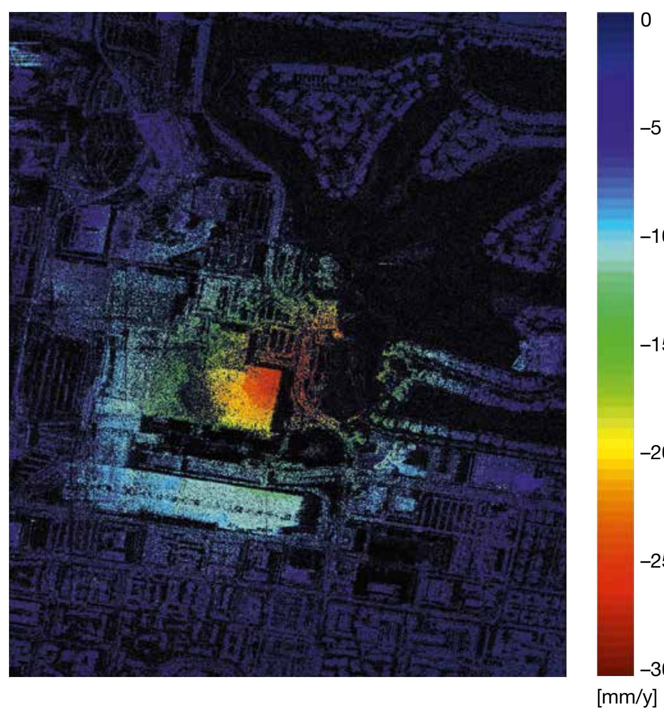
Once TDX joined TSX in space, they began to operate together as an even more powerful instrument: a SAR interferometer. “This is where we get something like a stereo view,” explains Prof. Michael Eineder, a department head in the DLR Earth Observation Center. “But unlike with optical stereo camera arrangements, we determine the 3-D position of a point by tiny differences in distance to the two SAR satellites. These differences are measured by finding the relative phase shifts of the two received wave packages. A map of these phase differences is called an interferogram. In X-band, an interferometric phase of 360 degrees corresponds to a wavelength of 31 mm.”

Fine tuning required

On a global scale, TanDEM-X has delivered 12-meter resolution for surface areas and height resolution of 2 meters. Considerable fine tuning was required to achieve this with the first-ever tight formation flight for stereo radar, while also dealing with an assortment of technical challenges.

Sometimes TSX and TDX fly parallel to each other, sometimes more or less in single file, depending on what kind of scanning is desired. Imaging can be done along or across the flight track, and in modes ranging from broad scans to a “spotlight.” Regardless of the flying formation or imaging mode, in TanDEM-X only one of the satellites is transmitting a radar signal while both are receiving and recording the reflections. Since differences between arrival times recorded for the two satellites will form the basis of the images – affecting every subsequent step in processing and analysis – a number of measures were designed-in or developed to account precisely for timing and position.

For example, a dedicated radio link between TSX and TDX is used to monitor any frequency difference in the two independent oscillators that “keep time” for their radars. This allows interferometric phase correction during processing on the ground to an accuracy of about 1 degree. Also, GPS and other means are employed to determine the relative posi- ▷



Monitoring subsidence: The top image is a TerraSAR-X view of Las Vegas Convention Center and an adjacent golf course. The bottom image shows ground subsidence of up to 3 centimeters per year caused by withdrawal of ground water near the Convention Center between 2009 and 2010. Radar interferometry is used to measure many subsidence phenomena, e.g. in former mining areas or the effects of gas extraction, oil pumping or subway construction.

Picture credits: DLR

“Every bit of the raw data from these satellites runs through algorithms developed here by DLR and TUM scientists.”

Richard Bamler

Richard Bamler and Michael Eineder

Teaming up for TanDEM-X

Richard Bamler (top) studied electrical engineering and communication theory at TUM, completing his doctoral work and habilitation here in the 1980s. He joined the German Remote Sensing Data Center (DFD) in 1989, where he was responsible for the development of signal processing algorithms as well as enabling technologies for synthetic aperture radar and atmospheric sounding. In the mid-1990s he spent time at NASA’s Jet Propulsion Laboratory as a visiting scientist and at the University of Innsbruck as a guest professor. Bamler served as co-director of the German Remote Sensing Data Center at the German Aerospace Center (DLR) from 1998 to 2000 and established the DLR Remote Sensing Technology Institute (IMF). As director of that institute, part of DLR’s Earth Observation Center, he is responsible for around 150 scientists and engineers working in a wide range of fields. At the same time, Bamler is a professor at TUM’s Department of Civil, Geo and Environmental Engineering, where he has headed the Chair for Remote Sensing Technology since 2003.

Upon receiving his diploma degree in electrical engineering and telecommunication science from TUM in 1990, Michael Eineder (right) joined the German Aerospace Center (DLR) to develop synthetic aperture radar (SAR) signal-processing algorithms for the SIR-C/X-SAR radar mission with NASA. While maintaining his affiliation with DLR, he completed his doctoral work at the University of Innsbruck in 2004. In 2013 he was appointed Honorary Professor at TUM. As a department head in the DLR Earth Observation Center, he leads algorithmic research and development of processing software for satellite missions that exploit synthetic aperture radar and SAR interferometry. One of Eineder’s current efforts focuses on expanding collaboration between the space agency and researchers in various disciplines of the geosciences.

Picture credits: ediundsepp

tions of the satellites – to within 1 millimeter. The distance between any point on the surface and TSX is minutely different from its distance to TDX, and obtaining accurate height measurements globally depends on precisely recording these distances in the first place. Given the extremely small baseline between satellites compared to the 500-some kilometers between the satellites and the ground, errors and uncertainties could otherwise be greatly magnified.

Further adjustments and processing steps of a more mathematical nature – such as phase unwrapping, atmospheric delay compensation, and geocoding – address unavoidable physical and technical artifacts in the data. Many of these essential algorithms have been developed by a joint team at TUM and DLR headed by Profs. Bamler and Eineder. They guarantee the world-leading accuracy and performance of the mission.

Erasing borders, pushing boundaries

TanDEM-X provides a geometrical basis for harmonizing all kinds of remote sensing data. This is information you can build on, literally, as it is needed for the planning of large construction projects, new rail lines, and the like. The new global DEM enables timely updating of existing maps and vastly more reliable mapping of poorly studied or inaccessible regions, including parts of Africa, Asia, and of course Antarctica.

In addition to producing the first seamless, borderless, high-resolution digital elevation model on a global scale – the primary mission goal – TanDEM-X is also enabling a wide range of scientific studies. Researchers at TUM and DLR are pushing the limits by generating even more accurate DEMs on local scales, and they are testing the feasibility of applications based on new interferometry and SAR techniques. A few striking examples illustrate the potential for monitoring Earth systems and our built environment. One doctoral candidate observed the growth of rice crops with decimeter accuracy. Another candidate is determining the ice loss of glaciers all over the world.

Within the TerraSAR-X mission alone, researchers demonstrated the possibility of precisely measuring changes in the land, whether due to tectonic, environmental, or human activity. A joint DLR/TUM research group sponsored by the German Helmholtz Association developed a new method called imaging geodesy. This method allows for centimeter-accuracy measurements from space, comparable to the capability of GPS receivers on the ground but without the need for such expensive devices. Using imaging geodesy, available maps and optical satellite imagery can be geometrically pin-pointed to the centimeter level – for example, to support self-driving cars with precision maps and landmarks.

Another experiment targeted remote monitoring of critical but relatively inaccessible infrastructure. This test focused on checking the structural integrity of an offshore platform, anchored to the sea floor and subject to tremendous forces, that houses AC-to-DC conversion equipment for a wind farm. Other DLR researchers use SAR to investigate parts of the Earth that are hardly accessible even via remote sensing, such as the polar regions and the oceans. They have charted the velocity of glacier flows in Antarctica, and the paths of drifting icebergs that could threaten shipping. By analyzing surface wave patterns in the ocean, they were able to produce bathymetric profiles of coastal areas where changes can occur relatively quickly, offering an alternative to time-consuming and expensive sonar surveys. Also proven was the power of SAR to clearly map the extent and mark the edges of an oil slick on the ocean, based on the contrast between oil-smoothed waters and the normal surface roughness. The same technology could help identify which ship spilled the oil, using specialized algorithms that fingerprint vessels according to structural features and their characteristic wakes.

By exploiting the interferometric phase of multi-temporal SAR images, researchers can measure slight geometric changes of Earth's surface and of urban infrastructure, on the millimeter scale and below. Studies have documented seasonal deformation in buildings and bridges, which swell slightly in warmer months and contract in winter, as well as one-time changes such as the compaction of recently completed steel-and-concrete skyscrapers.

A strong impetus for future missions comes from what TerraSAR-X and TanDEM-X have enabled scientists to see in relation to important areas of the Earth sciences: climate change impacts reflected in melting ice or altered ocean currents; the slight heaving of a volcano that hints at a coming eruption; ground deformations that show how a recent earthquake has rearranged the land; signs of potential hazards from flooding or landslides. This approach has also been successfully tested to characterize forests in different parts of the world, to measure the heights of the trees, and to chart the path of deforestation.

To do this even better, DLR and TUM researchers have proposed a future satellite mission – again using SAR interferometry with a pair of satellites orbiting in close formation, but equipped with larger antennas, L-band radars, and other technical innovations tested or inspired by TanDEM-X. The wave band is key. While the present missions have had some success with 3-D imaging of vegetation, most of the X-band signal reflects off the canopy. In the L band, with a central wavelength around 24 cm, all levels of a forest are illuminated, from the treetops to the ground. The technology and operational plans for the envisioned mission, named Tandem-L, are optimized for observing dynamic processes on Earth's surface: in the biosphere, geosphere, cryosphere, and hydrosphere. With this, Tandem-L is expected to achieve new heights in mapping, observing, and monitoring our living planet.

Patrick Regan