



German Remote Sensing Data Center

Deutsches
Fernerkundungsdatenzentrum

Status Report 2013 – 2021



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Cover	DFD's Earth sculpture in the exhibition „The Fragile Paradise“ at the Gasometer Oberhausen (p.112) © picture: Thomas Wolf

German Remote Sensing Data Center

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Fernerkundungsdatenzentrum
(DFD)

Status Report 2013 – 2021



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Foreword

The German Remote Sensing Data Center (DFD) forms together with the Remote Sensing Technology Institute (IMF) DLR's Earth Observation Center (EOC), the largest European institution devoted to Earth remote sensing. This status report was written in preparation of DFD's fourth institute evaluation after 1990, 2007, and 2013. It details the scientific, engineering, and operational achievements of the institute from November 2013 until October 2021.

Remote sensing has undergone an unprecedented dynamic development during the reporting period. National and programmatic Earth satellite observation missions have been and are being implemented in public-private partnerships or in close cooperation with industry. New mission concepts were conceived at DLR (e.g., Tandem-L). With the launch of the first Sentinel-1A satellite in 2014 as part of Europe's Copernicus program and its subsequent fleet of Sentinel satellites, Earth observation (EO) has evolved to a main player in the big data era – a real game changer. In addition, private NewSpace companies have launched a large number of satellites with off-the-shelf components and are exploring novel business models. Internet giants like Google and Amazon have entered the Earth observation market with their cloud computing power and artificial intelligence algorithms.

DFD has played a major role in shaping many of these developments. Its extensive participation in ESA's Sentinel mission operations, cooperation with industrial partners, and participation in the establishment of Copernicus core services and the CODE-DE platform in Germany are just a few examples. In the scientific domain, DFD has been involved in many international projects to develop and operationalize geoinformation solutions with artificial intelligence procedures. At the same time, global satellite data product portfolios were developed using large-scale computing structures. And not to be forgotten is our pioneering co-

operation with the Leibniz Supercomputing Centre (LRZ), which along with our joint "*terabyte*" infrastructure represents one of the world's largest purely scientific satellite Earth observation clouds.

Our current tasks are manifold. With our engineering and operational capabilities, national and international large-scale facilities, and technologies for acquiring, processing, archiving, and distributing payload data from satellite-based missions, DFD contributes decisively to DLR's overall ability to carry out satellite missions independently. This makes us part of DLR's and Germany's systems capability for EO space missions. At the same time, we explore the application potential of remote sensing for scientific, societal, governmental, and even commercial issues in a wide range of areas. Information is generated on the status and progress of global change and on the prevention or management of the consequences of natural disasters. Our goal, however, is to promote the benefits – but also the fascination – of satellite-based Earth observation through appropriate public relations activities and modern, expressive communication of our results.

Over the past four decades, DFD has achieved an excellent scientific and technological level, especially as EOC in conjunction with IMF: through participation in national and European satellite missions, through internationally acclaimed projects and through valuable national services such as ZKI-DE on behalf of the German government. In particular, the internationally unique combination of payload data ground segments and remote sensing/geoscientific research enables us to develop dedicated system solutions and services quickly and efficiently, such as in our Maritime Security Research Lab in Neustrelitz. Developing these unique selling points further and continuing to fulfill our role as a remote sensing center active worldwide to shape the coming decades represents an extraordinarily exciting prospect.

The results presented in this report have been achieved by enthusiastic DFD scientists and engineers supported by highly motivated technical and administrative staff, to all of whom I express my sincere gratitude.

Many have contributed to the preparation of this document. My special thanks go to the department heads Prof. Dr. Michael Bittner, Dr. Erhard Diedrich, Prof. Dr. Claudia Kuenzer, Holger Maass, Eberhard Mikusch, Nils Sparwasser and Prof. Dr. Guenter Strunz and all other colleagues who have provided text and pictures. Many thanks also to the editorial and layout team around Dr. Doris Klein, Dr. Tanja Kraus, Gunter Schreier, Nils Sparwasser as well as Katrin Molch and Christian Gredel, Sonja Hiepp, Monika Woehrl and our controlling department headed by Hans Voss for their support. And finally, special thanks go to Susan Giegerich for language check and the colleagues of the institute council for proofreading.

Much of what is described in this report was achieved in close cooperation with IMF. I am very grateful to my colleague and IMF director, Prof. Dr.-Ing. Richard Bamler, for his cordial and efficient cooperation and more than two decades of jointly shaping the EOC in true partnership.

Finally, I would like to thank all our partners, customers, and funding organizations for their collaboration and support during the past decades.

Oberpfaffenhofen,
25 January 2022



Prof. Dr. rer. nat. habil. Stefan Dech
Director

DLR, German Remote Sensing Data Center



German Remote Sensing Data Center

Introduction

The Big Picture: Major Developments in Earth Observation

Often changes seem to be small and the scientific progress manageable when you yourself are part of a profound development in a specialized domain. In this respect, the last decade is an exception in the use of space technologies for Earth observation. Even for us remote sensing specialists, it is a challenge to grasp the technological leaps and the tremendous opportunities they bring, and to exploit and help shape them for our scientific and technological developments.

One of the main drivers of this development is the European Copernicus program with its fleet of Sentinel satellites. Since the launch of Sentinel-1A on April 3, 2014, one successful mission has followed the next. To date, eight Sentinels have already been successfully placed in orbit and are continuously providing data. They already cover a considerable range of application fields and observation technologies, ranging from high-resolution optical and Synthetic Aperture Radar (SAR) techniques to spectrometers for atmospheric sensing. In the near term, the launch of additional satellites will expand the portfolio for atmospheric and climate research. New acquisition and technological observation techniques are already on the timeline, including the use of hyperspectral sensors and additional SAR frequencies (L-band), as are special mission schemes such as formation flights. Since all data from the Sentinel satellites are free and open, they are one of the most important drivers of progress in civil Earth observation to meet the needs of the science, public, and private sectors.

With the availability of Sentinel data and new emerging commercial Earth observation systems, the amount of Earth observation data available for analysis has also increased enormously. The Copernicus program brought the topic of big data with all its facets into the focus of technological and programmatic developments. The key question is how to exploit the daily flood of data. Once-set paradigms have been superseded. Today we have completely new usage scenarios. All data is made available via freely accessible data hubs and portals. The enormous amount of data in turn implies further changes. At the storage location, large computing capacities are created to enable data analysis. As a result, users from research and industry usually no longer download the data. Instead, they bring their algorithms to the data and to computing capacities in the cloud. Only the results are downloaded. Thus, major advances and breakthrough findings in satellite data analysis are no longer the preserve of highly specialized groups in large research centers. Any small group, indeed any individual scientist, can now apply an algorithm to global data with a few clicks and achieve globally significant insights. True democratization of research opportunities with satellite Earth observation data has taken place.

All these developments have been significantly boosted by the triumph of artificial intelligence methods. More and more, once purely physically motivated methods are being replaced by machine and deep learning approaches. Their effectiveness and efficiency in big data analysis was unimaginable just a few years ago. Trainable algorithms in combination with almost unlimited computer capacities and universal data availability in the cloud are currently opening up completely new dimensions in global data analytics. And we are already anticipating the tremendous potential that could arise from the future use of quantum computers.

“More and more, once purely physically motivated methods are being replaced by machine and deep learning approaches”

On the right side: Only Earth observation allows the assessment of the state of Earth's ecosystems and to monitor the global implications of human activities (blue: flight tracks, orange ship tracks).

The imagination stimulated by all these technological leaps in the last decade knows hardly any bounds. This is particularly well illustrated by the concept of digital twins that in industry allow for highly interlinked research, fast product development, and testing. This concept has now also become popular in the geosciences and remote sensing. The future goal is to create a digital twin of the entire earth system that incorporates huge amounts of data, especially from satellite-based Earth observation. This twin will enable the holistic exploration of Earth's state and the prediction of its further development.

Human impact on Earth's ecosystem is obvious and counteracting it is the Herculean task of this century. Earth observation has a special role to play; it provides scientifically objective and unbiased evidence of the real dimension of global change and its consequences. Thus, we can not only support political decision-making in Germany or Europe, but also stimulate awareness through the power of images that show a fascinating yet already severely damaged planet Earth.



Earth Observation at DLR

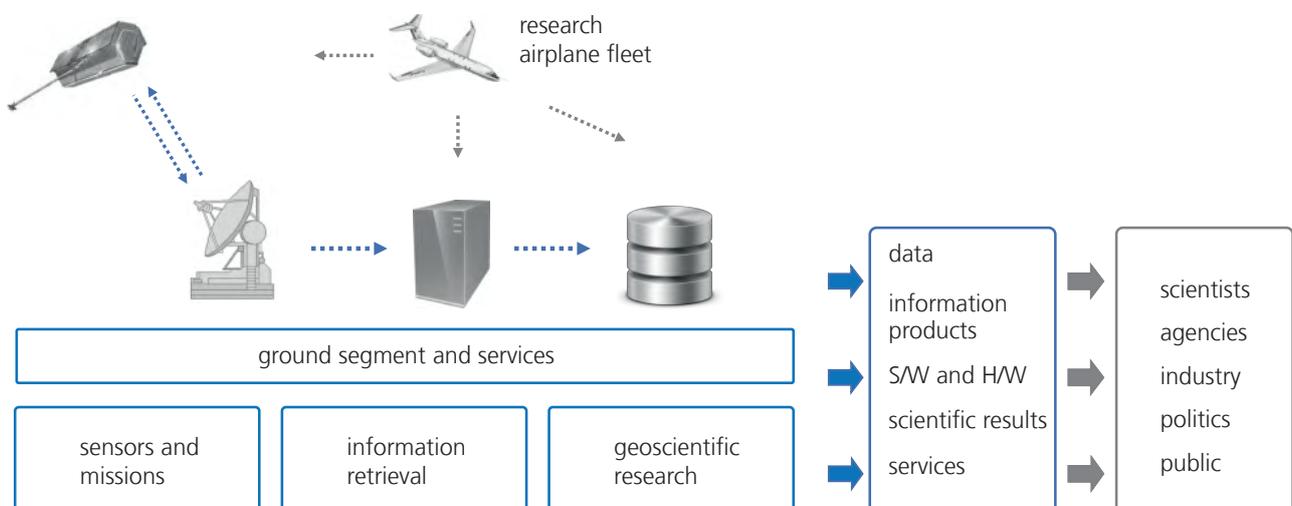
The program topic "Earth observation" represents the largest part of DLR's space program in terms of the use of basic funding resources. In this way, DLR also reflects the societal importance of exploring the Earth system using remote sensing techniques. Earth observation is indispensable for repeatedly acquiring objective geophysical and biochemical variables of the Earth system and deriving area-wide environmental parameters. Remote sensing from space is the only technology today that provides consistent measurements of these variables regularly and reliably over space and time.

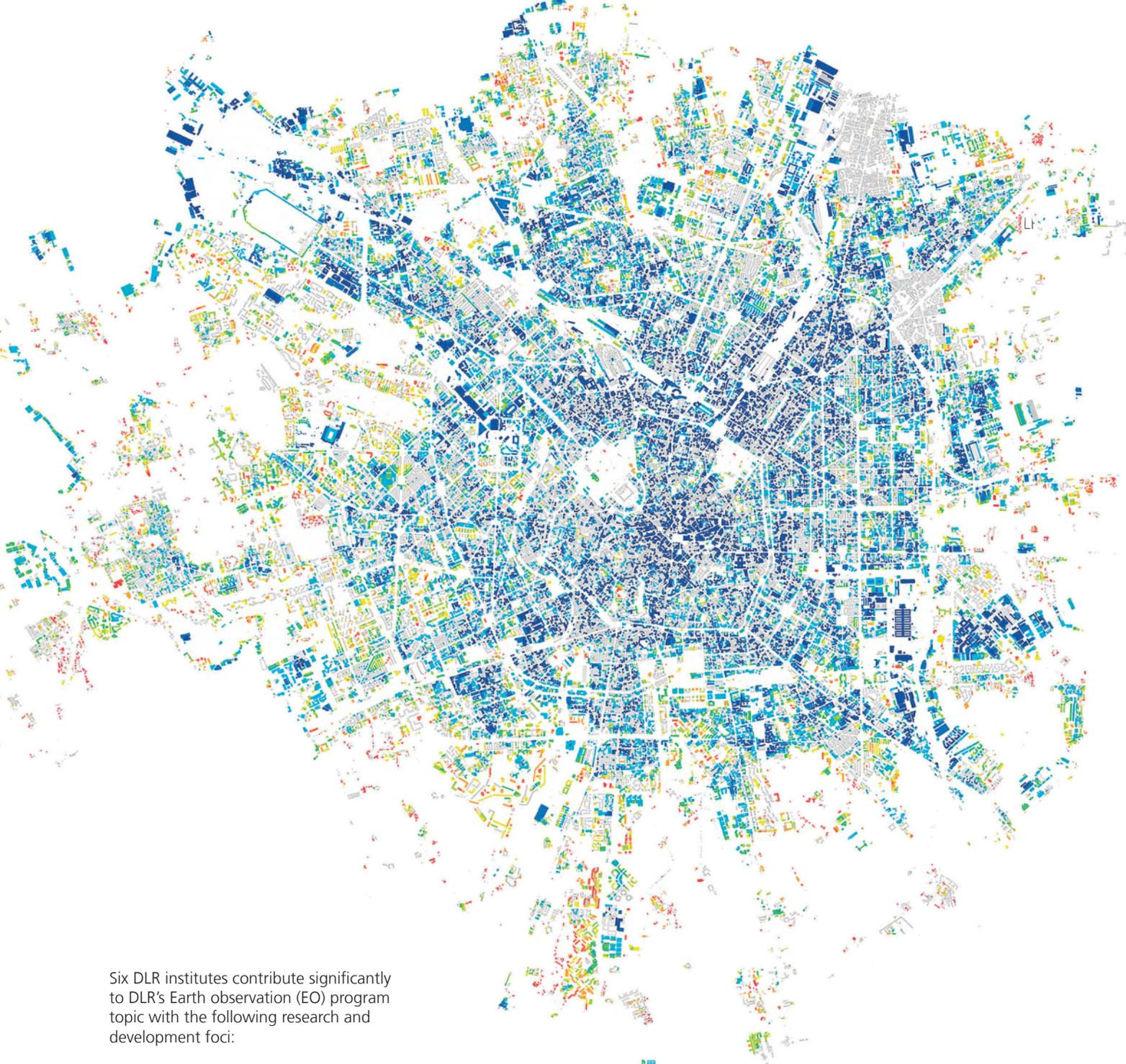
DLR masters the entire system chain of remote sensing, including mission concepts, sensor technology, precursor experiments, algorithms for (geo-) information retrieval, satellite command and control, payload data reception with its own national and international station network, data management and operational processing, value-added product

development, project-oriented geoscientific research, and dedicated user services. This systems capability is unique in Europe. It is one of DLR's greatest assets for addressing some of the important questions of society that can be anticipated for the future.

Our systems capability enables us to design, execute, operate and optimize novel Earth observation missions in a flexible, cost-efficient, and quality-conscious manner, also in collaboration with industrial companies. Two public-private partnership missions, TerraSAR-X, the first SAR system in space with a resolution of one meter and an accuracy in the sub-meter range, later complemented by TanDEM-X, the world's first SAR interferometer flying in formation, would not have been possible without this comprehensive systems capability. Likewise, we contribute to the design of Europe's Copernicus program and, in turn, also benefit from the knowledge gained from the operation of the Sentinel satellites.

A strategic strength of DLR in EO is its end-to-end system competence which covers all elements of this scientific and engineering chain.





Six DLR institutes contribute significantly to DLR's Earth observation (EO) program topic with the following research and development foci:

- Microwaves and Radar Institute, HR: *Radar sensors and mission concepts*
- Institute of Optical Sensor Systems, OS: *Optical sensors and systems*
- Remote Sensing Technology Institute, MF: *Information retrieval from remote sensing data*
- German Remote Sensing Data Center, DFD: *Ground segment engineering, operations, EO informatics, and geoscientific research*

- Institute of Atmospheric Physics, PA: *Lidar development, atmospheric research, and models*
- German Space Operations Center, GSOC: *Satellite control and orbit determination*

Green roofs have a positive impact on the urban climate. The figure shows for Milan, Italy, where green roofs would have the greatest benefit in an otherwise sealed environment (the darker the colors, the more positive the effect).

In March 2018 DLR's "Space" research program underwent extensive evaluation on behalf of the Helmholtz association, with the "Earth Observation" program topic receiving the highest possible grade, "outstanding".



DLR's Earth Observation Center in Oberpfaffenhofen near Munich

DLR's Earth Observation Center

The Remote Sensing Technology Institute (IMF) and the German Remote Sensing Data Center (DFD) have formed DLR's Earth Observation Center (EOC) since 2000. In addition to close scientific cooperation in mission projects, we are technically and structurally linked through joint controlling and management and engineering, quality assurance, and public relations activities.

The EOC of 2022 comprises more than 400 scientists, engineers, and technicians in 12 specialized departments that supplement each other in their competencies. The boundaries between the departments are flexible. For example, some of IMF's work also extends into DFD's applications domain, while DFD also conducts methodological research in selected areas. This creates an innovative

environment for exchange, joint projects, and competition for the best ideas. Over two decades, we have been able to continuously build up the scientific and engineering expertise that allows us to assemble challenging projects, from raw data to solutions, in a flexible and responsive manner. This has been successfully demonstrated in major Earth observation missions and many research and development projects jointly executed by teams from both institutes.

The principle division of tasks between IMF and DFD is as follows:

- Three engineering and operations departments at DFD develop and operate DLR's EO payload data ground segment, including data receiving stations and processing, archiving, and access systems. Likewise, the payload ground segment develops advanced EO-specific information technologies in interaction with EOC research teams and beyond.
- Five IMF departments focus on physical and mathematical methods to develop algorithms and processors to extract information from remote sensing data, starting from raw sensor data.
- Three scientific DFD departments are engaged in applied research, including geoscientific and complementary methodological developments, and service functions.
- A DFD division focusing on scientific visualization supports the entire EOC in communicating its accomplishments and results to a broad public.

In adaptation to constantly evolving societal issues, strategic priorities, and programmatic requirements at DLR, the tasks, departments, and teams at EOC are modified from time to time. This approach also helps to preserve the com-

mitment, enthusiasm, initiative, and dedication of our scientists and engineers, who are the core of EOC's success.

EOC is highly international in scope. We perform acquisition, processing, and archiving functions on behalf of the European Space Agency (ESA) as part of the European Copernicus program. We also partner with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) in operating Satellite Application Facilities and we perform ground segment functions for European and international customers and partner organizations, and implement remote-sensing-based project solutions in many countries around the world.

EOC is led by two directors, each of whom is assigned to lead one institute, for IMF Prof. Dr. Richard Bamler and for DFD Prof. Dr. Stefan Dech. A spokesperson function alternates between the two directors at three-year intervals.

Background and Structure of this Report

Typically, DLR institutes are scientifically evaluated every five to six years. For large facilities or institutes, the cycles may be slightly longer. Since its founding, DFD has been externally evaluated three times: in 1993, in 2007 for the first time as part of the EOC, and in 2013. In addition, DFD's work has been evaluated in 1999 as part of the overall evaluation of Earth observation at DLR, and four times by international experts as part of the evaluation scheme of Helmholtz research programs, most recently in 2018.

This status report was prepared in the second half of 2021 for a review of DFD to take place in April 2022. It covers the institute's achievements since its last

review in October 2013, a period of eight years. The review panel will also discuss the long-term direction of the institute after its current director retires in 2026 and develop recommendations for the DLR Executive Board.

The structure of this report takes both requirements into account: In the second chapter, the development of the institute, its current main tasks and their embedding in the national and international research environment are described in a highly condensed form. Additionally, DFD's participation in the most important national and European Earth observation missions as well as its manifold connections to the private sector are presented.

The third and fourth chapter describe in more detail the technological and scientific work carried out during the review period and the results achieved in the focus areas of payload ground segments and applications-oriented research. In these two chapters, with only a few exceptions, the presentation reflects the organization of the institute in departments and teams.

The fifth and sixth chapter highlight work and projects that have resulted from close interdisciplinary cooperation between the engineering, informatics, and geoscience disciplines across departmental boundaries, as well as EOC-wide services.

We have deliberately avoided citations in the text for the sake of better readability. The interested reader may like to take a look at the documentation part of this status report, where DFD's scientific record such as publications, lectures, awards, patents and international exchange are listed. A brief summary is provided at the end of this report.

For the full version of the documentation, please scan the QR code below or follow the link: https://pub.eoc.dlr.de/eoc-dfd_statusreport_documentation.pdf



Institute Orientation and Development

Institute Orientation and Development

DFD's Historic Development

DFD was founded in 1980 as DLR's main department for Applied Data Techniques (WT-DA). Initially since 1986 within DLR and from 1993 also in external relationships it bears the designation Deutsches Fernerkundungsdatenzentrum / German Remote Sensing Data Center (DFD). At that time, DFD had already begun not only to receive but also to process the growing volume of remote sensing data. It was the time of Europeanization of aerospace activities and an ever-diminishing prospect for national missions in Germany. Crucial to the rapid development into the German Remote Sensing Data Center was its successful participation in the development and operation of the payload data ground segment for ESA's ERS-1 satellite (launched in 1991). DFD was primarily concerned with data from the main sensor on board ERS-1, the Synthetic Aperture Radar (SAR). The technical foundations for the development of such SAR processors were laid as early as 1983, building on the knowledge and experience gained with the U.S. Seasat L-band SAR satellite.

Since then, SAR data processing, with its functions of receiving, processing, archiving, and distributing data, formed an important methodological pillar and complemented the multi-mission payload data ground segment of DFD. This was followed in 1995 by the processing of spectrometer data acquired from the atmosphere by the GOME sensor on ERS-2.

Since no commercial image processing software existed, in-house systems had to be developed, such as DIBIAS, Upstairs, and ISM. As a result, a group of scientists worked intensively on data analysis and applications. They soon formed a semi-formal user interface with universities and other groups in Germany that were also beginning to use remote sensing data.

With German reunification, DFD was able to further expand its capabilities with the Neustrelitz Remote Sensing Station. Thus, by 1999, three main pillars existed: payload data ground segment, processors for SAR and atmospheric spectrometers, and a variety of scientific applications.

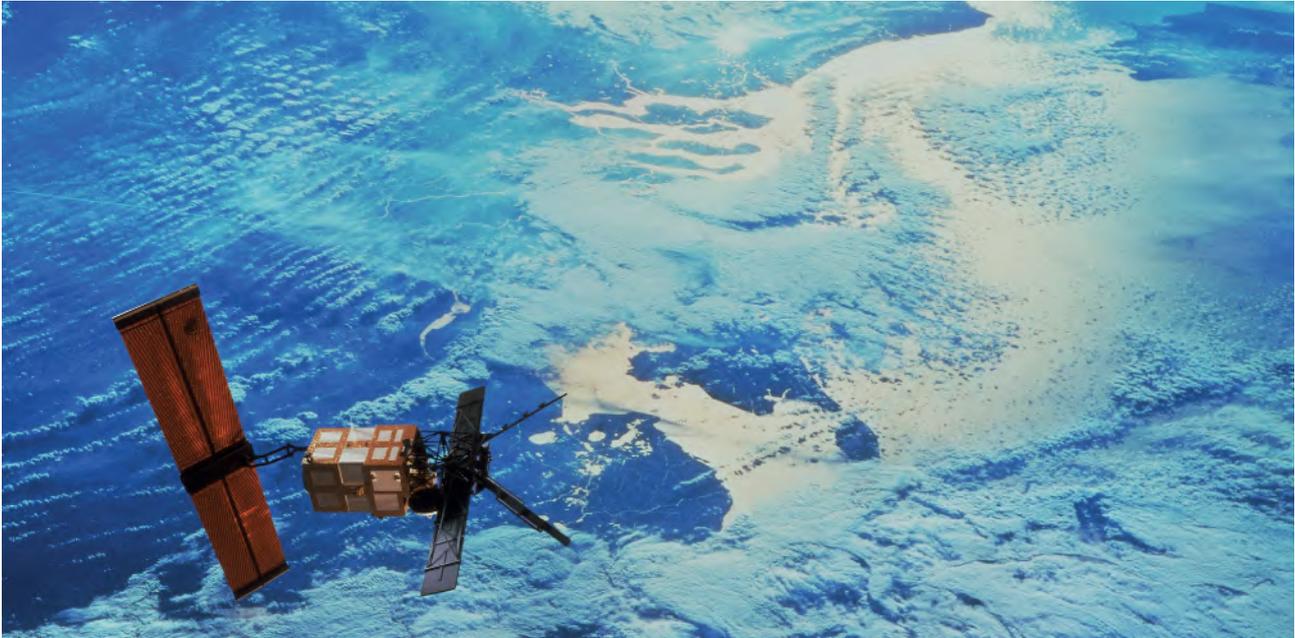
When DLR's Earth observation (EO) activities were reorganized in 1999, DFD was able to prevail with its proposal to bundle methodological and application-related remote sensing in two institutes. Thus, the Cluster for Applied Remote Sensing was founded in 2000, comprising the two institutes IMF and DFD. In 2010, the cluster was renamed the Earth Observation Center, EOC.

After reorganization, the newly founded sister institute IMF specialized in SAR and atmospheric spectrometry and received a third pillar with photogrammetry from the former Institute of Optoelectronics. DFD focused on the further development of the ground segment with national and international ground stations and a national data archive and expanded its competencies in the application areas of land surface dynamics, civil security and geohazards, atmosphere, and scientific visualization.

The research was supplemented by user services such as the World Data Center for Remote Sensing of the Atmosphere (WDC-RSAT) in 2001, the Center for Satellite Based Crisis Information (ZKI) in 2004, and a significant contribution to the DLR Research Center Maritime Security in Neustrelitz in 2012.

The achievements of this long-term development culminated in the successful SRTM, TerraSAR-X and TanDEM-X missions, as well as in important contributions to ESA/EU Copernicus missions such as Sentinel-5 Precursor (Sentinel-5P). Since 2000, DFD's task portfolio has proven to be very stable and at the same time flexible enough to take up new developments.

“Since 2000, DFD's task portfolio has proven to be very stable and at the same time flexible enough to take up new developments”



General Approach of the Institute

DFD links engineering expertise in handling data from EO satellite missions with application oriented scientific analysis and development. This unique combination is a key asset of the institute.

Three departments are more data-driven and are concerned with the acquisition, processing, archiving, and distribution of EO data and information products. They form DFD's payload ground segment and represent an independent component of DLR's system capability for autonomous planning and execution of innovative Earth observation missions.

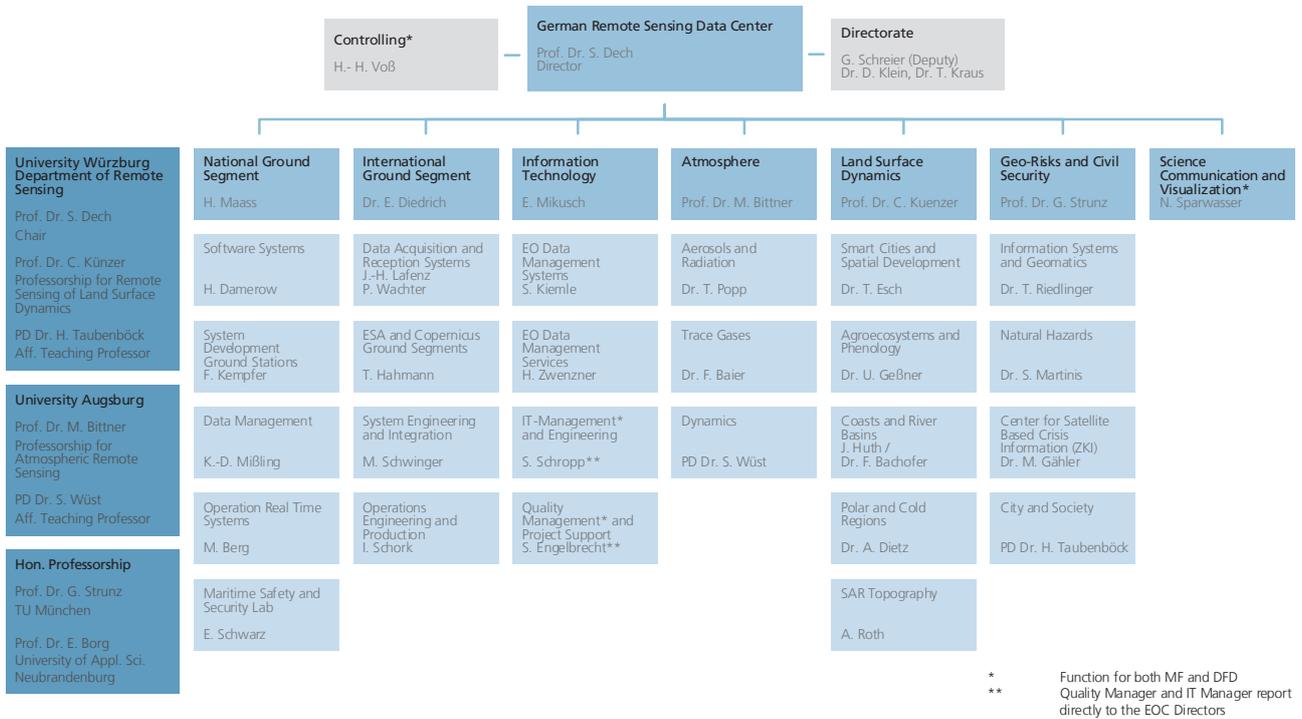
Three science departments are more content-driven. Based on satellite data they develop new high-level geoinformation layers for research on global and climate change, environment and ecosystems, georisks and health. This provides the framework for many applications in

municipal, state, and federal planning as well as for civil protection, many of which can also be used by the private sector. DFD thus plays an important bridging role in the Helmholtz Association. It has comprehensive remote sensing know-how in a wide range of applications and, at the same time, broad expertise in the geoscientific disciplines. This promotes close exchange with Helmholtz centers in the Earth and Environment research field and with many universities.

The combination of its competencies and technologies allows DFD to efficiently develop and prototype end-to-end system solutions. In addition, interdisciplinary skills make it possible to address challenges in information technology, such as global big data processing in private clouds. In this way, new technologies can be made directly usable for research at DLR. The goal is to exploit the potential of satellite-based remote sensing as an indispensable space technology. We want to establish it as an outstanding tool in all areas of research, for societal issues, and industrial applications.

European Remote Sensing satellite ERS-1
© ESA

Institute Orientation and Development



Organizational chart of DFD

DFD's profile:

- 256** DFD employees (85 women/171 men)
- 212** scientists/engineers (101 in PDGS; 111 in application research, 30 doctoral students)
- 10** employees in the EOC controlling dept.
- 45,6 million** EUR turnover 2020
- 24,8 million** EUR (**54%**) third-party funding 2020 after full costs
- 46%** basic funding, thereof **90%** from space program (in 2020)
- 82** peer-reviewed SCI publications per year (5-year average)

The wide range of topics, tasks, requirements, and the associated national and international networks represent a challenge. At the same time, it is the key to fully exploiting the possibilities of data engineering and scientific data analysis. This requires deep understanding on both sides to realize system solutions that ultimately benefit science as well as mission tasks and data engineering. Again, this is the central unique selling point of DFD.

DFD has seven departments with a total of 256 employees. The National Ground Segment (in Neustrelitz), International Ground Segment and Information Technology departments represent DFD's engineering competence related to the payload data ground segment.

The Atmosphere, Land Surface Dynamics and Geo-Risks and Civil Security departments predominantly represent DFD's research and application activities.

The Science Communication and Visualization department ensures the transfer of the achieved results to a broad public. In addition, EOC's central Controlling department handles all administrative functions with respect to human resources, finance, large-scale facility management and project controlling.

Payload Data Ground Segment

Whereas mission control, i.e. the maneuvering and housekeeping of satellites, is performed by DLR's German Space Operations Center (GSOC), Payload Data Ground Segment (PDGS) activities are carried out by DFD. The PDGS encompasses the reception, processing and further management of data gathered by satellite instruments. In addition, the PDGS is flexible enough to support GSOC in national and international satellite missions. For example, all DFD ground stations can also relay satellite command and control information, especially during the critical positioning of satellites in the launch and early orbit phase of a mission.

Historically, Payload Data Ground Segments for satellite missions were designed on a mission-specific basis. Therefore, recurrent functions such as processing and distribution could not be easily transferred to subsequent missions. It was DFD that advanced multi-mission-capable ground segment concepts as early as the 1990s. The institute's development project DIMS (Data and Information Management System) in partnership with Werum Software & Systems AG was a visible expression of this development. The proof of its performance attracted international attention, for example at NASA in the course of SRTM in 2000. ESA took up the concepts and later implemented them for the Sentinel missions. DFD was a requested partner, and DFD's own developments found their way into ESA's architecture.

The core functions of a PDGS have become considerably more complex than they were in the early 1990s. Elaborated processors convert the data after reception into various standardized data and information products. In addition, for special missions even more elaborate

processing steps can follow to generate e.g. the global digital elevation model from the TanDEM-X mission.

Processing raw data into products involves a large number of intermediate steps. These include geometric and radiometric calibration and correction for atmospheric effects or sensor irregularities, and require sophisticated data management to achieve intelligent interaction of large data caches, long-term archives, fast networks, and efficiently integrated processors. All steps must be flexibly orchestrated, controlled, and monitored at all times, including the tasks of the ground stations. The resulting data products are directly made available via portals or special hubs and additionally stored in long-term archives. This ensures that users or downstream services have fast and reliable access to the data at any time. Only the precise interaction of reception, processing and data access also enables near real-time services, e.g. for maritime security or disaster management tasks. Data security requirements and certain access restrictions, such as those established by the German Satellite Data Security Act (SatDSiG), add to the complexity of PDGS.

Such complex ground segment developments are decadal by nature. DFD solutions have been used for a large number of national missions such as SIR-C/X-SAR, TerraSAR-X, TanDEM-X, as well as DLR programmatic missions such as FireBIRD and DESIS. In the future, EnMAP, High Resolution Wide Swath (HRWS), and/or Tandem-L will also be supported. DFD's PDGS encompasses a worldwide ground station network with sites at Neustrelitz, Oberpfaffenhofen, GARS O'Higgins in Antarctica, and Inuvik in the Canadian Arctic. Those facilities and capabilities have been used to conduct developments and operational tasks for ESA missions such as ERS-1, ERS-2, Envisat, Sentinel-1, Sentinel-3, and Sentinel-5P.

“Only the precise interaction of reception, processing and data access enables near real-time services”

The combination of national developments and participation in European tasks has always been a driver for innovation.

In addition to ESA, also industry benefits from DFD's expertise in ground segment mission operations. European Space Imaging, for example, has been able to consolidate and even expand its commercial position in the market thanks to a long-standing partnership with DFD. Moreover, DFD cooperates with international (space) agencies such as USGS or KARI.

All satellite data received and processed by DFD are stored in a long-term archive. It was developed with programmatic funding and has effectively become the national remote sensing data archive,

though for political reasons still without a national mandate. The German Satellite Data Archive (D-SDA) contains the legacy of national and European Earth observation missions with DFD involvement and guarantees data access for future generations. It is an essential contribution to the documentation of terrestrial changes and to DLR's position in Earth observation.

DFD's payload data ground segment is an element of the national systems capability in Earth observation. Industry has usually neither an interest in non-commercial, long-term developments such as D-SDA nor the ambition to invest in mission control and complex PDGS facilities under national regime and ownership. However, this is required for highly complex mission scenarios, such as the planned HRWS multi-static SAR mission.



“Artificial intelligence methods will play an increasingly important role in the processing of global data sets”

Research and Applications Development

A second focus of DFD is research on remote sensing and its applications. In particular, we focus on changes in the Earth system due to global and climate change and its consequences for humans. This comprises land surface dynamics including the polar cryosphere, agroeco-systems, and urban agglomerations, as well as natural and anthropogenically induced changes in the atmosphere. As fundamental changes lead to higher risks for society, we also concentrate on geo-hazards, early warning and mitigation.

In this context, our aim is to build concrete applications for municipal, state, and federal users. In most cases, the topics are based on urgent societal challenges. They usually reflect DLR's programmatic priorities and those of third-party funding institutions. Mainly, our research is carried out as multi-year externally funded projects. The most important external funding sources are governmental agencies such as federal and state ministries, the EU or, in some cases, foundations. Projects are usually conducted not only with research institutions and universities, but also with companies. In this way, important developments and project results can be further evolved and permanently placed on the market.

In addition to content-related issues, we also address methodological topics. An important capability of DFD is analyzing large data sets, such as time series extending over several decades. The temporal signal, in addition to the spectral information, often provides the key to understanding dynamic processes. These usually take place on large regional or even global scales. Well-known examples for our global time series are information and value-adding products

on the atmosphere (trace gases and trace substances), on global urbanization, or on hydrology (water bodies and snow cover). These products are widely used by the international research community. New developments are, for example, global glacier and ice sheet dynamics.

Artificial intelligence (AI) methods will play an increasingly important role in the processing of global data sets. Machine learning and especially deep learning with the use of artificial neural networks have started a triumphant march in the information processing of remote sensing data. DFD scientists not only use the existing techniques, but also participate in the development of new methods in selected areas. These innovative approaches make it possible to incorporate outside auxiliary data in large quantities, such as from social media or Google Street View. For example, textual information from Twitter can be automatically searched for keywords in order to react more quickly after natural or man-made disasters. Ground-based pictures, meanwhile, can expand classification capabilities, for example, by using freely available facade imagery and remote sensing data to derive the functional use of buildings. The synoptic analysis of heterogeneous data sources with AI offers completely new remote sensing possibilities, which may include data collected directly from citizens (citizen science). Together with the enormous computing capacity available in cloud structures, the potential of remote sensing can be increased tremendously. DFD specifically fosters this development with its projects and initiatives.

DFD's research is not limited to sensors. In contrast to IMF, which develops very specific retrieval procedures for certain missions, DFD selects its input data with regard to the research question. This often involves a combination of remote sensing data and models. For example, DFD uses models to retrieve atmospheric constituents or to determine net primary production on the land surface in

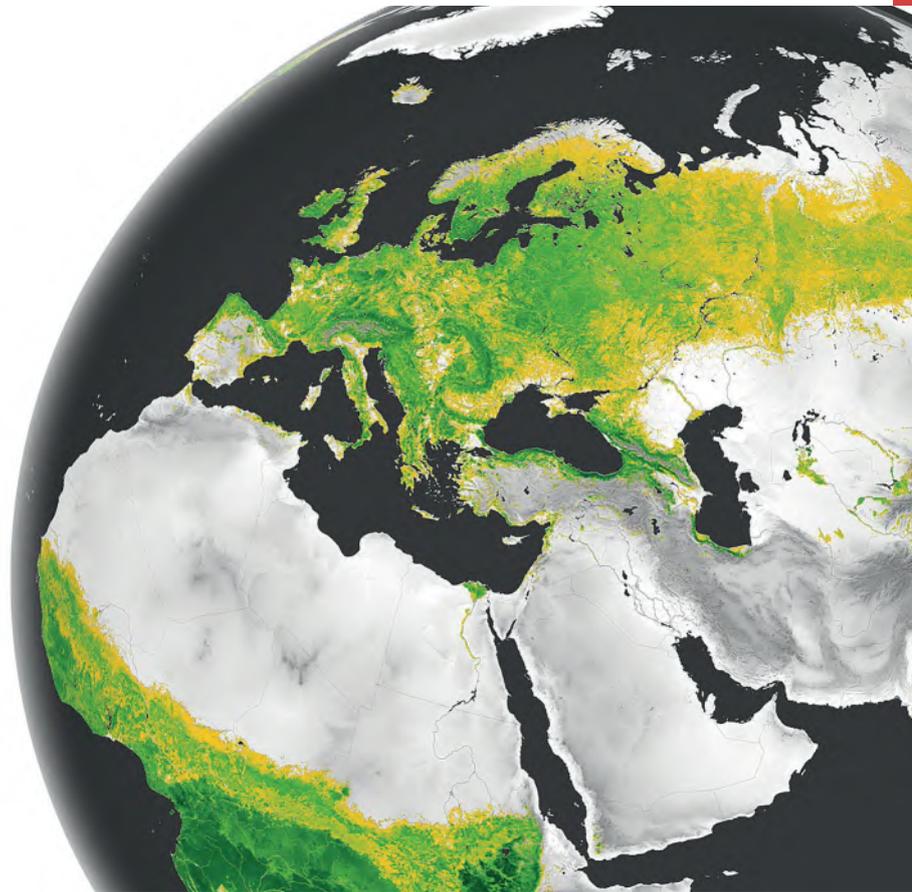
order to estimate carbon sequestration. Sensor-specific developments are carried out where they are part of DFD's mission involvement, e.g. in the area of SAR interferometric elevation model generation or for hyperspectral applications.

Scientific developments often end with the expiry of third-party-funded projects. To guarantee the sustainability of DFD's developments, one of our fundamental goals is to ensure that our products are also used by third parties in the long run. Geoinformation systems have proven to be particularly effective here. They provide user-friendly access to a wide variety of data sets with the possibility of visualizing and evaluating them. Hence DFD established an in-house project called UKIS (Umwelt- und Kriseninformationssysteme/Environmental and Crisis Information Systems), which provides an open-source software framework for GIS solutions. It offers generic modules which enable fast and efficient configuration of information systems for environmental and crisis applications. These are not restricted by commercial licenses and can be developed further. This not only guarantees that once-developed systems can remain in use in the long-term, but also that new projects benefit from earlier developments.

One of the decisive factors for DFD's evolution was the development of user services. The co-development of research and user services, such as the ZKI, allows us to transfer the results directly to the respective communities. Founded in 2004, the ZKI has since established remote sensing as an integral part of the German government's civil security tasks. In consequence, ZKI's standard operational duties were transferred to the Federal Agency for Cartography and Geodesy (BKG) in 2021. Since then, ZKI has taken over the exploration of new methods and approaches for satellite-based crisis management on behalf of the Federal Ministry of the Interior and Community (BMI).

In parallel to research at DFD, the departments benefit significantly from institutional collaboration with universities. Particularly notable are the collaborations with the University of Würzburg and the University of Augsburg. Since 2001, the director of DFD has held a Chair for Remote Sensing at the Institute of Geography and Geology in Würzburg. The associated group constantly comprises 20-30 PhD and Post-Doc scientists. In this framework, the international Master's study program EAGLE was established in 2016. Since then it has been a great success and allows direct access to young scientists from various nations, an immediate advantage in DFD's international project business. Complementary to DFD, the group in

Net Primary Productivity modelled using the Biosphere Energy Transfer Hydrology (BETHY/DLR) model



ZKI operations room for data analysis and mapping



Würzburg works on remote sensing applications for selected ecological topics in Africa and in the field of animal behavior. The latter is supported by intensive cooperation with the University's Biocenter and with the Max Planck Institute of Animal Behavior in Radolfzell. In addition to content-related work, methodological developments are being advanced, e.g. in the field of data cubes. In addition to the DFD director, the head of the DFD Land Surface Dynamics department holds a professorship in Würzburg. Another appointment in the area of global urbanization is close to finalization. Furthermore, the head of DFD's Atmosphere Department is professor of atmospheric remote sensing at the Institute of Physics at the University of Augsburg. The group complements DFD's research on atmospheric dynamics and environmental health risks. The exchange of staff between DFD and universities, e.g. as guest scientists, is an expression of intensive and fruitful professional cooperation.

In order to find new innovative topics and interdisciplinary applications for remote sensing, we also cooperate with DLR institutes from other disciplines, e.g. in the field of health or transportation research, to develop new products for future users such as insurance companies or the automotive industry.

This rather basic outline of DFD's research approach illustrates the importance of interdisciplinarity and networking. The professional background of our scientists and the extent of our networking with research, government agencies, and industry are correspondingly diverse. A combination of geoscientific, computer science, and remote sensing knowledge is essential for most topics in DFD today. The success of this approach is reflected in the number of peer-reviewed publications in ISI/Scopus-listed international journals.

Earth Observation Satellite Missions

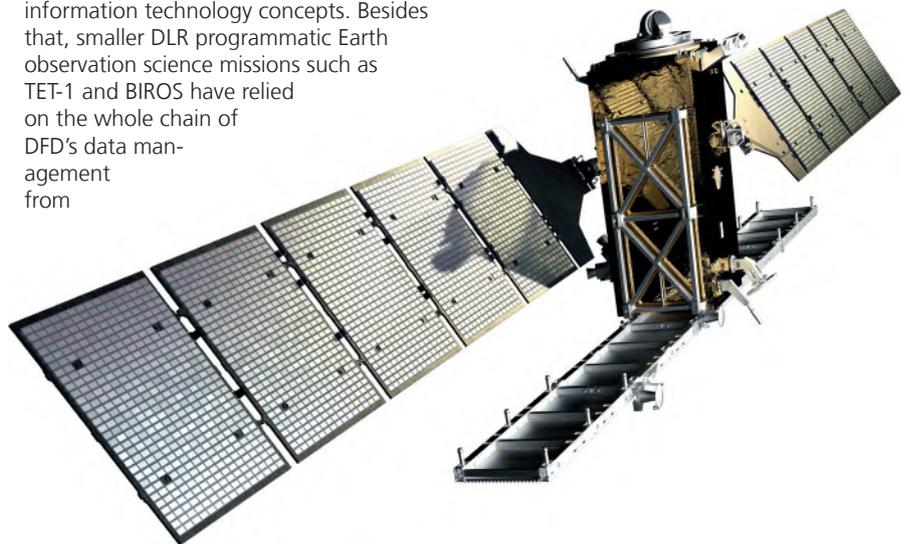
Earth observation satellite missions fuel many of DFD's innovations. Since the last report in 2013, significant advances in the quantity and quality of satellite missions have influenced the global setting and therewith the development of DFD.

The national missions TerraSAR-X and TanDEM-X were already launched in 2007 and 2010, respectively. However, the introduction of new SAR imaging modes and the creation of the first digital elevation model with consistent, high pole-to-pole quality took place in this reporting period. This demanded a high degree of flexibility and innovative approaches in the ground segment. DFD was able to implement the adaptations without interrupting its data and product services. The success of the WorldDEM was a milestone in the public-private partnership between DLR and its commercial partner Airbus.

The national SAR missions require the entire PDGS capabilities of DFD with its acquisition stations in Neustrelitz, GARS O'Higgins in Antarctica, and Inuvik in Canada. The latter, built as part of the TanDEM-X mission, was the nucleus of one of today's most important international station complexes near the Arctic Circle: the Inuvik Satellite Station Facility (ISSF). The entire management, processing, archiving, science coordination and distribution of the TerraSAR-X and TanDEM-X mission data was conceived, implemented, and operated by DFD. Our scientists and engineers deployed their wide experience and knowledge to implement an operational PDGS on time, within budget, and in many aspects far better than specified. They had to consider not only technical requirements, but also the needs of the industry partner and legislative requirements (e.g., the Satellite Data Security Act).

The next national X-band SAR mission is currently in preparation. In 2027, the HRWS mission is scheduled for launch. Furthermore, DLR has conceived Tandem-L. If realized, it would be the first bi-static L-band mission. The concept was proposed as a national large-scale research infrastructure for the German government and the Helmholtz Association. Both missions are planned with a significant contribution by DFD in providing the PDGS.

EnMAP is a demanding national hyperspectral mission, with a PDGS jointly conceived and implemented by DFD and IMF. Designed more than 10 years ago, the launch is now planned for 2022. The challenge is to respond to this long delay and adapt the systems to the latest information technology concepts. Besides that, smaller DLR programmatic Earth observation science missions such as TET-1 and BIROS have relied on the whole chain of DFD's data management from



European Copernicus Satellite Sentinel -1

acquisition, processing, data archiving, and distribution. For the ISS-based DESIS system a processing chain is also available as well as data archiving and access for scientific use at DLR. Both these missions can be regarded also as scientific precursors concerning IR-data or hyperspectral data.

“DFD often carries out data acquisition and management tasks in liaison with industrial partners who hold the commercial distribution license”

A significant milestone was the operational start of the Copernicus system of the European Union, implemented by ESA and EUMETSAT. By combining the financial and technical capabilities of the European Commission, ESA, EUMETSAT, and Member States, Copernicus is currently the world’s leading Earth observation program. Well into the 2030s it guarantees data and mission continuity. Although the administrative and technical framework conditions differed from previous missions, DFD was able to contribute its knowledge and experience to the Sentinel PDGS. Even after the reorientation of the Copernicus ground segment to a focus on commercial cloud systems, DFD has been tasked with its receiving stations and its expertise in processing, archiving, and distributing Copernicus satellite data.

By about 2025, the six High Priority Candidate Missions (HPCM) will add new observing technologies and parameters to the Sentinel fleet. Also, the next generation of Sentinels is already in preparation to provide continuity and further enhance the capabilities of the Copernicus system. DFD is involved in both and will primarily contribute its infrastructure and capabilities to the payload data ground segment.

In addition to striving for independence in space-based observation capabilities, Europe continues to rely on cooperation. The most important partner is the United States. For example, the recently launched Sentinel-6 satellite is a joint product of ESA, NASA, and NOAA. This cooperation has a long tradition, as the US has been operating a high-resolution optical satellite system, Landsat, since the 1970s. Today these data complement Sentinel-2 data and they have been of interest also to European users in the past. Hence, in the early 1980s ESA contracted DFD as national point of contact to archive and distribute Landsat data. Since 1997, DFD has carried out reception tasks with its receiving station in Neustrelitz, as well as with its tempo-

rary stations in Gabon and Mexico. DFD in Neustrelitz evolved to become one of the four selected global stations in 2015 to receive Landsat data in the USGS core ground segment. This long-standing excellent cooperation with USGS is to be extended to other topics in coming years. In this context, it is worth mentioning that DFD in Neustrelitz supports the newly established DLR Institute for Solar-Terrestrial Physics by regularly acquiring and near real-time processing satellite data from the ACE and DISCOVER missions in cooperation with NASA to obtain information on solar radiation and solar wind conditions.

DFD’s national ground segment in Neustrelitz also ensures the availability of data from other foreign national missions. Worth mentioning are the partnership with GAF AG in receiving EO mission data from the Indian space agency ISRO and the contract with the Korean agency KARI to receive data from the KOMPSAT mission.

DFD often carries out data acquisition and management tasks in liaison with industrial partners who hold the commercial distribution license. More and more, commercial partners are themselves acting as mission owners and operators.

In the U.S., demand for very high-resolution (VHR) optical data is primarily driven by US defense and security requirements. As a result, several US companies have consolidated into one large player, Maxar. Since 2003, DFD has been cooperating with the European licensee of these US VHR missions. For the Munich-based company European Space Imaging, DFD operates receiving and tasking stations in Oberpfaffenhofen. This collaboration began with the IKONOS mission, continues with WorldView, and will be extended in 2022 with the Maxar LEGION mission constellation. Most of the data over Europe from these constellations were received by DFD and timely processed and delivered.

Meanwhile, more and more companies and commercial EO constellations are entering the scene. Start-ups develop new capabilities and challenge existing industrial players. They use cubesats, miniaturization, off-the shelf-components, on-board intelligence, and cloud computing. Last but not least, they benefit from available venture capital. ICEYE and Capella, for instance, are offering operational services with their X-band SAR constellations. The German companies Ororatech and ConstellR are planning a constellation of thermal imaging satellites. DFD is in discussion with all these start-ups to cooperate in the ground segment and to jointly develop new applications.

EO Informatics and DLR-wide Interdepartmental Links

In addition to providing historical and current data from a wide range of sensors, especially from national missions and Copernicus, the PDGS supports our research departments with various in-house services through the D-SDA. The ground segment set up, for instance, computer systems similar to a private cloud for DFD's own research at an early stage. One of these systems is the so-called GeoFarm, which is also used for processing ESA/EU Sentinel-5P mission data. However, compared to the large commercial cloud providers with almost unlimited resources in terms of network, computing capacity, online mass storage, and data provision, these in-house solutions can only compete to a limited extent. This is why providers such as Google and Amazon have become very attractive to scientists, also at DFD. They offer powerful, easy-to-use processing systems like the Google Earth Engine



with fast connections to huge archives of USGS and Copernicus data. And they do it free of charge.

However, this very attractive offer leads to a quasi-monopoly and creates strong dependency. There is no guarantee that the services will be available in the long-term or free of charge. In addition, there are concerns about data and algorithm security as well as compliance with government regulations. Further disadvantages arise from the limited functionalities and proprietary operating systems of the commercial platforms. In the long run, this could not be a standard solution for DFD – and the whole DLR.

DFD has therefore initiated an alternative development called *terrabyte* that is to be implemented by 2022. This High Performance Data Analytics (HPDA) platform will enable applied Earth obser-

Infrastructure of the *terrabyte* project at the Leibniz Supercomputing Centre

vation at DLR – not only at DFD or EOC – to perform global big data analyses independently and in a secure manner. It is based on vast computing power and a large online cache at the Leibniz Supercomputing Centre (LRZ) of the Bavarian Academy of Sciences. The cache is connected to DFD's D-SDA via an up to 100 Gbit data link. DFD handles the availability of EO data in the online cache, including its interaction with D-SDA. Together with other DLR institutes, it develops on-boarding techniques that facilitate the transfer of scientific algorithms and their efficient use of the *terabyte* infrastructure at LRZ. LRZ is responsible for the system setup and long-term operation of all hardware and software components. The new infrastructure is available to both partners.

Through the *terabyte* collaboration, a new domain is currently emerging from initial in-house developments, which can best be described as EO Informatics. Scientists are working together with experts from computer science and engineering to develop modules, functions, and processes. Their goal is to enable scientists to upload their algorithms to the *terabyte* system and run them without significant effort.

This development was only possible due to the close interaction of PDGS and research departments and it shows the great benefit of joint evolution of ground segment engineering, informatics know-how, and applied remote sensing at DFD. In the future, *terabyte* is to be expanded into a universal data technology tool that can also be used for other DLR applications besides Earth observation.

In addition to this important long-term initiative, there has been a wide range of other successful interdepartmental activities in the reporting period, such as UKIS, TIMELINE, and IF-Bund. These developments are discussed explicitly in chapter 5 and will be covered also in chapters 3 and 4.

Science Communication and Visualization

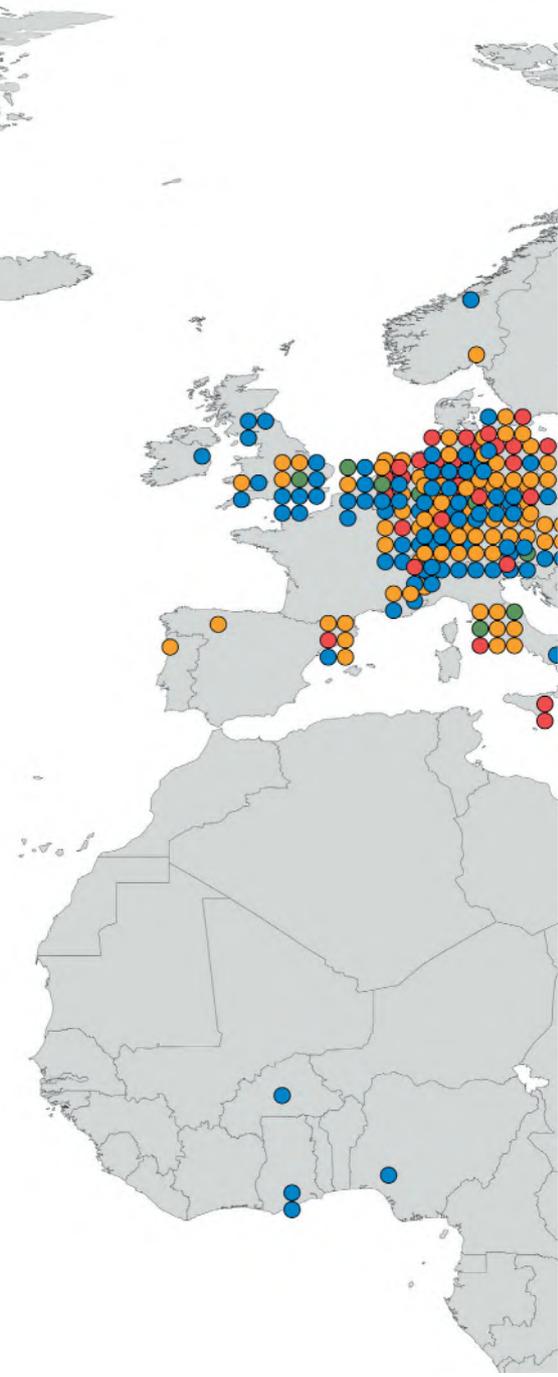
Today, visual communication has a great influence on which topics the public perceives. Visualizations attract attention and at the same time help scientists and non-experts to understand complex topics. For this reason, DFD began creating scientific animations for visual interpretation of long time series in the early 1990s.

From these beginnings, a separate department has evolved to focus on the visualization of scientific data and complex topics in order to communicate the capabilities of Earth observation to a broad audience.

The department combines scientific data processing with methodologies from the film and animation industries. The portfolio has grown with the needs of the scientific departments and external clients such as ESA, and now includes animations as well as cinematic project documentation, virtual reality applications, web development, and physical exhibits. It also creates exhibitions such as "World of Wonders" in the Oberhausen Gasometer. Among other exhibits there, a seemingly free-floating, oversized earth sculpture fed by 13 projectors with dynamic earth observation data conveyed DLR's mission and its technological capabilities to more than 1.3 million visitors. The department also manages EOC's extensive web presence.



3D-visualization of Annapurna taken from "m⁴ mountains – the fourth dimension": a DFD publication together with Reinhold Messner.



Framework and Collaboration

Political Framework and Programmatic Specifications

Although DLR is legally organized as a registered association, it is a purely governmental large-scale research institution with the main shareholders being the German federal government (90% of funding) and the federal states that host DLR facilities (10% funding). The Federal Ministry for Economic Affairs and Climate Action (BMWK) provides the majority of DLR's public funding and monitors the fulfillment of its duties. In addition to the statutory tasks, so-called "policy guidelines" form the framework for the priorities and direction of DLR.

The government budgets for DLR's research (basic funding), with its more than 55 institutes and facilities, are separated from the funding for the DLR Space Agency. DLR as a research center is part of the Helmholtz Association, but is the only center therein that does not report to the Federal Ministry of Education and Research (BMBF).

DLR research is conducted in its Aeronautics, Space, Transport and Energy divisions as well as in the two cross-section divisions, Security and Digitization. DFD is part of the "Earth Observation" topic within the Space program. DLR's basic funding is awarded for multi-year cycles (currently seven years) after comprehensive evaluation of Helmholtz programs. The last review of the Space program took place in 2018. All DLR funds are then allocated to the institutes in an annual DLR-internal planning process. The institutes can propose their own topics for funding, 5% of the research funds are awarded as Blue Sky Research, and another 5% for strategic topics specified by the DLR Executive Board.

DFD receives most of its basic funding (ca. 90%) from the DLR Space program. Smaller shares come from the Transportation, Security and Digitization programs. Financing is provided in the form of projects and undertakings ("Vorhaben"). While projects are narrowly defined in terms of content and time, "Vorhaben" are more flexible and long-term in nature. Thus, they lay the methodological, content-related and data-related foundations for successful applications for third-party funding. Since around 60% of all institute funding is regularly obtained through third-party projects, stable basic funding plays a major role at DFD. It is a decisive factor for our success in external competition.

DLR-internal and National Collaboration

To foster interdisciplinary cooperation between DLR institutes, DLR-internal projects involving several institutes have special priority. In addition to the very close cluster collaboration with IMF, DFD teams up in particular with the following institutes:

- Institute of Atmospheric Physics (missions, middle atmosphere research, air quality, climate)
- Institute for Solar-Terrestrial Physics (ground segment, processing, and data technique services)
- Microwaves and Radar Institute (SAR missions, science coordination, research SAR applications)
- Institute of Optical Sensor Systems (IR missions, ZKI applications)
- Institute of Data Science (citizen science, archive technologies)
- Institute of Transport Research (research, urban space theme)

- Institute of Aerospace Medicine (research, health topic)
- Institute for Software Technology (*terabyte* project/HPDA technologies)
- Space Operations and Astronaut Training Facility (ground segment for EO missions)
- Institute for Communications and Navigation (research, hazard management)
- Institute of Planetary Research (information systems)
- Institute of Engineering Thermodynamics (research, energy distribution)
- DLR facility Flight Experiments (training and validation campaigns)

the Technical University of Munich. This is also the case with consortium partners of the Virtual Institute Environmental Research Station Schneefernerhaus (UFS) of the Free State of Bavaria on the Zugspitze mountain.

Of particular importance on a national level is also the cooperation with downstream upper federal authorities in Germany, especially with the:

- Federal Agency for Cartography and Geodesy, BKG (ZKI, VLBI at GARS O'Higgins, and EO data use)
- Federal Environment Agency, UBA (ground environmental regulations at the GARS O'Higgins station)
- German Weather Service, DWD (WDC-RSAT and atmospheric products)

The most important professional cooperation on a national level is with Helmholtz centers in the Earth and Environment research field. Particularly close professional connections exist with groups at:

- Helmholtz Centre Potsdam, German Research Center for Geosciences, GFZ (georisk research and early warning systems)
- Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, AWI (cryosphere and cold regions, climate)
- Helmholtz Centre for Environmental Research, UFZ (terrestrial ecosystems, climate)
- Helmholtz Centre Munich, German Research Centre for Environmental Health, HZGM (air quality and health)

On the academic level, there are particularly close links to cooperating universities in Würzburg and Augsburg, as well as to

International Collaboration

Space research and Earth observation is international by nature. International satellite missions and EU and ESA-funded projects demand transnational partnerships. DFD scientists need to validate their results in the field on other continents. Finally, in the ground segment we rely on a worldwide network of receiving stations. In particular, DFD's polar stations in Antarctica (GARS O'Higgins) and in the Canadian Arctic (ISSF Inuvik) are subject to logistical and regulatory challenges. Operations must be ensured even under the most adverse conditions. All of this can only be done by establishing and maintaining long-standing, trustful collaboration with governmental bodies, agencies, organizations, universities and research institutions in other countries.

The expertise and infrastructure of the DFD ground segment has been frequently requested by international partner agencies. For example, data reception and archiving for the Landsat, MODIS, and DSCOVR missions initiated fur-

“All of this can only be done by establishing and maintaining long-standing, trustful collaboration”

Subset of DFD's map on worldwide cooperation partners (blue: universities, orange: companies, red: national agencies, green: international agencies)

ther collaboration with USGS, NASA, and NOAA. Cooperation in the PDGS was soon extended to other partners, including those from the now increasingly commercial environment. Besides the established global players (e.g. KSAT, SSC, ATOS), DFD also cooperates with young medium-sized companies (e.g. EOX, Sinergise).

A comparable network has also grown up within the framework of European research programs and ESA. Within national and European-funded projects, DFD scientists are working in international teams applying the latest Earth observation technologies to detect and map environmental and societal change at global hot spots. Personal contacts with experts are of great value here and help to quickly activate this network of academic, institutional, and commercial partners for future projects.

Naturally, DFD is looking for European and global partners with a similar set-up and mission statement in civil Earth observation. Some of these new partners explicitly refer to DFD as a role-model as to tasks and structure for their own development. DFD works with similar centers in Bozen (Eurac Research) and Vienna (EODC), and supports the development of new EO centers in Cyprus, South America and elsewhere.

Furthermore, DFD is represented in international science committees (e.g. GEO) and standardization bodies (e.g. CEOS, OGC). Its scientists are involved in the technology reviews of tendering agencies, in the design of new European EO missions, and in the definition of data information standards. This enables DFD to incorporate its developments into international standards. In addition, DFD is not only active in international scientific bodies, but also actively contributes its data and infrastructure to international networks, such as the International Charter on Space and Major Disasters.

Collaboration with Industry and Technology Transfer

As already mentioned, industrial partners play a crucial role for DFD. Besides international partners like Kongsberg Satellite Services (KSAT) or the Swedish Space Corporation (SSC), extensive cooperation with German companies covers the joint realization of EO missions and the development of applications for the commercial market. In these collaborations DFD's goal is always to contribute with innovative technologies and solutions. Industrial partners take care of the further commercialization and marketing of these developments. The best example here is DIMS, which was developed jointly with Werum Software & Systems AG and is now being adapted and commercialized. Likewise, developments such as the processing suite for maritime awareness using SAR data has been licensed to Airbus.

The most important partners are:

- Airbus Space and Defense and Airbus DS Geo GmbH, Friedrichshafen (ground segment services for TerraSAR-X and TanDEM-X, layout for future mission proposals, science coordination, product development SAR, maritime applications)
- GAF AG, Munich and Neustrelitz (Copernicus services, ground segment services for Indian satellites under GAF license)
- European Space Imaging GmbH, Munich (ground segment services for commercial very-high resolution US satellites under European Space Imaging license)
- Werum Software & Systems AG, Lüneburg (technology and marketing partner in developing DIMS as a ground segment management tool)

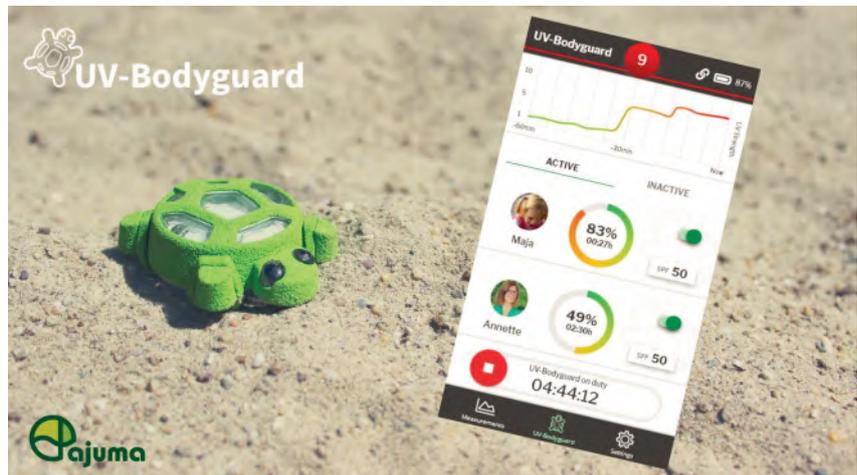
Page 28: With currently 256 employees DFD is one of the largest DLR institutes. Its staff is highly international with colleagues coming from more than 30 different nations.

Page 29: the extended management circle of DFD

DLR is also encouraging spin-offs. Through its participation in the European Copernicus Masters Contest, DFD helps entrepreneurs all over Europe to make their business ideas a reality. The most recent example is “ajuma”, a spin-off of DFD employees who have developed an intelligent wearable that is now available in pharmacies. It uses EO data to provide early warning of high UV radiation exposure.

DFD partly relies on open source to accelerate developments and thus also contributes to technology transfer. Moreover, most of the data is free and open, meaning available free of charge to everyone. With easy access to data and products via D-SDA and our Geoservice, DFD supports the development of applications. To create specific solutions, DFD is partnering with industry, such as in the case of the first national Copernicus data access portal, CODE-DE, and one of the Copernicus Data and Information Access Systems, MUNDI-DIAS.

The transfer of innovation and technology is not only limited to industrial partners. Governmental agencies and international organizations also profit from EO applications developed by DFD. The German Corporation for International Cooperation (GIZ), for example, established a framework agreement with DLR which led to closer cooperation with DFD. Additionally, international organizations such as the World Bank, the World Economic Forum, and others are interested in specific DFD innovations. The most prominent example, however, is the transfer of ZKI's standard procedures to the BKG, as already mentioned. Whilst DFD is still supporting the new BKG entity “Satellitengestützter Krisen- und Lagedienst”, the BMI created a framework agreement with DFD to ensure that all federal ministries continue to benefit from EO developments.

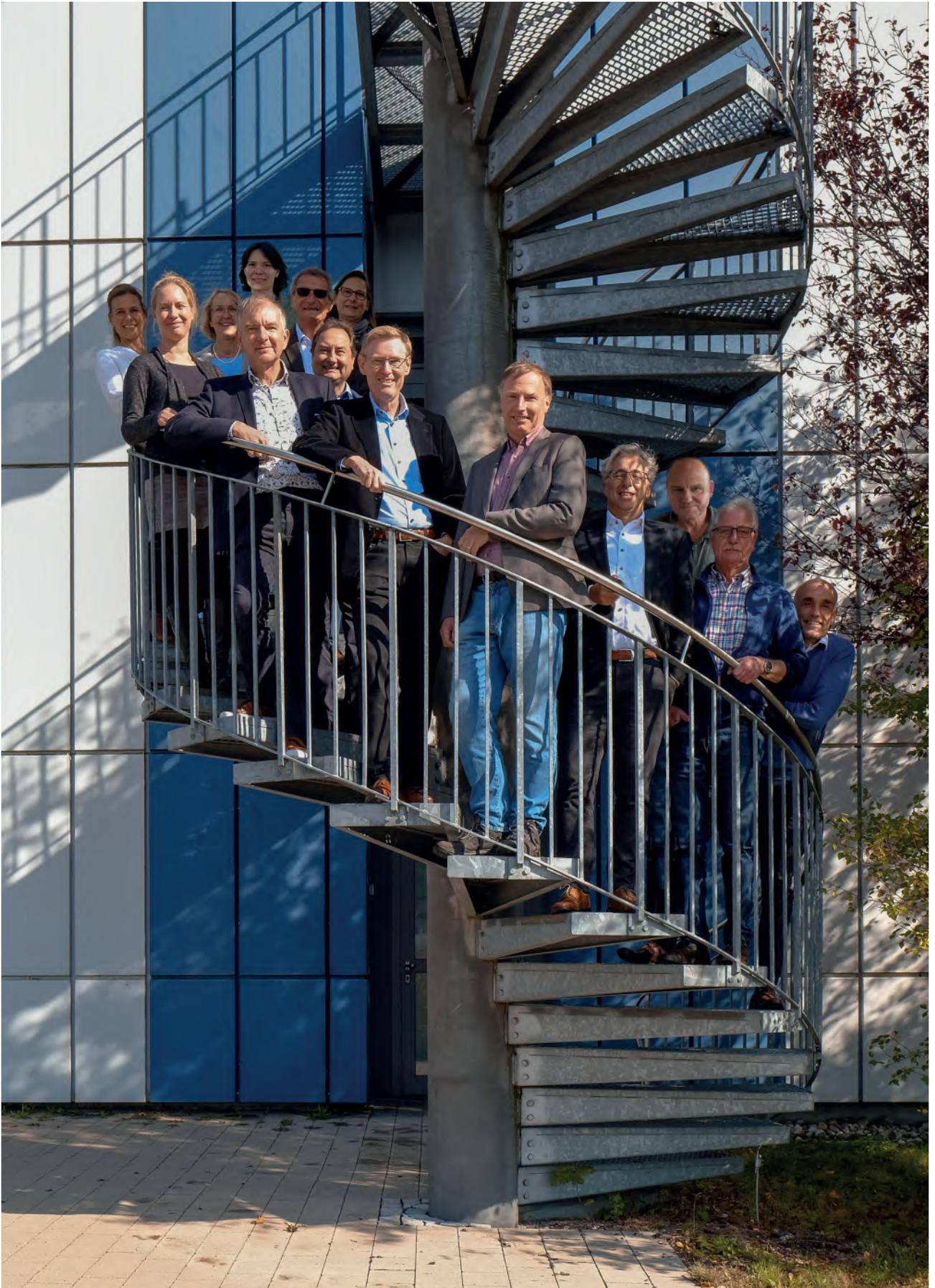


ajuma GmbH, a DFD spin-off, developed a UV Bodyguard that warns users when their individual healthy dose of sunlight has been reached.



The DFD scientist and his partner were able to raise venture capital for their start-up ajuma on a well-known television show © TVNOW/Stefan Gregorowius





Payload Data Ground Segment

Payload Data Ground Segment

“Data acquisition is one of the primary tasks of the PDGS, guaranteeing independent and fast access to the original information”

Three departments, National Ground Segment, International Ground Segment and Information Technology, form DFD's Payload Data Ground Segment (PDGS). Together they represent an independent component of DLR's systems capability for autonomous planning and execution of innovative Earth observation (EO) missions and for supporting international as well as scientific and industrial partners with national capabilities. The departments develop and operate the acquisition, processing, near real-time (NRT) services, and management of data gathered by satellite instruments. Driven by Earth observation data management, IT systems, and systems engineering, the departments' capabilities encompass new IT concepts, such as cloud-centric processing and virtualization, and therefore also form the technological backbone serving DFD's and EOC's science departments and establishing DFD as a key international player in the era of big data in Earth observation.

National Ground Segment in Neustrelitz

Orientation of the Department

Data acquisition is one of the primary tasks of the PDGS, guaranteeing independent and fast access to the original information detected by satellite sensors. The two DFD ground segment departments have large antenna systems for satellite data reception that are designed, erected, maintained and ultimately operated within the framework of a wide variety of Earth observation missions. The received payload data are subsequently transferred into various mission-specific

processing systems for conversion into products of different information-content levels. For this purpose, comprehensive engineering tasks have to be performed.

Since the reunification of Germany and the integration of the former Remote Sensing Station Neustrelitz into DFD in 1990, the National Ground Segment department in Neustrelitz has been responsible for high-rate data reception and near real-time data provision with an almost complete European visibility circle. The Neustrelitz location has been continuously upgraded with new antenna systems, IT technologies and building infrastructure. The National Ground Segment in Neustrelitz is complemented by the International Ground Segment department in Oberpfaffenhofen, which specifically operates DFD's near-polar stations serving global mission scenarios. The payload ground segment of both departments and developments in the information technology domain guarantee the continued acquisition of world-class knowledge and engineering in the PDGS and, moreover, independent access to critical national EO missions for Germany. Joint developments in the fields of data reception, data processing, archiving and networking in all three PDGS departments at DFD are continuously optimized with the goal of maximum effectiveness and minimum overlap of responsibilities.

The multi-antenna station set-up at Neustrelitz requires specific capabilities regarding the engineering, integration, and operation of hardware and systems. These are driven by a multi-mission scenario where besides a large number of Earth observation satellites also small explorer missions are supported. A wide variety of mission-specific requirements concerning data provision, formats and interfaces need to be met, resulting in continuous adaption and development of hardware and software systems.



One strategic focus of the department is on the development of NRT capabilities in the delivery of remote sensing information products. Very fast access to critical satellite-based information within minutes after sensing has become an increasing demand from institutional, science and commercial users in recent years. We have developed and optimized systems to meet these challenging timeliness requirements, and later developed support systems for data evaluation using approaches such as artificial intelligence. Having gained initial experience in the department's contributions to DLR's Maritime Safety and Security Lab team, the development of overall systems competence with specialization in real-time services runs through all of the department's teams. These include the development and finally the operation of data acquisition services, processing suites, and information system services on a 24h/365d basis.

The high level of latest-technology equipment and systems in Neustrelitz, the technical expertise, and the high reliability of the services provided have led to increased networking with

international partners in recent years. Examples of partners in successful long-term cooperation include ESA, EMSA, USGS, JPL, ISRO, KARI, GAF, and Airbus. These collaborations led to significant insights into international systems and corresponding technologies. Our subsequent developments and the support of our partners' EO missions have also triggered investments in the antenna segment to ensure data reception capability. These include investments in two innovative Tri-band (S-, X-, Ka-band) antenna systems, expanding the data acquisition capabilities also into Ka-band with higher data rates for current and future satellite missions.

DFD also supports the newly founded DLR Institute for Solar-Terrestrial Physics located in Neustrelitz in receiving space-weather data from US satellites. Data reception support for the CHAMP and GRACE science satellite missions, now continued with GRACE-FO, are the grounds for the long-standing partnership with the German Research Center for Geosciences (GFZ) in Potsdam. Furthermore, DFD and GFZ jointly operate the DEMMIN Earth observation

DFD's antenna array in Neustrelitz with Tri-band-1 antenna in the foreground



Tri-band-2 antenna in Neustrelitz

test site and contribute science data to the TERENO initiative of the Helmholtz Centre for Environmental Research (UFZ).

The structure of the department basically follows a logical path from data reception to processing, archiving, and provision of data. This results in five teams responsible for the necessary developments, implementation, and operations, namely ground station systems development, software systems development, data management, real-time systems operations, and a specific team for the Maritime Safety and Security Lab. All teams cooperate closely in technological development and in meeting mission-specific requirements and project demands. These start with the system design, continue with implementation, and end with the assurance of operational reliability.

Ground Stations Systems Development

Driven by new development projects and EO missions, we have continuously extended our capabilities and ground station infrastructure, also backed up by DLR and third-party investments. Meanwhile, our ground station facility in Neustrelitz consist of numerous components including six antenna systems (with parabolic dish diameters of 2 x 11m, 3 x 7.2m and 1 x 6.3 m), different baseband systems (13 CORTEX, 4 TTC support systems), eight front-end processing (FEP) systems, as well as corresponding back-end and infrastructure systems.

The Ground Station Systems Development team is responsible for these technical components, including high frequency signal acquisition, processing systems, and complex interfaces and links to applications. The goals are to develop the satellite ground station systems for the highest data rate reception, fastest data delivery and highest reliability in operations, in order to participate in EO projects and missions. These activities require broad knowledge in system engineering, high frequency technology, measurement, and test procedures. We investigate antenna designs and modern communication technologies, including optical data transmission, to meet the requirements of future missions and to evaluate new technical concepts. To maintain our internationally accepted engineering expertise and to guarantee high-quality operational data reception, we need to continuously develop our stations.

A major milestone on the way to higher downlink data rates was the ground station preparation for new Ka-band downlink technologies. This was realized with a new Tri-band-I antenna established in 2015/2016 with the related capabilities in all frequencies based in one feed. In order to accommodate the new antenna, the existing X-band antenna system X1

was relocated to the roof of a new building, a major engineering and logistical achievement accomplished in 2014.

The know-how of the team allows negotiations on equal terms with the leading manufacturers of antenna components. Thus, our specifications for the new Tri-band-I antenna could be elaborated, resulting in a unique Ka-band technology installation assuring in an optimal way our preparedness for this frequency domain while also responding to the needs of multi-mission operation. The antenna was inaugurated in May 2016 - a milestone of intensive and successful cooperation with VERTEX as the selected prime contractor for the antenna.

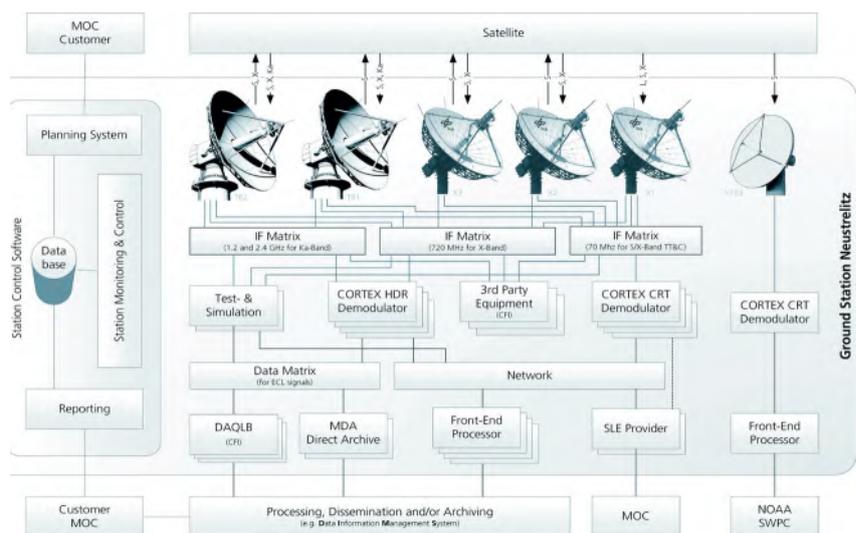
The block diagram of our multi-mission station shows the complexity of the entire station. The station concept with a main structure of antennas, intermediate frequency matrixes, demodulators, data matrixes, and FEP was developed and implemented to a significant extent by the team.

We have developed and implemented a matrix approach which enables us to flexibly combine receiving components for different missions in a chain from the antenna, via the demodulator to the in-house-developed FEP or the commercial direct archive system DAS. It guarantees flexible and redundant configuration for different missions. In the matrix, the antenna systems are connected via fiber links to the IF-matrixes. The demodulator with a mission specific set-up for the transmission parameters in up-link and down-link plays a key role in the configuration. Experience showed the necessity for redundant demodulators with corresponding mission configurations and eventually licenses for high data rate missions. In cases of highest reliability requirements, the parallel data acquisition of sun-synchronized EO satellites with up to four antennas simultaneously requires the use of nearly all the equipment, including backup components.

Measurement devices and test equipment are elementary components in station operations. For error analyzing and troubleshooting we need to verify the link between satellite and ground and have to check our own ground equipment to detect the reason for an eventual communication failure. Our test equipment includes a 19 sqm radio frequency test and clean room as part of the technical facilities in our building.

Especially in the preparation of satellite missions, our test and simulation functionalities are important capabilities. To this end, the team tested the RF-compatibility of the EnMAP satellite with the acquisition loop by using the Neustrelitz antenna systems and manufacturer-supplied original satellite components in our clean room.

Block diagram of the ground station in Neustrelitz



Software Systems Development

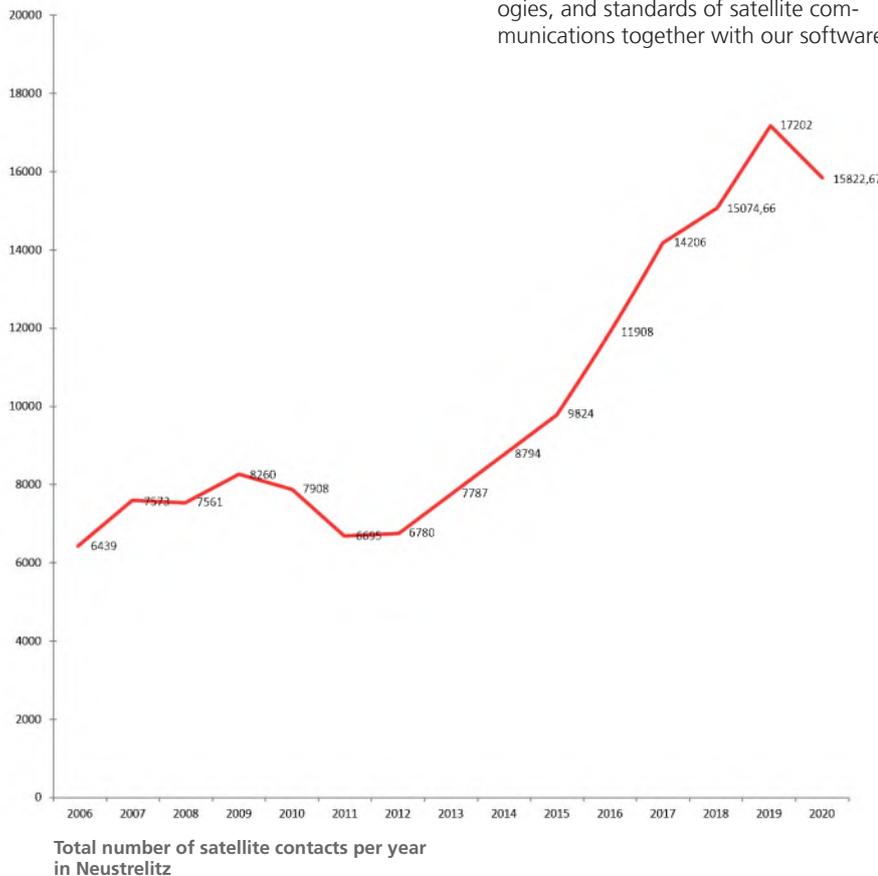
All station components mentioned in the previous chapter, the interfaces, data flows, and operational procedures of the entire Neustrelitz data acquisition site require a complex system of station control and monitoring software. In contrast to control of the remote polar stations of our DFD partner department in Oberpfaffenhofen, the requirement here is to flexibly configure a complex multi-systems installation at one site. For this purpose and in the absence of a customizable commercial solution, the Software Systems Development team designed and developed a modular, flexible software system. On the one hand, the system reflects our high degree of knowledge of the processes, technologies, and standards of satellite communications together with our software

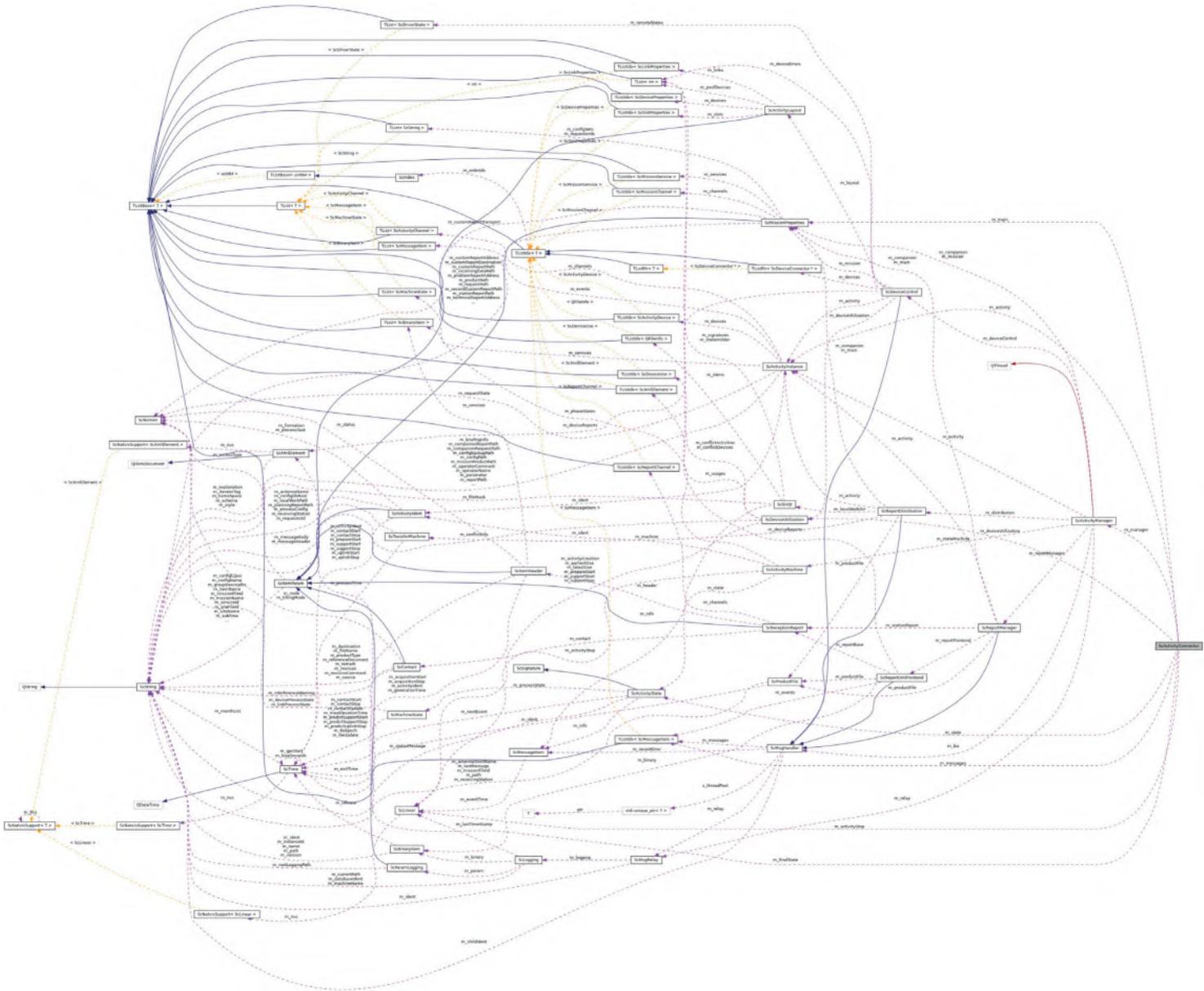
development skills. On the other hand, it enables the automatic and effective use of the Neustrelitz multi-systems approach, improves the ground station operations, and increases our expertise.

The functionalities of the Neustrelitz station control and monitoring software include integrating the commercial off-the-shelf and self-developed devices within the system matrix as well as configuring related interfaces to fit exactly our specific setting in the framework of a multi-mission, multi-antenna station concept. Key functionalities of the software are the simulation of workflows prior to data acquisition and subsequently the realization of workflows, monitoring of data acquisition, validation of telemetry data, uplink support, voice loop, error detection, and finally generating reports. The system now allows dynamic configuration of all our acquisition chains within the multi-antenna matrix to establish redundant capabilities with distributed automation. Additionally, it provides to engineers and operators flexible support in the form of an assistance system.

Finally, the highly modularized control and monitoring system is able to select required information directly from the incoming data stream and forms a key element of the department for supporting NRT applications for different missions.

For NRT applications, it is essential to access the payload data as soon as possible, i. e. immediately after data reception and before product generation. This was amongst the reasons for developing our own FEP. Here again, we were able to develop a solution optimized and flexibly configurable for our needs, independent of commercial license policies and with the additional advantage of increasing our knowledge in this domain. Our FEP implements a large variety of functions required for different EO missions. We started FEP development for the small national explorer missions CHAMP, GRACE, BIRD, and GRACE-FO to analyze





Context diagram of a station control application module

and process the incoming low-rate data stream without data loss. Understanding the data formats of the Consultative Committee for Space Data Systems and the internal data structure of our missions' payload data resulted in the current FEP hardware and software solution. FEP allows us to work with the content of the data stream immediately after synchronization, and supports native raw data formats such as CADU (Channel Access Data Units) or ISP (Instrument Source Packets). One important functionality is online data quality verification, including the reconstruction of missed instrument source packets and real-time quicklook functionalities for optical missions like the Landsat series.

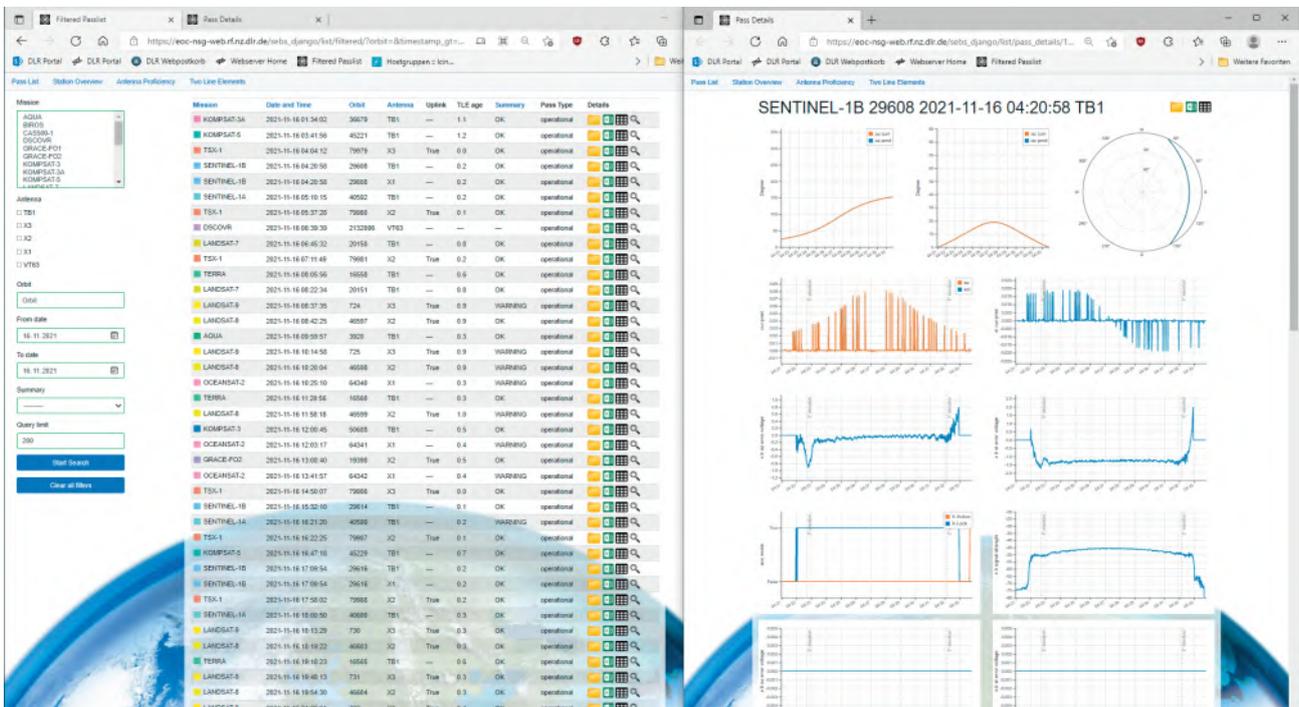
We updated the FEP successively for high data rate missions, e.g. Landsat-7, Landsat-8, and Landsat-9, TerraSAR-X, TanDEM-X, Sentinel-1, and Sentinel-2. Work is progressing on new functionalities to meet future requirements for even

higher data rates up to 10 Gbit/s. The FEP has been integrated into the TerraSAR-X/ TanDEM-X ground station operated by Kongsberg Satellite Services (KSAT) in Svalbard, into the DFD station in Inuvik for Sentinel-5P, and into Copernicus Sentinel data acquisition in Neustrelitz under ESA contract - three examples for its reliable operation.

Data Management

A Data Management team is responsible for developing and implementing the environment for processing, archiving, and data distribution. In coordination with the Information Technology department in Oberpfaffenhofen, this includes all aspects of operations and maintenance of the robotic archive at Neustrelitz as well as the Data and Information Management System (DIMS) as the current data management backbone of DFD. Collaborating with DFD's International Ground

Web tool for the evaluation of reception passages



Segment department, the team currently focuses its activities on developing a new framework for a processing orchestration suite in order to operate also in a distributed processing environments. We developed the processing environment for the DESIS and EnMAP missions, which has successfully passed all subsystem and end-to-end tests.

In addition to satellite data, we also manage other data types, like meteorological and in-situ data from our DEMMIN test site. As part of a large Helmholtz observation network, we maintain the DLR DEMMIN infrastructure as an EO calibration site. The site consists of weather stations, corner reflectors, lysimeters and mobile spectrometers. These instruments are used in campaigns to provide in-situ measurements especially for agricultural EO products, e.g. for the AgriSense and WETSCAPES projects in cooperation with GFZ and the DFD Land Surface Dynamics department.

DLR in Neustrelitz has long experience in ionospheric research measurements. This work has been conducted by a team of the DLR institute of Communication and Navigation in Neustrelitz, and led to the foundation of a new DLR institute in Neustrelitz, the Institute for Solar-Terrestrial Physics. Our DFD department in Neustrelitz supports these activities with data reception from the solar observation satellites ACE and DSCOVR, which measure solar activity at the L1 Lagrange point. Additionally, we integrate scientific algorithms into operational environments for space weather applications and provide products over web portals. The fruitful cooperation of both groups led to the establishment of an ESA Expert Service Center for Ionospheric Weather. Primed by colleagues from the new DLR institute, we collaborate on several projects, e.g. AFFECTS, ESPAS, RHEA, SSA-SWE and PECASUS. The World Meteorological Organization has audited the European consortium PECASUS for providing information on space weather to the International Civil

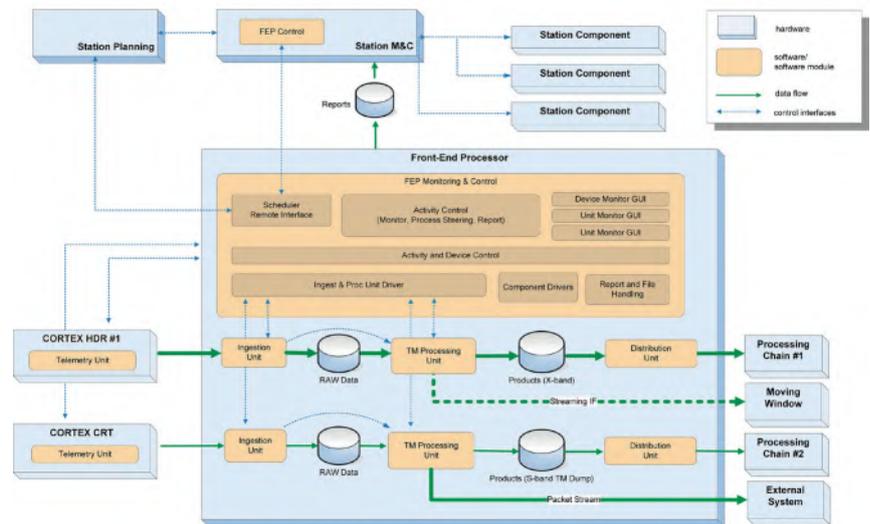


Diagram of the Front End Processing module, which is responsible for real-time processing of the received data.

Aviation Organization, with the potential to improve communication, navigation, and the health of passengers and crews.

Furthermore, we acquired and managed several national and international projects, e.g. DWH, RICOPA, TechTIDE, and DSCOVR in collaboration with ESA, the EU, JPL, and national research organizations.

Real-Time Systems Operations

The operational availability of hardware, software, and reliable services of the department's real-time systems is guaranteed by a dedicated team. Supported by colleagues from other teams, it operates on a 24h/365d basis and ensures a reliable data acquisition and command uplink for a growing number of remote sensing and small scientific satellites. At the same time the team is also responsible for various processing systems – including NRT applications for space weather and maritime security.

Partnering with European Space Imaging in a demanding European maritime surveillance project, we have been delivering time-critical information on a daily basis

for several years as a reliable provider for the European Maritime Safety Agency (EMSA).

The complexity of the multitude of our sophisticated systems requires regular theoretical and practical training of staff and close communication with the systems engineers of other teams in order to discuss operational requirements, desired functionality, and high efficiency to achieve robust systems. Besides providing high-quality operational service, we are involved in the ongoing development of the ground station. Background knowledge about systems and processes and direct feedback concerning the handling and functionality of station control software represents valuable input for the developers and engineers in the other teams. Thanks to a high level of systems automation, the extensive use of our own station control and monitoring software, and front-end processor software offering a uniform, abstracted system view, we managed with the minimum of only one operator at a time to achieve operational reliability exceeding 99% while supporting the acquisition of up to 24 different satellite missions, many of them with a command uplink as well.

Besides operating, for instance, the Radarsat-2 regional ground station, we operate the KARI overseas ground station terminal for the acquisition of Kompsat-3, Kompsat-3a and Kompsat-5 data while also offering the possibility of command uplinks.

Objectives of the team not only consist of the acquisition and uplink of satellite data, including quality control, error assessment and customer specific reporting, but also operating, monitoring, managing and error handling of currently 26 processing systems to ensure the generation and delivery of higher level data products. This also includes quality control and project-specific reporting.

To be able to monitor such a high number of processing systems, to check conditions, to apply corrections to the data for a number of error situations in order to make them processable, and to check and be able to assess quality, various software tools have been developed by the team over the past years in order to improve functionality, reliability and quality.

The team also operates the NRT-service for the International Civil Aviation Organization mentioned above. It ensures daily delivery of products, such as Total Electron Content over Europe and globally.

Maritime Safety and Security Lab

Safe maritime transport routes, efficient and safe shipping, and an unpolluted marine environment are important societal needs and a research topic for maritime safety and security. Maritime security research at DLR is a cross-cutting topic that addresses various aspects of the aerospace and transport programs with direct relevance to civil maritime security issues. The Maritime Safety and Security Research Cluster consists of four research locations (named Maritime Safety and Security Labs), located in Braunschweig, Bremen, Neustrelitz and Oberpfaffenhofen. In addition to both EOC institutes, five other DLR institutes are involved in the research network. The Maritime Safety and Security Lab Neustrelitz, established in 2014 as a virtual research lab, combines expertise in the areas of real-time satellite remote sensing and maritime traffic engineering.

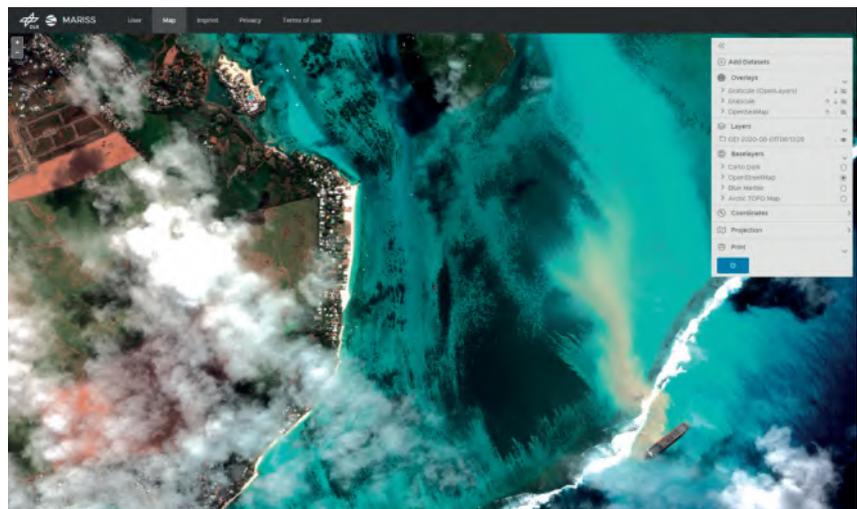
Our activities concern the development of EO based analysis methods to optimize processing chains and workflows in order to deliver information as fast as possible (NRT) and to develop prototype information and visualization systems in cooperation with public authorities. Some of our technical developments are also licensed to commercial partners.

A major part of our work is to develop EO-based analysis methods and NRT information systems to support national and European authorities for navigating ships safely through ice-covered waters and to support them in combating illegal activities like hazardous materials dumping, illegal fishing, and piracy. While the scientific research at the Bremen research lab (of the EOC Institute Remote Sensing Technologies) focuses on radar data analysis, our scientific work focuses on deriving information products from high-resolution and very high-resolution optical data. The developed systems work without operator interaction in an automated way and fuse the EO data with additional data, e.g. from a vessel's Automatic Identification System (AIS), to investigate navigation irregularities or detect oil spills. Today we increasingly use artificial intelligence methods in addition to algorithms based on physical models to support or improve our analysis. Artificial intelligence methods help us to analyze incoming satellite data according to selected features and characteristics.

To enhance NRT analysis capabilities we also investigate hardware solutions, e.g. using GPUs for dedicated processing. The methodological developments and system capabilities are tested, validated, and extended in projects and campaigns with scientific, governmental, and industrial users. A prominent example is an ongoing European Horizon 2020 project which is intended to enable our Cyprian partners to deploy maritime security systems in the Eastern Mediterranean.

The national EO-based Maritime Surveillance System (EO-MARISS) development project constitutes our information technology basis for applications-oriented research. It involves the entire processing chain, including image data processing, object detection, identification, and classification of hazardous material and sea ice. EO-MARISS has also driven the final product development, as well as the development of information technology system components for real-time pro-

cessing, visualization and dissemination of EO data. We used the DFD in-house development UKIS (Environmental and Crisis Information Systems) to build a web based client for end users.



Besides mission data acquired directly by DFD (Landsat-8, Landsat-9, Sentinel-1), we also use Sentinel-2, WorldView1-3 or GeoEye-1, and Deimos-2 data, which allows us to extract information relevant to maritime security directly at the ground station in NRT. One example is our contractual partnership with European Space Imaging, a leading supplier of very-high resolution satellite imagery. In an EMSA project, European Space Imaging is acquiring on a daily basis high-resolution (0.5 m) data supported by DFD's International Ground Segment department in Oberpfaffenhofen. In partnership with European Space Imaging, we developed the processing chain that transports the data acquired in Oberpfaffenhofen via fast network to Neustrelitz and processes image and value-added-analysis products at 0.5 m resolution. These products are delivered to EMSA within 30 minutes and 50 minutes after sensing, respectively.

Grounded freighter MV Wakashio (lower right) causing oil spill off the southeast coast of Mauritius © 2020 European Space Imaging / Maxar Technologies

One project challenge was to develop the image processing software responsible for atmospheric correction, orthorectification and mosaicking (in cases of multi-strip acquisition) to adhere to the given delivery timelines. Another challenge was to develop a preselection vessel-detection workflow for the MAXAR VHR optical satellite images based on a Convolutional

like cyanobacteria, which is expected to increase as a result of climate change, will be detected and classified more precisely than before, through use of the large number of hyperspectral data channels. This opens up new possibilities to investigate hazardous substances more intensively with a view to developing early warning systems.



The EO maritime surveillance system MARISS: automatically detected ships based on radar satellite acquisitions (here: Sentinel-1)

Neural Network (CNN) as a class of deep learning. Developing these technologies represents one of the main research priorities of the team in support of applications for maritime domain awareness. In addition to multispectral data, in 2021 we started working with hyperspectral data from the DESIS mission in preparation of the EnMAP mission. Harmful substances such as oil spills introduced into the environment, as well as hazardous substances of biogenic origin

Our developments in radar-based ship detection in close cooperation with the Bremen research lab have been transferred to operations within the TerraSAR-X ground segment, specifically fully automated vessel detection based on SAR data, and are now licensed to our industrial partner Airbus. At Airbus it forms part of their (near) real-time processing application for their international customers. We successfully coped with the challenging integration of SAR

data of different frequencies, acquisition modes, and spatial resolutions. Likewise, DLR's Technology Marketing division has licensed to Airbus UK our software that fuses results from SAR-based ship detection using TerraSAR-X or Sentinel-1 data with AIS. Another example of the development results is NRT processing capability in support of Arctic research campaigns, e.g. MOSAiC, just minutes after acquisition by the TerraSAR-X satellite. The data were downlinked to the Neustrelitz ground station and the images were immediately processed to deliver the information in NRT to the German research vessel RV Polarstern, making it possible to find a robust ice floe to which it could be moored.

Outlook and Challenges

The results of national and international cooperation, the investments, and initiated developments testify to the validity of our research, developments and operational capabilities. While cooperation led to an increase in mission acquisitions, the investments in infrastructure and systems paid off in higher capabilities and increased competitiveness, and ultimately to new projects, which then allow us to further develop our knowledge, capabilities and facilities. We have already and will further upgrade our data acquisition station systems and interfaces to be up to date in technology and mission demands. Thus, we are prepared for new developments, like the new ESA setup of a service-oriented ground segment cloud-based architecture. Our qualification and selection as one of the Copernicus Sentinel core ground stations is confirming our approach.

Besides continuity in X-band systems, new generations of EO satellites are demanding the use of Ka-band capabilities with higher data rates, requiring corresponding ground infrastructure. We have started to built-up Ka-band capabilities and also to upgrade and exchange the oldest X-band systems.

We continue our development of a front-end processor to process data from our own antenna systems in the most-effective way and will adapt its capabilities also for optical ground stations planned as a future installation in a network of worldwide stations.

Together with the Maritime Security Lab in Bremen, we will continue to develop even more-sophisticated near real-time applications for maritime situational awareness, deployed together with industrial partners and for demonstration services with public authorities. The integration of artificial intelligence algorithms into our operational processing chains will be the baseline for future support systems.

Most recently, DFD in Neustrelitz was selected to host the Antenna Site East for the geostationary communication satellite Heinrich-Hertz to be launched in 2023. Two Ku-Band antennas will be installed to receive the science technical payload of the mission. The extension of our antenna capabilities towards geostationary satellites is another option for future data acquisition from relay satellites such as the European Data Relay Satellites, EDRS. The ability to receive Earth observation satellite payload data both directly and via relay satellites expands our capabilities for NRT product development and delivery beyond the Neustrelitz visibility circle and opens a path to NRT maritime applications and services beyond the European waters.

International Ground Segment

Orientation of the Department

The increased number of Earth observation satellites and the amount and variety of data delivered by them constitute a technological and operational challenge for the PDGS. The International Ground Segment department responds to these challenges by focusing on international station locations for satellite data reception and developing and engineering EO data processing chains. Sharing infrastructure and responsibilities with the National Ground Segment department, our worldwide stations guarantee DFD independent and global access to critical national and European primary mission data. Whereas the National Ground Segment focuses on managing one multi-antenna site for many different missions in Neustrelitz, the International Ground Segment organizes a variety of station locations, among them remote polar antenna sites (O'Higgins in Antarctica and Inuvik in the Arctic).

The department designs, establishes, maintains and operates large antenna systems in extremely harsh polar environments for satellite data reception for a wide variety of Earth observation missions. In order to guarantee reliable and fully automated station operations for unmanned stations at remote locations worldwide, we have developed our own satellite ground station control and monitoring system.

Further, we develop and operate mission-specific processing systems where the received payload data is transferred to various processing systems and converted into products of different content depth (levels). With different focal points, these developments and comprehensive engineering tasks are also shared with the National Ground Segment depart-

ment. This combination of infrastructure and knowledge results in our strong and internationally acknowledged competence in effective and reliable data access and data processing in the context of a PDGS or for geoscientific research.

Satellite EO data processing is facing the challenge of very high data volumes combined with a significant rise in processing complexity. TanDEM-X bi-static processing or the interdependent product variety of Sentinel-5P data – we developed and operated both PDGS – are examples of this development. To cope with these demands we developed a cloud-computing-compatible workflow and resource management system for EO data processing, named proEO, as an open source project. We further expanded the DFD in-house GeoFarm private cloud facility to a highly available and scalable data processing infrastructure for multi-mission operations.

In the PDGS, we have carried out tangible activities for major national and ESA/EU Copernicus missions in the last few years. To be emphasized is our participation in Tandem-L and HRWS mission studies because they accelerated our developments in the area of very high data rate downlink and the conceptual design of a mission exploitation platform. The latter is a good example of major IT trends that have guided our new PDGS developments: hardware virtualization and service-oriented architecture. Formerly, IT hardware properties were included and set-up in dedicated mission-specific engineering processes. Meanwhile, hardware virtualization to a certain degree makes applications independent of the actual hardware used. While this is already quite common for virtual machines in computing centers, it is also increasingly being applied to ground station hardware. We have developed concepts and software to apply this approach for nearly all hardware resources in PDGS – for ground stations as well as for computing platforms.

“Satellite EO data processing is facing the challenge of very high data volumes combined with a significant rise in processing complexity”



Service-oriented architecture does for software what virtualization does for hardware. Software functions provided as services can be re-used in different contexts by different applications and make the users independent of the actual software implementation. The use of virtualized hardware via a specific service may also cross organizational boundaries. In this context we are significantly contributing to the development of the *terabyte* project, our future EO science big data computing platform, in cooperation with the Leibniz Supercomputing Centre (LRZ) in Garching.

The department's cross-cutting activities are highly interconnected and follow the data chain from satellite to ground, via processing of the data and product delivery to users. Combined with the fact

that the systems developed and integrated in the department are also operated in the department, the team structure is organized according to this systematic. It starts with the development and operation of our antenna systems by the Data Acquisition and Receptions Systems team. The System Engineering and Integration team participates in the EO mission definition and set-up phases, develops scientific processing methods, and supports the other teams with development tasks for other department activities. The ESA and Copernicus Ground Segment team focuses on PDGS set-up and operations optimization within European ground segments. Whereas this has formerly meant integration of third party developments into a specific IT-environment it now includes the integration of processors in cloud systems following the

DFD's antenna system of the German Antarctic Receiving Station GARS O'Higgins in late winter season



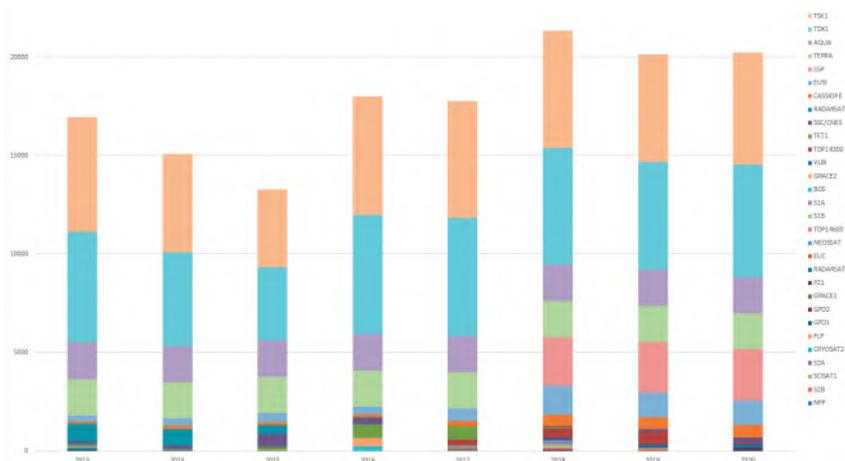
DFD's antenna in Inuvik features an art work of the Gwich'in artist Ronnie Simon. The winter scene depicts the traditional activities of the Gwich'in people hunting, trapping, and fishing which to this day remain significant elements of Gwich'in economy and way of life.

new PDGS philosophy. Finally, the Operations Engineering and Production team operates the PDGS for national missions and a variety of projects.

Data Acquisition and Reception Systems

Our expertise and capabilities in the development of technology, establishing systems and operations concepts for the acquisition of EO payload data, satellite platform data, and organizing global station networks for missions are used for a number of EO missions.

Operating within a global station network, we receive payload data in X-band and have supported telemetry, tracking, and command tasks in S-band for TerraSAR-X and TanDEM-X since the beginning of these missions and for Sentinel-5P from 2018 onwards. Furthermore, missions like Cassiope, FireBIRD, Eu:CROPIS and GRACE Follow-On have been or are being supported by our international station network. We directly receive and provide data from the US Terra and Aqua satellites, as well as from NOAA and additional satellites via the EUMETCast system.



Development of successful satellite passes for payload data reception or TT&C support for the station location GARS O'Higgins, Inuvik and Oberpfaffenhofen for all missions supported by DFD

The Launch and Early Orbit Phases (LEOP) were supported for missions like TET-1, BIROS, Eu:CROPIS, Flying Laptop, PAZ, and recently for Virgin Orbit's LauncherOne. This support quite often includes the very first telemetry acquisition of the spacecraft after launch, requiring the highest quality and reliability of the ground systems and station operations. We successfully managed the challenges of setting up the network and interfaces and provide tracking and ranging services as well as real-time telemetry to the mission owners.

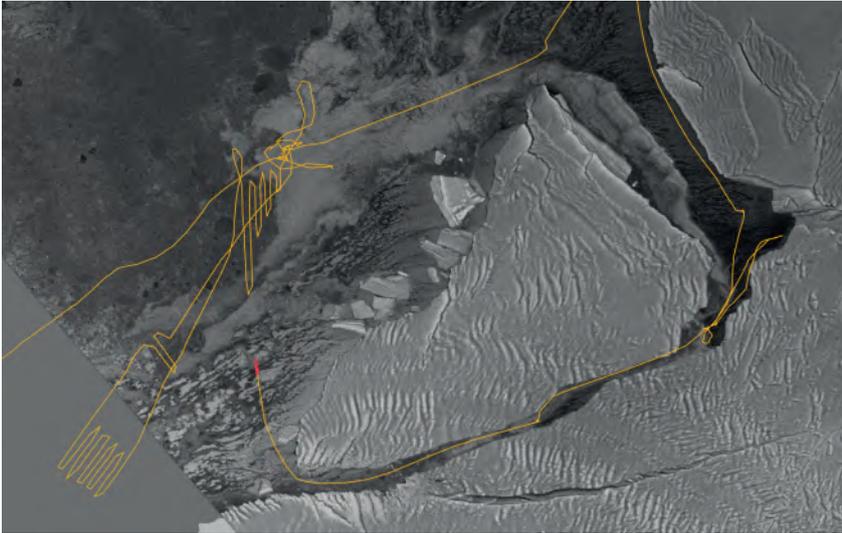
The cornerstones of our global station network are the two stations at GARS O'Higgins, Antarctica, and in Inuvik, Canada. Together with DFD's stations in Neustrelitz they provide satisfactory orbit coverage by our global station network for most missions. Further stations such as those in Kiruna (Sweden) and Svalbard (Norway) can and have been flexibly added via partnerships in place with the Swedish Space Corporation (SSC) and KSAT. Overall, the use of station capacities has increased and the reliability of station operations has constantly improved during the reporting period.

Our initial Inuvik station development motivated the Canadian Government to establish the Inuvik Satellite Station Facility, ISSF, meanwhile an interna-

tional endeavor, which now comprises the Canadian Centre for Mapping and Earth Observation (CCMEO), the C-Core company, SSC, and DLR. The DLR Inuvik station is mainly unmanned and remotely controlled from Oberpfaffenhofen using a ground station control and monitoring system developed by the department. The station remains fully operational even during the corona pandemic. Regular preventive maintenance campaigns are conducted by DLR personnel, keeping the station's reliability well above 99%.

The German Antarctic Receiving Station GARS O'Higgins is located in the direct neighborhood of the Chilean Army's General Bernardo O'Higgins Antarctic Base on the island of Isabel Riquelme at the northern tip of the Antarctic Peninsula. The station's operation is organized in cooperation with the Chilean Antarctic Institute (INACH).

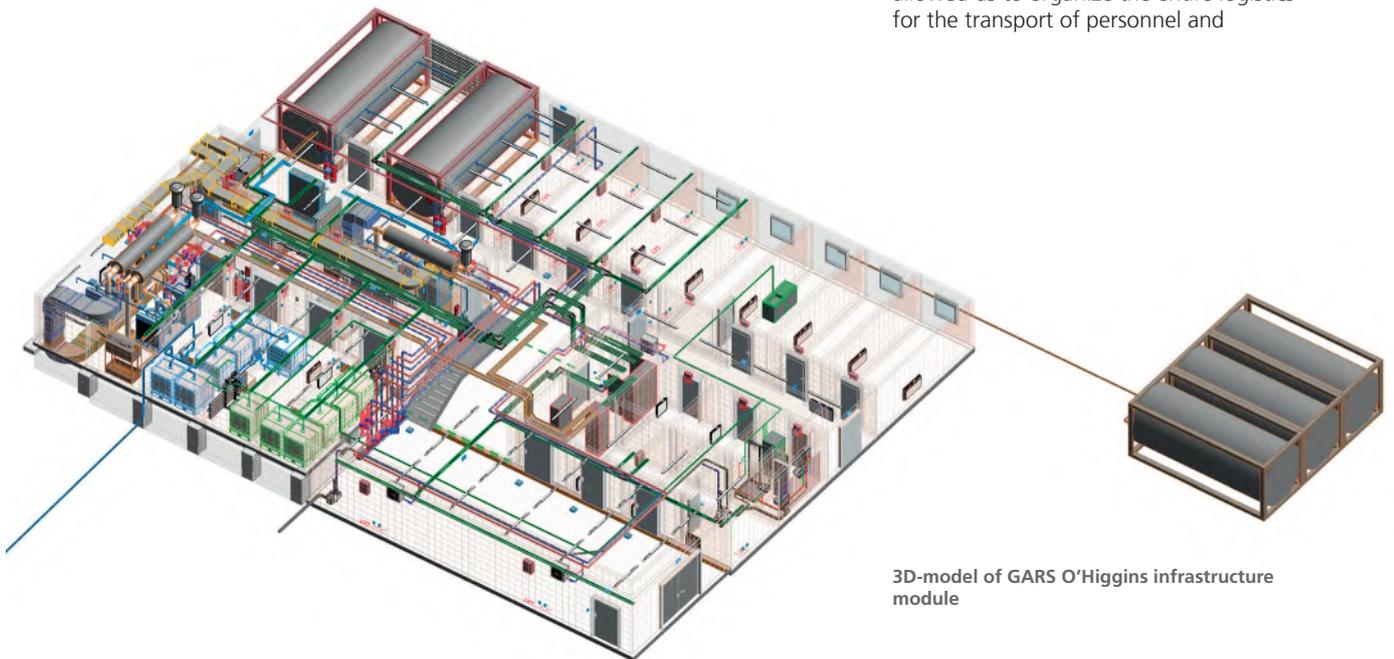
GARS O'Higgins is equipped with NRT processing capability for TerraSAR-X and TanDEM-X data. This expansion of the overall TerraSAR-X/TanDEM-X ground segment allows generation of NRT sea ice information to support of research vessels routing in the Southern Ocean. TerraSAR-X/TanDEM-X data contain precise ice cover information, independent of the time of day and cloud coverage, which is sent directly from GARS to the vessels



DFD supported the Polarstern research vessel in circling around iceberg A74 with TerraSAR-X imagery received and processed at GARS O'Higgins and delivered to Polarstern in near real-time.

typically within 30 to 50 minutes after data acquisition. The service is provided to the Alfred Wegener Institute (AWI), the US Antarctic Program, and the International Ocean Discovery Program, and the data are usually reused for further scientific analysis.

As GARS O'Higgins has been operating for 30 years, an analysis was carried out on how to bring the station into the future, move it to other locations, even including dismantling the station. In 2016 the decision was made at DLR to completely refurbish and modernize the station's infrastructure and technology within a project kicked off in early 2017. It included an analysis of the station status, the reusable parts of the station, safety aspects such as structural fire protection, and an environmental impact study. The corona pandemic delayed the still ongoing project, which should be finalized by the end of 2023. Nevertheless, GARS O'Higgins has remained fully operational during the pandemic, was manned all the time, and included long-term engineering campaigns involving DLR engineers. It should be noted at this point that the operation and the technological modernization and further development of the GARS O'Higgins station is only possible thanks to a network of trustworthy contacts with many partner organizations in South America, especially in Chile and Brazil, that has been closely established over 30 years. Only these reliable personal contacts have allowed us to organize the entire logistics for the transport of personnel and



3D-model of GARS O'Higgins infrastructure module

technical equipment with comprehensive requirements regarding safety, conditions and availability of ships and aircrafts. This effort cannot be overestimated, especially for the smooth operation of GARS.

Downlinking large data volumes at high data rates can be achieved by using higher carrier frequencies, namely Ka-band between 25.5 and 27 GHz. In Ka-band, however, atmospheric signal attenuation is more likely than at the lower X-band frequencies used so far. Thus, we have developed overall operational concepts together with space parts suppliers (TESAT, Airbus) that include flexibly commanding the modulation scheme and planning the downlinks according to weather forecasts.

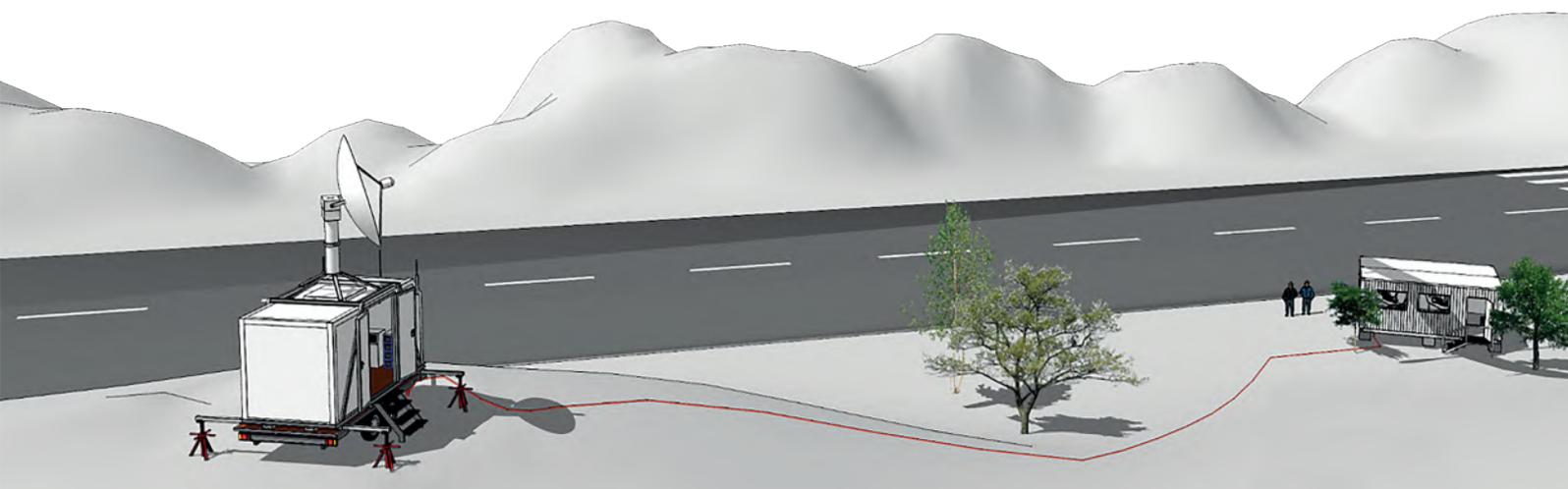
A completely different area of development is the communications concept for High Altitude Platforms (HAP), which are generally seen as a promising enhancement to satellite based earth observation. In the DLR cross-sectional HAP project, the department is responsible for ground segment design, the capability of commanding and controlling the aircraft platform in S-band, as well as receiving the onboard instruments' payload data in X-band. Besides the ground infrastructure, the payload data link includes the technical design of the payload data transmitter on board the HAP. This hardware was specified together with TU Berlin and IQwireless GmbH.

A further area of development and cooperation with industry is the Ka-band ground station hosted by DFD in Oberpfaffenhofen for receiving data from the Technology Demonstration Payload 1 (TDP-1) on the geostationary

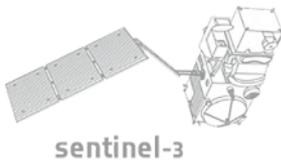
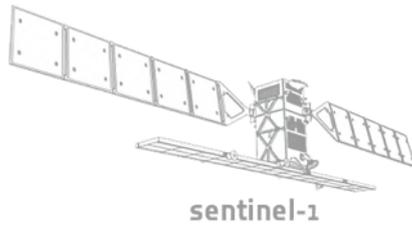
satellite Alphasat I-XL. With this antenna system, we have supported the very first EO payload data transmission projects from Alphasat in Ka-band, receiving Sentinel-1A satellite data via optical inter-satellite link. Furthermore, commissioning the optical link data transfer for the Sentinel-1 and Sentinel-2 satellites was supported with this ground station. The Ka-band downlink was tested and validated in cooperation with TESAT and in turn the station is used to provide laser communication terminal (LCT) house-keeping data to TESAT for improving and constantly monitoring the LCT operations. Additionally, in cooperation with Inmarsat, the station constantly receives housekeeping telemetry from the satellite.

The very successful cooperation with European Space Imaging, Munich – starting in 2003 with the acquisition of IKONOS Satellite data – was continued and extended. From 2013 onward, the number of data acquisitions from the MAXAR-operated very high-resolution optical satellites by antenna systems hosted by DFD in Oberpfaffenhofen continuously increased. A major jump in activities was achieved by establishing the so-called Constellation Direct Access Facility, which was kicked off in 2016. Since 2018, acquisition planning, payload commanding, and data reception have been performed for the full range of GeoEye-1 and the WorldView-1/2/3/4 satellites (WorldView-4 until its failure in 2019). The combination of DLR technology expertise and European Space Imaging business development forms a

Schematic view of a HAP ground segment providing support for overall mission management, monitoring and control. Innovative communication solutions are essential for a lightweight HAP construction.



Payload Data Ground Segment



Production statistics for the Sentinel-1/3-OLCI PAC at DFD

13.374.910
products

16,53
petabytes

reliable partnership to ensure the supply of optical very high-resolution data to European users.

ESA and Copernicus Ground Segments

Since 1991, ESA's European EO missions form a second main focus of the DFD PDGS beside DLR national mission development and operations. This participation not only ensures a national presence of DLR systems and engineering in European programs, but also represents a platform to develop our systems and skills benchmarked in a growing competitive environment against challenging technical requirements. Copernicus ground segment facilities and centers are distributed throughout Europe. Partnering with other institutions in Europe has become a standard feature for our Copernicus PDGS participation. It has been and still is a major strategic activity from the viewpoint of the entire DLR space program.

The role of the team has been and still is focused on recent and future European missions, primarily in the resulting Processing and Archiving Centers (PAC), where we are to a large extent responsible for the design, engineering and operations of the data flow, data processing, and data archiving. Until the recent change in Copernicus PDGS architecture (from 2014 onwards), we mostly operated processors developed by third parties in other ESA contracts which were implemented for final operations at DFD PACs. There, we concentrated on processing operations, tool development for optimizations, set-up of archiving services together with the Information Technology department, and monitoring and reporting tasks. Within this specific ESA PDGS set-up, the team also operates these elements within Copernicus, whereas the Operations Engineering and Production team is in charge of the operations of PDGS primarily developed by DFD. Providing us with a insight into

third party systems and therewith fostering the own PDGS developments, this was always an anchor to sustain systems and operations know-how within the institute. Quite often, third-party systems provided us with needed intensive validation and optimization. Therefore, the team gained specific experience and knowledge in bringing systems from the "developed and tested" status to smooth and effective operation.

Ground Segment services for the Copernicus program are operated by DFD in continuation of its long-standing participation in European ESA missions. This history dates back to participation in the development and operation of the payload data ground segments for the ERS-1, ERS-2 and ENVISAT satellites between 1991 and 2017. It also included reception of the ERS-1 payload data at DFD's GARS O'Higgins station. Another focus was on data from the GOME instrument on ERS-2, and from the GOMOS, MIPAS and SCIAMACHY instruments on Envisat, all processed by our systems and facilities. SCIAMACHY data, for example, contributed significantly to monitoring the size of the ozone hole over Antarctica.

The user community continues to use ERS and ENVISAT data long after the end of the active mission phases. Starting in 2012, we made available from our archives over 600 terabytes of ERS-1/-2 and Envisat data. We were also tasked by ESA in 2018 to consolidate and repatriate about 60 terabytes (20,300 datasets) of ERS-SAR data from the Alaska Satellite Facility, Canadian acquisition stations (Gatineau and Prince Albert), and from JAXA (Japan).

Our active participation in Copernicus started in 2012 when in a competitive framework ESA awarded the Sentinel-1A Processing and Archiving Center (PAC) contract to DFD based on our experience and project acquisition activities. The necessary infrastructure for the PAC operations was set-up at DFD and included a

dedicated 2 x 10 Gbit/s link to the Copernicus Wide Area Network. Operations of the PAC started in 2015, with Sentinel-1B and Sentinel-3A/B OLCI added later to our PAC activities on behalf of ESA. With the Sentinel satellites we were faced with handling an entirely different order of magnitude of EO data than with previous ESA missions. During the six years of routine operations (March 2015 – March 2021) we managed to process and archive nearly 13.4 million datasets at the Sentinel-1/3-OLCI PAC at DFD. The amount of data processed totaled over 16,900 terabytes - more than 20 times the amount of data accumulated during the entire 26-year lifetime of the combined ERS and Envisat missions.

Starting in February 2020, the DFD-PAC additionally took over the responsibilities of the British partner facility (UK-PAC) after ESA discontinued its operation. Since then, we have successfully managed the entire load of all Sentinel-1 data processing and archiving as the only Copernicus PAC.

Since ESA no longer provides older Sentinel data online via its data portal, requests from the Copernicus Open Access Hub for data from the Long-term Data Archive (LTA) of the PAC increased considerably since 2019. We have retrieved more than 1.3 million datasets with a volume of almost 3 petabytes from the PAC LTA. The data throughput was increased by our developments at all service levels: archiving technology, retrieval methodology and network performance. In addition to the core project tasks, activities included the operation of a data hub relay (2015-2020) within the Copernicus Collaborative Ground Segment and supplying Sentinel-1 data to the Copernicus MyOcean project and its successor, the Marine Environment Monitoring Service. At the end of the contract we transferred a significant part of the data from the LTA via a so-called “data bridge” into the new Copernicus PDGS service architecture. The nominal duration of ESA’s Copernicus PAC con-

tract was extended twice, to June 2021, to secure a proper phase-over to the successor entities in the new Copernicus architecture.

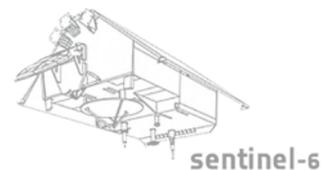
This new Copernicus PDGS architecture constitutes a change in paradigms for the Copernicus ground segments towards a service-oriented architecture. Together with the DFD Information Technology department we have contributed our expertise in discussions, workshops and ESA studies to the definition of this new Copernicus cloud-centric architecture. Therefore, and in continuation of our fruitful participation in European programs, the team replied to the corresponding ESA Invitations to Tender. In a two-stage competitive tendering process, we were awarded a contract for generating Sentinel user-level data as a Copernicus Production Service for Sentinel-1B. The project was kicked-off in September 2021 and went into full operation in early 2022. In order to start a production service operated by DFD, we selected a public cloud infrastructure for the processing tasks and configured the proEO processing workflow suite developed at the department (see next chapter). Managed and operated by the team, the Sentinel Production Service hosts the processing software and is connected to the cloud-based interface points within the new ESA PDGS architecture.

Systems Engineering and Integration

Systems engineering as well as systems integration is an integral part of the PDGS. The team’s competence in this domain represent an important contribution to in-house projects, to supporting departmental functions, to EO informatics system developments, and it is also an integral part of internal and third party EO projects and missions.

The beneficiaries of this competence in the reporting period include amongst others TerraSAR-X, TanDEM-X, EnMAP, CO2Image, and mission concepts for

“This new Copernicus PDGS architecture constitutes a change in paradigms for the Copernicus ground segments towards a service-oriented architecture”



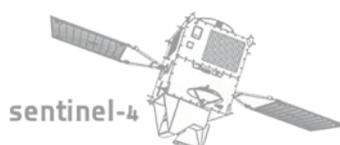
sentinel-6



sentinel-5p



sentinel-5



sentinel-4



The large Ka-band antenna is visible on the roof of one of the DFD buildings. In addition to Copernicus satellite data processing, the building also houses the German Satellite Data Archive (D-SDA).

Tandem-L. Besides supporting many smaller science projects with software engineering and operationalization tasks, our major focal points are the Copernicus mission Sentinel-1B with our project management and supportive software engineering, and the Copernicus Sentinel-5P mission with PDGS project management and comprehensive PDGS systems- and software-engineering. To

enable our work and contributions to projects and missions, we have designed, set-up and operated several software and hardware infrastructures implementing configurable processing workflows, data flow solutions for data processing, hardware resource management solutions for processing, interfaces to the reception systems and archives, and interfaces to third party systems, as well as control software for ground stations.

Moving away from mission-specific monolithic IT systems laid out to fit exactly the requirements of the hosted application, we have designed and implemented the GeoFarm processing environment as a virtualized infrastructure. In addition to processing the data of the Sentinel-5P mission, GeoFarm supports numerous in-house research projects. Operating and maintenance processes are greatly simplified as a result of our GeoFarm layout as a homogeneous hardware structure.

Succeeding earlier implementations, complementing other in-house IT environments, and driven by the transition of the Copernicus ground segment to a service-based architecture, we developed a novel system for PDGS-relevant Earth Observation data processing tasks, prosEO. It is a microservice-based and cloud-enabled framework for an operational EO processing environment. The challenge for organizing and managing EO processing workflows and orchestrating processing steps and tasks is nowadays increased by the need to achieve solutions in a short time and to allow for quick deployment of solutions into scalable cloud environments. This is a quite common challenge. As no commercial off-the-shelf system is available to support the variety of scenarios needed, we developed prosEO based on our experience in EO data processing and our need to fully understand and modify the workflow for further coming requirements. Besides being cloud-native, a distinguishing feature of prosEO is its ability to configure and execute tasks by applying dependency-based rules. These

rules determine the most effective way to generate a new EO data product and to execute a pre-defined workflow. The system is now in use for Sentinel-5P data, for the Copernicus Production Service (see section 3.2.3 above), and for an increasing number of scientific processing tasks in the context of the *terrabyte* project; it will be our basis for data processing in future EO missions.

A similar path from static infrastructure via virtualization to a service-oriented architecture was taken in order to fully automate the operation of DFD's unmanned global receiving stations by introducing a Station Monitoring and Control System (SMCS) designed and developed by the team. The SMCS abstracts the ground-station-specific infrastructure, provides services transparently, and thus simplifies the integration and use of individual and remotely located stations. Although the number of station locations and commercial station networks increases and this problem is common to station operators, there is no commercial off-the-shelf solution. Through the SMCS we achieved highly reliable and fully automated ground station operation of our remote stations, while having all the concept and source code available for future needs. We use and share SMCS with DLR partners, e.g. DLR GSOC, and commercial partners like SSC in operating our station in Inuvik.

terrabyte creates an EO science big data computing platform in cooperation with the LRZ in Garching. The project benefits from our extensive experience in scientific algorithm implementations of varying maturity, supporting science projects to generate added-value products, and science analysis. To this end, the team supports the generation of tooling and standards for coding, SW and processing workflows, as well as their implementation. This becomes particularly relevant since the character of EO science data processing has shifted from regional analysis within small time scales to global applications often covering a long

temporal range. Efficient use of the large hardware infrastructure of *terrabyte* in this context requires completely automated set-up and operation of the corresponding environments.

terrabyte targets the abstraction of many software functions away from scientists, while still allowing them to themselves intervene. It will relieve the scientist from as many non-scientific IT tasks as possible, with the aim to provide EO data services up to the level of Functions-as-a-Service. Further on, *terrabyte* will allow the use of further LRZ resources as if in a cloud environment, taking a hybrid path between cloud and high-performance computing (HPC) clusters. To this end *terrabyte* is part of a new general DLR big data computing initiative and strategy enabling DLR engineers and scientists to have access to corresponding computing facilities. Overarching aspects of the *terrabyte* project are described in a separate section of this document.

Operations Engineering and Production

Originating mainly in the production management established for the TerraSAR-X mission, the team supports the PDGS operations engineering and production within the department. It covers the entire order request workflow from the initial user order via an acquisition request to the satellite to data processing to dissemination of products. Within the production management, activities include monitoring all aspects of operations, manually interacting with the systems, handling anomalies either in systems or data, report status, performance, and communicating with the users, supporting them in their data requests. Our prime responsibility is to deliver all user orders in time, complete, and with the specified quality. In this sense the team performs user-oriented systems operations as 1st level operations and support for PDGS activities in the department, for selected science projects,

“terrabyte will relieve the scientist from as many non-scientific IT tasks as possible”

“Developing serverless computing for geoscientific data processing will be continued to further support in-house research activities”

and for external commercial partners for their mission exploitation. With the PDGS developed by DFD, this also includes the operations for the Sentinel-5P mission. Further, we also support projects like AC-SAF under contract to EUMETSAT and constellation Direct Access Facility (cDAF) operations in support of European Space Imaging, and we also prepare the production management for EnMAP.

The whole team is frequently trained in systems engineering for opportunities to implement best practices and standards for operation of IT systems, such as the Information Technology Infrastructure Library (ITIL). Here, we managed to implement and adapt the ITIL to the PDGS to allow the introduction of role-based service provision. In order to cope with the need to speed up and organize change, the operations team is applying agile best practices such as DevOps. Therefore, the roles have expanded as have methodologies and means for operations management, incident handling, and systems monitoring during the operational phase of a satellite mission. This resulted in more efficient and synergetic operation of multiple missions and projects. Whereas operations planning and preparation have so far been done during later mission development phases, in current and future projects we initiate operations preparation already during the early mission definition and design phases. Introducing the operational perspective and our knowledge and experience already at that stage optimizes processes and reduces the final operational costs.

The nature of tasks handled by the team has changed in the last few years. Monitoring and quality assurance functions were introduced in response to the higher workload as well as the increasing number of missions. The team also implemented access control procedures as required by the German Satellite Data Security Act (Satellitendatensicherheitsgesetz, SatDSiG), applicable e.g. to the TerraSAR-X mission. Thus, the system red-flags product deliveries to users who

are prohibited from receiving TerraSAR-X data. For EnMAP, the service desk function was extended to also include scientific evaluation and user support during order generation.

The current development of the Copernicus PDGS towards a service-oriented architecture and our proEO development create strong synergies between our Operations Engineering and Production team and the ESA and Copernicus Ground Segments team.

Outlook and Challenges

The developments described in the previous sections pave the way for further evolution. Consequent hardware virtualization and implementation of a service-oriented architecture will speed up future PDGS developments.

We continue to consolidate and upgrade our data acquisition stations in the Canadian Arctic and Antarctic. In Inuvik, we are prepared for further national missions and plan to upgrade our station capabilities also to Ka-band reception. Our partnership at ISSF will yield new missions and projects to have our station used nearly to capacity in the coming years. The refurbishment of our GARS O’Higgins station in Antarctica is also progressing. In perspective, we are also looking at upgrades to Ka-band and mastering the challenge of acquired data transmission from O’Higgins, possibly by terrestrial lines.

Implementing innovative communication concepts for high altitude platforms and for very high data rate downlinks of EO payload data from satellites with a target of 10 Gbit/s in high frequency technology, and the application of software-defined radio technology will keep the department at the forefront of technology.

Widespread application of our prosEO development in internal and third-party projects, both for payload ground segments and for geoscientific data processing, will allow us to set up processing chains faster and provide more flexibility for complex processing environments. prosEO will be used and further optimized in future national missions like CO2Image and HRWS.

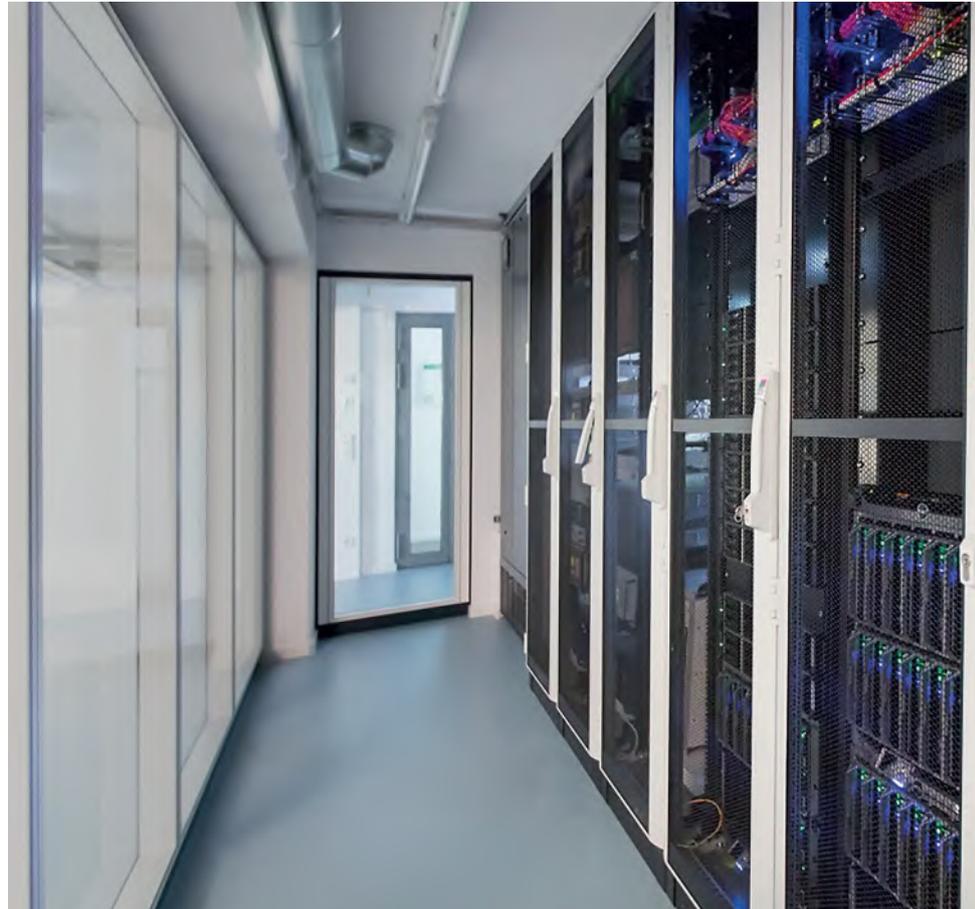
Developing serverless computing for geoscientific data processing will be continued to further support in-house research activities. To this end our major contributions to the *terrabyte* big data computing platform will yield a multitude of developments and experience and will keep us at the forefront of similar developments in Europe and worldwide.

Information Technology

Orientation of the Department

Managing large-volumes of EO data during their life cycle is the main task of the Information Technology department. Our key competence lies in data modeling and developing technologies to efficiently orchestrate complex data flows, to preserve data for tomorrow's users, and to provide high quality data access via internal and external platforms. Our main focus is on EO data management systems, EO data management services, IT management and engineering, as well as quality management and project support. The latter two focal points support both EOC institutes.

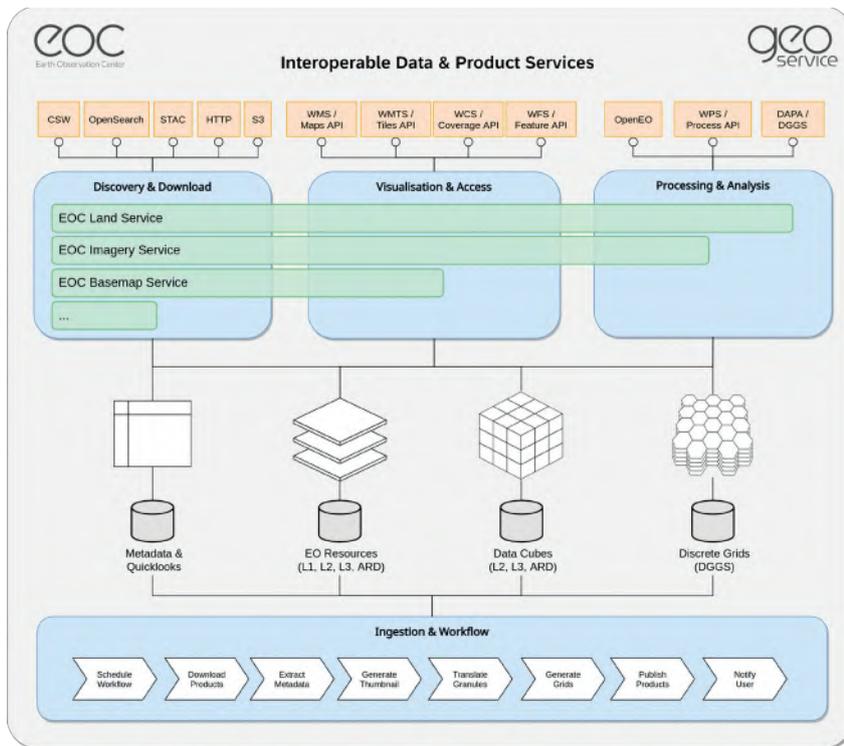
In the context of EO mission payload data ground segment projects, the Information Technology department collaborates closely with the two other ground segment departments. Likewise, we have intensified our collaboration with the



GeoFarm: DFD's private cloud infrastructure

EOC research and application departments on large-scale EO/geoinformation projects such as TIMELINE or So2SAT, and on establishing powerful data access and analytics infrastructures such as the High Performance Data Analytics (HPDA) infrastructure to be established within the *terrabyte* project.

The latter symbolizes the paradigm shift in PDGS and scientific exploitation towards big data computing and analytics platforms. This paradigm shift calls for state-of-the-art infrastructures and novel online EO data management technologies. To keep pace with this evolution, we concentrate our efforts on the corresponding technology develop-



DFD’s Geoservice encompasses state-of-the-art spatial data management functions including standardized, interoperable service interfaces. Through its flexible architecture new features can easily be integrated.

ment. Focusing on standardization and interoperability in all aspects, the DFD EO-infrastructure are ready to federate with large-scale multidisciplinary data exploitation ecosystems, such as the European initiatives Destination Earth and GAIA-X.

Providing state-of-the-art access to the DFD EO data assets is crucial. Over the past few years, we put particular emphasis on making our data holdings accessible in a convenient way to a broad spectrum of internal and external users by reducing legal and technical barriers. The vast majority of data are now discoverable in national and international portals such as GeoPortal.de, INSPIRE, GEO/ GEOSS, and the Committee on Earth Observation Satellites (CEOS) International Directory Network. Accessibility is greatly enhanced by way of the interoperable

data viewing and data download services of the EOC Geoservice, developed by DFD.

Since 2007 we developed the Geoservice with a view towards establishing a comprehensive data backbone servicing a multitude of frontends, portals, and GIS tools. For these, the Geoservice features a map client as well as interoperable discovery, visualization, download and processing services, based on the standards of the Open Geospatial Consortium (OGC). The underlying modular architecture allows to build scalable spatial data infrastructures; customized instances can be deployed on different platforms including HPC and cloud environments. By integrating vector and raster data formats and adding innovative services - processing interfaces, data cubes, global grids - the Geoservice lets users interact with spatial data in new ways. The Geoservice is being used to publish the majority of DFD’s scientific geo-information products. It also feeds DFD data and products into various UKIS-based project portals such as the Maritime Security Services (MARISS), the ZKI-Viewer, and the Coastal Explorer.

The most widely used DFD EO data and geospatial information products are now available for internal users, sustainably managed and directly connected to the internal processing environment GeoFarm for analysis. A similar architecture, albeit an order of magnitude larger, is being implemented with the HPDA platform *terabyte* – coupled with performant low-latency archive access for bulk data transfer. Beyond providing infrastructure and data management services, we have begun to process and make available EO data in user-friendly, analysis-ready data formats and data cubes to further facilitate accessibility and use for a variety of specialist and non-specialist users.

The major developments and systems follow stringent processes for system engineering and operations (ECSS standards) as well as the widely used IT-service good

practices of the Information Technology Infrastructure Library (ITIL) and are ISO 9001 certified.

We contribute our broad expertise to shape the next generation EO and research data management architectures through participation in OGC testbeds, in working groups of ESA, the European Commission, and CEOS. We provide technology solutions which improve, for instance, the Copernicus Sentinel ground segment. On a national level, our expertise flows into national research data infrastructure initiatives (e.g. NFDI4Earth) as well as into the DLR research data management steering committee.

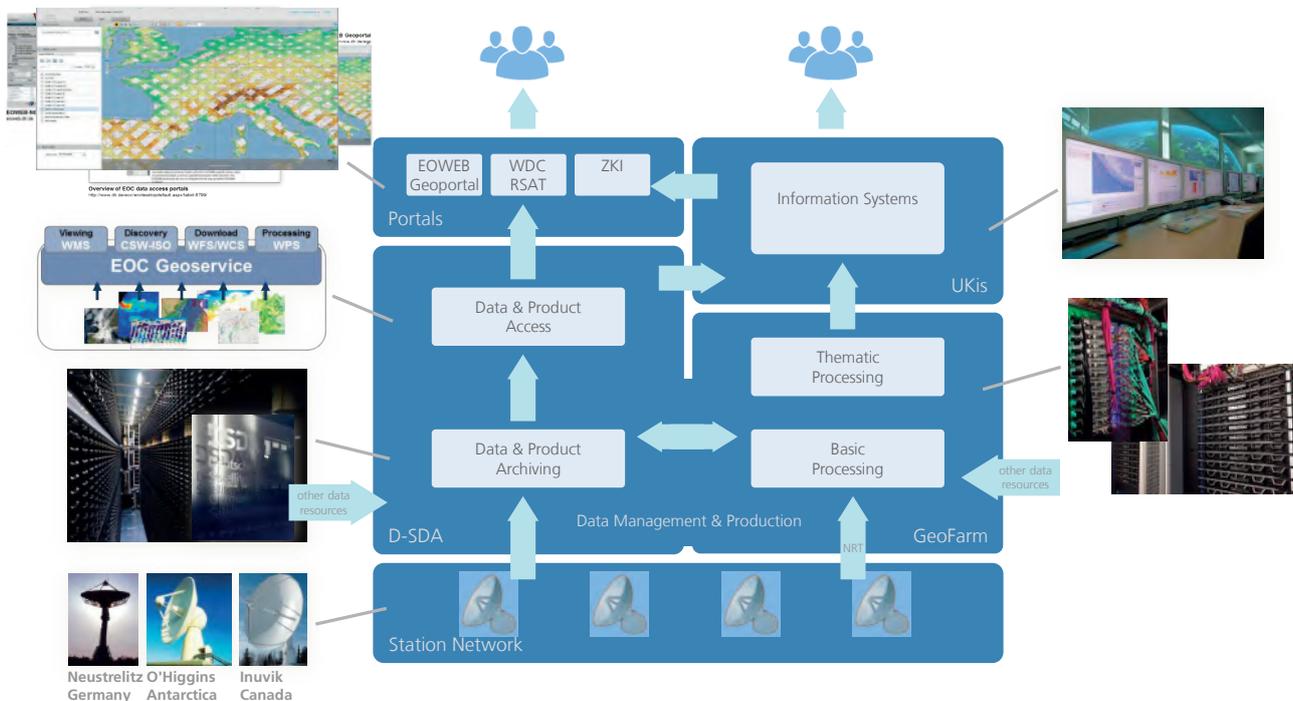
EO Data Management Systems

Within the topic of EO Data Management Systems we focus on the development and engineering of software systems operated as distributed services. These cover the full range of EO data

management functions, including the core functions of long-term data preservation and data access as well as auxiliary functions such as service monitoring and reporting. In this context, the team maintains complex software systems consisting of its own developments as well as external open source software in order to implement the requirements of multiple EO missions and projects such as:

- DIMS - the Data Information and Management System for managing heterogeneous EO data and controlling complex data and order workflows for a variety of scenarios, being the essential basic operating system for the PDGS of EO missions,
- GDAS - the Geospatial Data Access System for managing spatio-temporal data and providing interoperable web services for data discovery, visualiza-

Formerly separate system components have evolved into a comprehensive, integrated EO data management and analysis system landscape which is being operated in close inter-departmental collaboration.





The Online Data Management System (ODMS) manages very large EO data volumes stored online in platform environments.

tion, analysis and download, based on OGC standards, enabling access, interpretation and exploitation of valuable EO mission results by external users,

- ODMS - the new Online Data Management System for managing pre-processed EO data and value-added products, as well as associated information in platform environments. ODMS is connected to external data sources and long-term archives, enabling the specific, large-scale online exploitation and processing of large-volume EO datasets for individual Earth science applications.

These multi-mission solutions benefit from synergies across projects and unify the system development and operations processes, providing a standard and sustainable way of storing, handling, accessing, and using the vast amount of EO data maintained at EOC. This way, DFD has supported more than 40 Earth observation space missions over the past 20 plus years, including the Shuttle Radar Topography Mission (SRTM) in early 2000 and the national TerraSAR-X and TanDEM-X missions since 2007, respectively 2010. Since 2014 we are also managing the data from the Copernicus missions Sentinel-1, Sentinel-2, Sentinel-3 OLCI, and Sentinel-5P.

EO-mission PDGS are gradually moving onto online platforms. Building on extensive know-how, we have invested in developing innovative technologies for managing EO data in online, cloud-based, and high-performance data analytics environments. As a result, we have contributed significantly to ESA's definition of the Copernicus LTA service interface. Likewise, these new technologies will be further enhanced to support, e. g., the upcoming national HRWS radar mission.

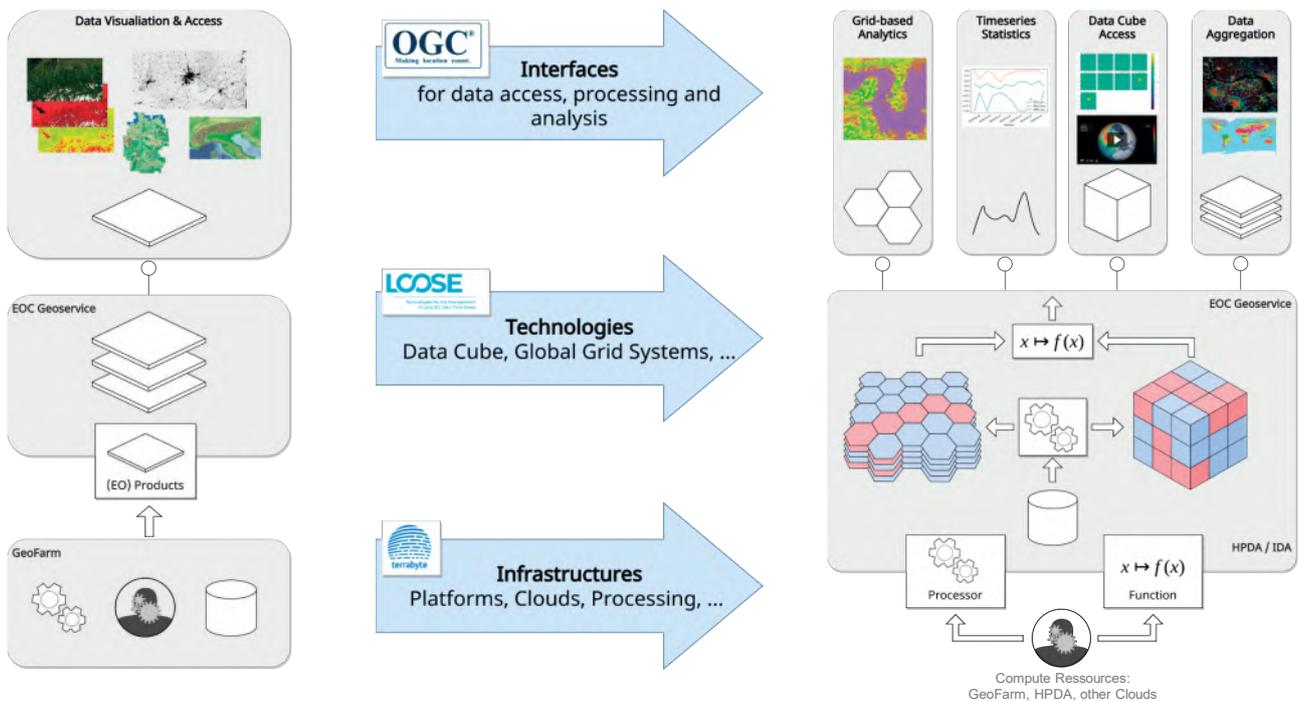
Over the years, the team has acquired comprehensive expertise in the end-to-end engineering and development of

complex software systems typical for EO mission projects. This includes the definition and setup of configurations, data models, workflows, and metadata structures. These strongly depend on the mission and sensor characteristics and may include systematic, data-driven tasks as well as individual, request-driven data acquisition, processing, and delivery. Finally, the systems are incorporated into operations, including documentation, training, and support for the system operators. We have established different system environments which now support projects in their development, verification, and validation phases.

Following the paradigm shift towards online EO platforms, we have intensified the development of services to analyze, process, and provide EO data in user-friendly, analysis-ready formats and data cubes. Through the national Copernicus project CODE-DE I (2016 – 2019) we have acquired know-how in online EO data management on exploitation platforms. We have successfully completed related ESA technology projects (EvoODAS, LOOSE), which support these developments and show their benefits in concrete use cases provided by DFD's science departments and external partners.

Thus, we moved towards using innovative systems engineering and software development approaches such as agile development and continuous integration. Such projects also foster new software and IT technologies for EO data management, access, and exploitation. One example is the integration of new disk-based archives, container-deployable services, dynamically scalable processing workflows, online data cubes, as well as streaming-based monitoring and reporting.

Our long-standing collaboration with Werum Software & Systems AG is an example of a successful DLR partnership in which DFD has supported a German SME to establish successful business relationships in the space sector. We jointly



developed the Earth observation data and information management system DIMS. While the intellectual property rights are shared, the industrial partner holds the global marketing rights. This collaboration has resulted in a software product that has been widely used in, for example, ESA EO data management operations. Another important collaboration concerns the development of EO specific extensions for the open source software GeoServer, in which the reference implementation of multiple web mapping standards has been conducted by an Italian SME, GeoSolutions.

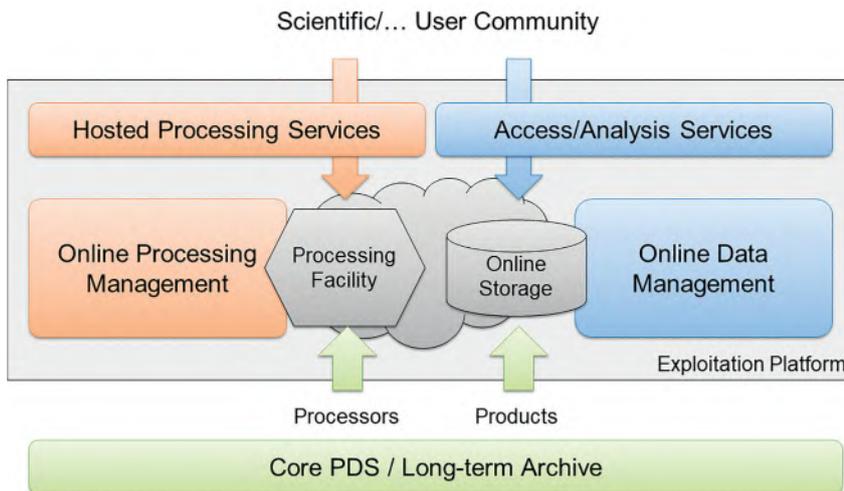
EO Data Management Services

The main tasks of EO Data Management Services are service operations and providing user support for numerous EO data management software components for data archiving, ordering, access, and integration on internal and external platforms. Of particular relevance is the associated data curation, ensuring long-

term data preservation and usability and providing sustainable user-friendly data access. This also includes the responsibility to preserve the unique value of historical data from national EO missions such as SRTM, TerraSAR-X, TanDEM-X, and in the near future EnMAP, as part of our national digital heritage.

The EO data archiving and cataloging services which we maintain ensure that data can be accessed by processing systems as well as by various user communities, who can process and download data, place an order for customized products, or task the acquisition of new satellite images. All components are monitored continuously. We currently operate the following main services:

Innovative interfaces, technologies, and infrastructures change the way users interact with geospatial data.



On a data exploitation platform EO data storage and access functions are closely integrated with processing functionality. Platform infrastructures serve scientific data analytics and EO mission payload data ground segments alike.

- multi-mission data archiving, catalog and delivery services as part of the PDGS for Sentinel-5P contracted by ESA and for TerraSAR-X/TanDEM-X in collaboration with the commercial partner Airbus,
- data archiving, catalog and access services for EOC projects (e.g. TIMELINE) and third party projects (e.g. AC-SAF, RESA),
- data archiving and data access services to ensure that the complete Copernicus Sentinel-1, Sentinel-2, and Sentinel-3 user level data archive is accessible to internal and external users,
- the EOWEB GeoPortal and Geoservice as the main data access portals of DFD,
- visualization, download and catalog services based on OGC standards for 50 datasets mostly provided by DFD scientists,
- D-SDA user management services, reporting and monitoring services,
- online data management services for internal (IDA) and external (DIAS Mundi) platforms.

During recent years, the availability of our services has consistently exceeded 99% – a key factor in successful projects and missions.

One of the major achievements in the context of maintaining service stability into the future has been the successful migration of the core database system with several million entries. This has been done during regular operations without major constraints on users in terms of availability and performance.

Over the past few years, we established the role of an EO Data Librarian. Promoting the use of the EOC Earth observation data, he facilitates user-friendly access to data and products while observing applicable data policy restrictions. The Librarian is also the central point-of-contact for all EO data services offered by the department. These include archiving and providing access to data from the D-SDA; publishing geo-information products via the web services of DFD's Geoservice, including persistent identification; storing data on the internal data access systems (IDA, U-Shelf); and providing data management solutions for the *terabyte* infrastructure. The evolution of these services has fostered an increasingly close exchange between our department and internal scientific users and has led to a profound understanding of their demands. To an increasing degree, team members are now providing guidance to scientific users to efficiently use centralized data offerings and data management services, thereby underpinning the acceptance and relevance of such services.

In response to platform-based EO data analytics, we now also provide access to data in analysis-ready, cloud-compatible formats and have built-up expertise in deploying and operating data services in the cloud. In this context, we explore and coordinate related projects, such as providing data to the external, national scientific data exploitation platform EO-Lab, and lead the development of a data

management system for AI-based data analysis for the Federal Agency for Cartography and Geodesy (BKG). Likewise, we engage in activities surrounding the National Research Data Infrastructure in the NFDI4Earth project, as well as in two cross-cutting and strategic DLR projects, the Emissions Map (*EmissionsLandKarte*) and Digital Atlas 2.0.

IT Management and Engineering

IT Management and Engineering ensures that EOC IT infrastructure and services operate reliably in an EOC-wide functionality that is described in a subsequent chapter. Major challenges have arisen due to rapidly evolving IT technology in cloud computing and online storage over recent years. The same applies to the institute's overall IT infrastructure, e.g. network topology, IT security, and automated service deployment.

Our IT infrastructure has been successfully set-up and operated for long-term archiving of the payload data from national missions as well as from the Copernicus missions. Stable operations of a hierarchical storage management system, including safeguarding two copies of the data on tape in different locations in Oberpfaffenhofen and Neustrelitz, have provided reliable service over the past decades with no data ever lost.

Since traditional tape-based archives are challenged with retrieving large data volumes within a short timeframe, we have introduced a novel disk-based FastLTA technology for the primary copy, which will reduce data retrieval latency from several minutes down to seconds. Additionally, we are currently evaluating the capabilities of a new hierarchical storage management system for mass data management to manage ever increasing data volumes.

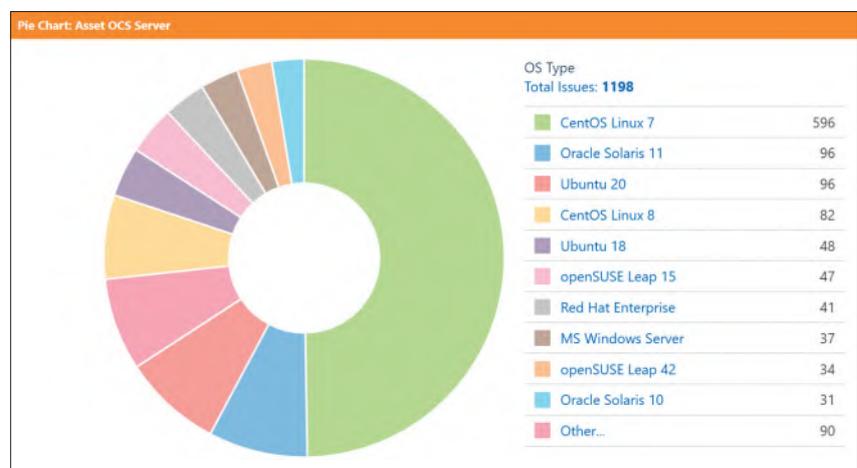
To relieve scientific users from complex storage administration, to meet their requirements for managing large amounts

of data, and to prevent data loss, the team has set up EOC Data Online Storage (EDOS). EDOS is the foundation for a harmonized internal data access infrastructure for Earth observation data available to all, as well as for individual project data holdings. EDOS is designed as an expandable storage system in the petabyte range and offers reliable and fast storage space with minimum onboarding effort and cost.

On the data access side, we are facing increasing demand for dynamic storage and computing resources that can be accessed from the internet, both from scientific projects and from PDGS projects. In response, a so-called midzone has been deployed, secure but flexible and with minimum effort for the individual projects. From the viewpoint of DLR IT security, this solution was part of an overall architectural redesign of the network security concept to fulfil, on one hand, the high security requirements of PDGS systems, while at the same time keeping the network structure at minimum complexity and supporting the dynamic and heterogenous requirements of scientific applications.

The availability of mass data is a crucial aspect for the *terabyte* platform hosted at the LRZ in Garching. For populating

The asset management system dashboard provides a live inventory of all active IT systems.



High-bandwidth network connectivity is essential to successfully operate the EOC infrastructure which is distributed across numerous locations around the globe and to efficiently connect to partner organizations via the Internet.

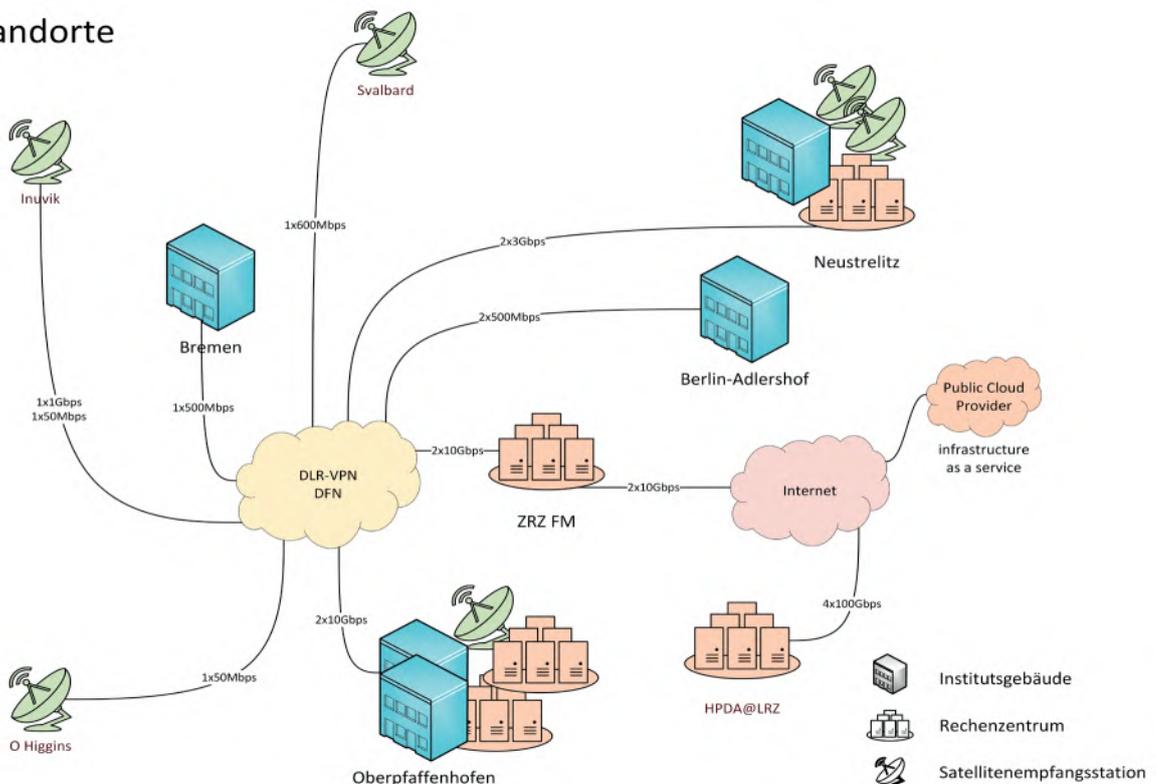
the online platform with data from the D-SDA in Oberpfaffenhofen, a network concept was implemented in cooperation with DLR's central IT service and LRZ. This solution provides a dedicated connection between Oberpfaffenhofen and Garching with data transfer rates of about 10 Gbit/s, scalable up to 100 Gbit/s to meet future needs. This is a key-implementation that guarantees perfect interaction between LTA and the online big data caches at *terabyte*.

Dedicated networking experts continuously monitor and improve network throughput, stability, and reliability to better support PDGS infrastructures for satellite missions and to achieve faster data access for scientific users. To ensure reliability, a corresponding maintenance coordination service has been imple-

mented. In the overall IT-infrastructure context, we are supporting the central DLR IT service by identifying and solving network issues in central DLR networks. The internal core network for both Oberpfaffenhofen and Neustrelitz has been reconstructed into a fully redundant solution with maximum throughput now reaching 100 Gbit/s. Likewise, the overall wide-area network uplink from DLR to the internet of currently 10 Gbit/s is being prepared for upgrading to 100 Gbit/s.

The sheer number of active IT systems at EOC (exceeding 2,500) would require more time for manual administration than the system administrators have at their disposal. Therefore, we have introduced a solution for automatic administration, auditing, and configuration management of all systems, which

EOC Standorte



has significantly reduced the workload on system administrators. In parallel, the development of an in-house Asset Management System was initiated to have a live inventory of all active systems, which are now also integrated into the automatic reporting tool.

To further consolidate the EOC IT infrastructure in response to user requests, the team is currently establishing an EOC-wide cloud infrastructure – EOCloud. As a private cloud, EOCloud will satisfy the demand for computing resources for scientific users as well as for PDGS projects. The main cluster driving EOCloud is GeoFarm, which has grown from being a mere processing platform into a general purpose IAAS platform for EOC.

Quality Management and Project Support

As a cross-sectional function, Quality Management and Project Support serves all departments in EOC. The team implemented and maintains a quality management system and supports projects with know-how and tools. Team members also take leading positions in EOC projects, contributing to the success of the projects with their in-depth knowledge and hands-on work.

The EOC quality management system, described in the EOC central functions chapter, was first certified to ISO 9001 in 2007. Until 2016, the system was successively expanded to include, next to projects for PDGS, all operational entities in the area of user services and PDGS services. As necessary, entities are restructured and processes are adjusted to meet changing operational and product requirements. With a view to the future, in which technologies and working conditions are changing ever faster, in 2021 the quality management system was converted from rather cumbersome pdf documentation to more agile docu-

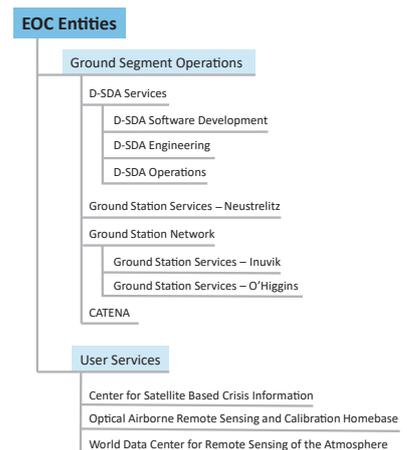
mentation in a DLR wiki system, which improves collaboration and supports the faster adaptation of processes.

Given the considerable third-party funding rate in EOC, project management skills, methods, and processes are of strategic importance, particularly for PDGS projects, both in development and operations. Starting with the TerraSAR-X mission, product assurance management was put in place for many projects. General processes based on standards of the European Cooperation for Space Standardization (ECSS) were defined together with project managers and project engineers, e.g. for risk management, requirements management, configuration and documentation management, test management, and defect and change management. Operational processes have been defined based on the framework of best practices for delivering IT services, known as the Information Technology Infrastructure Library.

However, given the system complexity of these PDGS projects, it became clear that tool support is needed to enforce process compliance within a project team, to document project status and enable its management, to share information, and to assist with document generation. As a result, the team has started developing two systems:

- Asset Management System (AMS) to support managing the extensive EOC IT Infrastructure and to provide up-to-date information to projects about the infrastructure they use,
- System Engineering Tool Set (SETS) to implement the above-mentioned management and engineering processes.

Both tools are based on commercial software and include a plug-in for test management and document generation. They are configured according to established EOC processes and can be adjusted to



EOC’s operational areas ground segment operations and user services with associated entities, certified to ISO 9001

Right side: More than 8000 satellites orbit the Earth and the number is growing. From 2021 to 2022, the United Nations recorded more than 1800 satellite launches. Thousands more satellites are to be launched into space, primarily to provide Internet access from space. Earth observation is also growing rapidly, but accounts for only a smaller portion of the total.

match project complexity. The AMS, e.g., generated the IT infrastructure inventory for the EOC IT audit in late 2021. It is implemented for the Sentinel-5P project, delivering input information required for configuration management in SETS.

Our work and tools also have tangible benefits both in EOC's project acquisition and project execution. Project proposals can be prepared efficiently and quickly, as many of the management, engineering, and operational processes usually requested by the users, are already defined and certified to ISO 9001. Once a project has been awarded, project staff can quickly embark on actual project work since they are familiar with the systematic and uniform processes and tools.

Various PDGS projects have established systems for handling scientific proposals or for accessing and processing data which require users to register with personal information. In order to avoid duplication of work and to assure compliance with applicable data protection regulations, we established an EOC-wide User Management System (UMS), an identity and access management solution developed jointly with Werum Software & Systems AG. The system manages users' personal information and related authentication and authorization information in a consistent, secure, and legally compliant way, and - additionally, handles legal and license requirements for the institute's EO data.

Among the systems connected to the UMS are the EOWEB GeoPortal, and the Geoservice. Furthermore, UMS supports projects and services such as IMPC, UKIS, and MARISS. User management support for the *terabyte* project is being prepared. As a commercial partner, Airbus connected to UMS via identity federation in late 2021. Furthermore, preparations have started to support federated identity management solutions with external EO platforms such as CODE-DE and EO Lab

and to join national and international federations, e.g. DFN-AAI, Helmholtz-AAI, and eduGAIN.

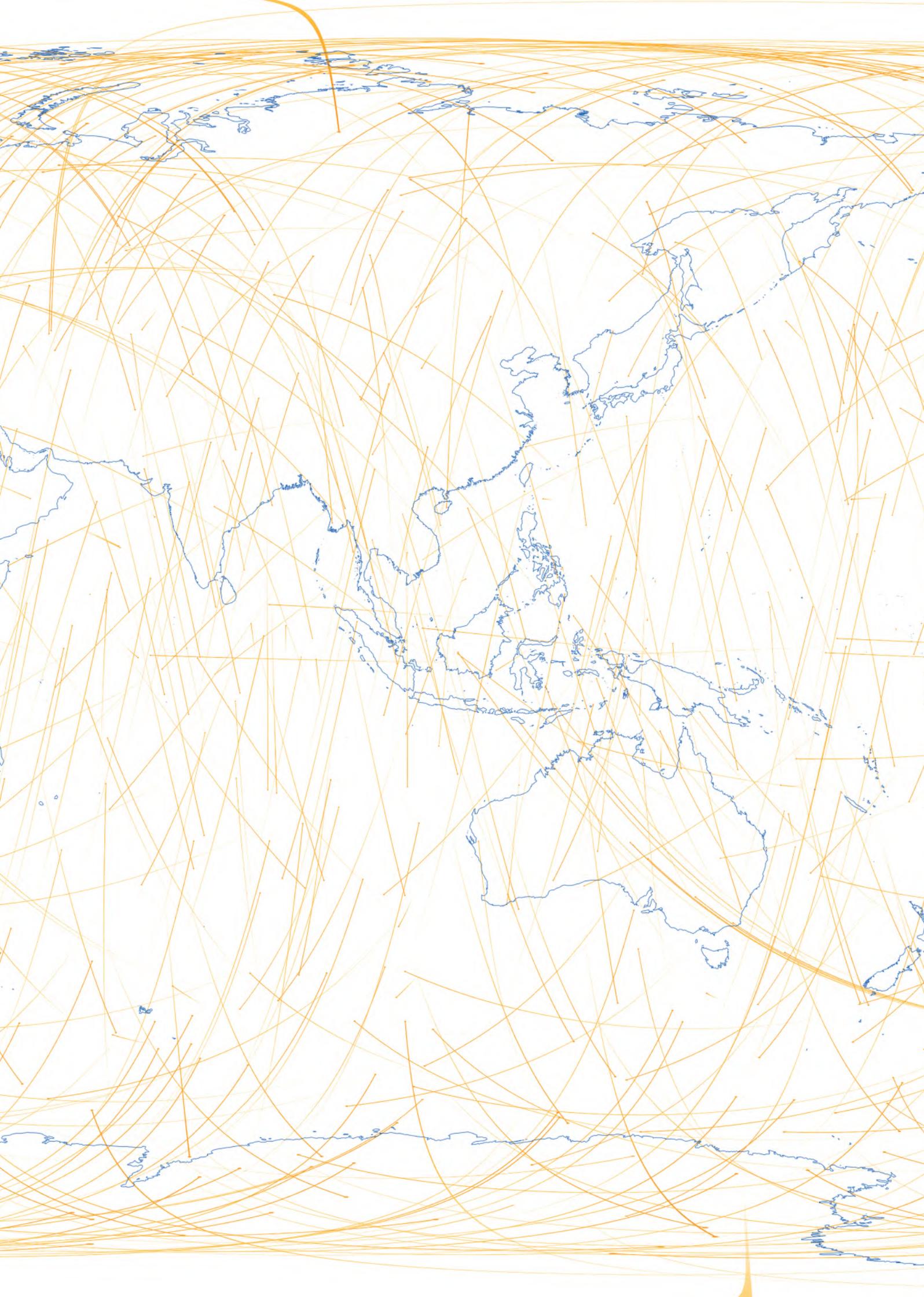
Outlook and Challenges

For the coming years the department will focus its activities on evolving its technology base, on participating in national and European Earth observation mission projects, and on developing its role as a partner in the management of EO research data within DLR and beyond.

One particular challenge will be the evolution of the overall architecture and technology base in light of a highly dynamic environment with increasingly shorter life cycles for proprietary system developments, third-party solutions, and applicable community standards. With a variety of new tools and technologies emerging and disappearing at high frequencies, system architectures have to be flexible and deployment procedures largely automated. To keep pace, it becomes imperative to avoid technology lock-in.

The departments' technology development focuses on providing flexible solutions for platform-oriented environments (cloud and HPC/HPDA) by integrating in-house developments with off-the-shelf and open source solutions. The results are generic, modular and service-oriented components configured for various EO applications. These innovations will be at the core of future mission PDGS, e.g. for HRWS and Tandem-L.

The multitude of emerging interdisciplinary platforms, such as GAIA-X, EuroHPC, EO SC, and Destination Earth, is an additional driver for our technology development to address demanding EO requirements. We will continue to observe these initiatives and evaluate opportunities to participate with EO specific service solutions.



Research and Applications Development

Research and Applications Development

Atmosphere

Orientation of the Department

The atmosphere is an important component of the Earth system. On the one hand, it protects Earth's surface from the influences of space. On the other hand, it has a great impact on Earth's climate and its changes due to complex chemical, dynamic, and radiative processes. Remote sensing of the atmosphere is one of the core competencies of DFD and therefore a central task in DFD's research and development.

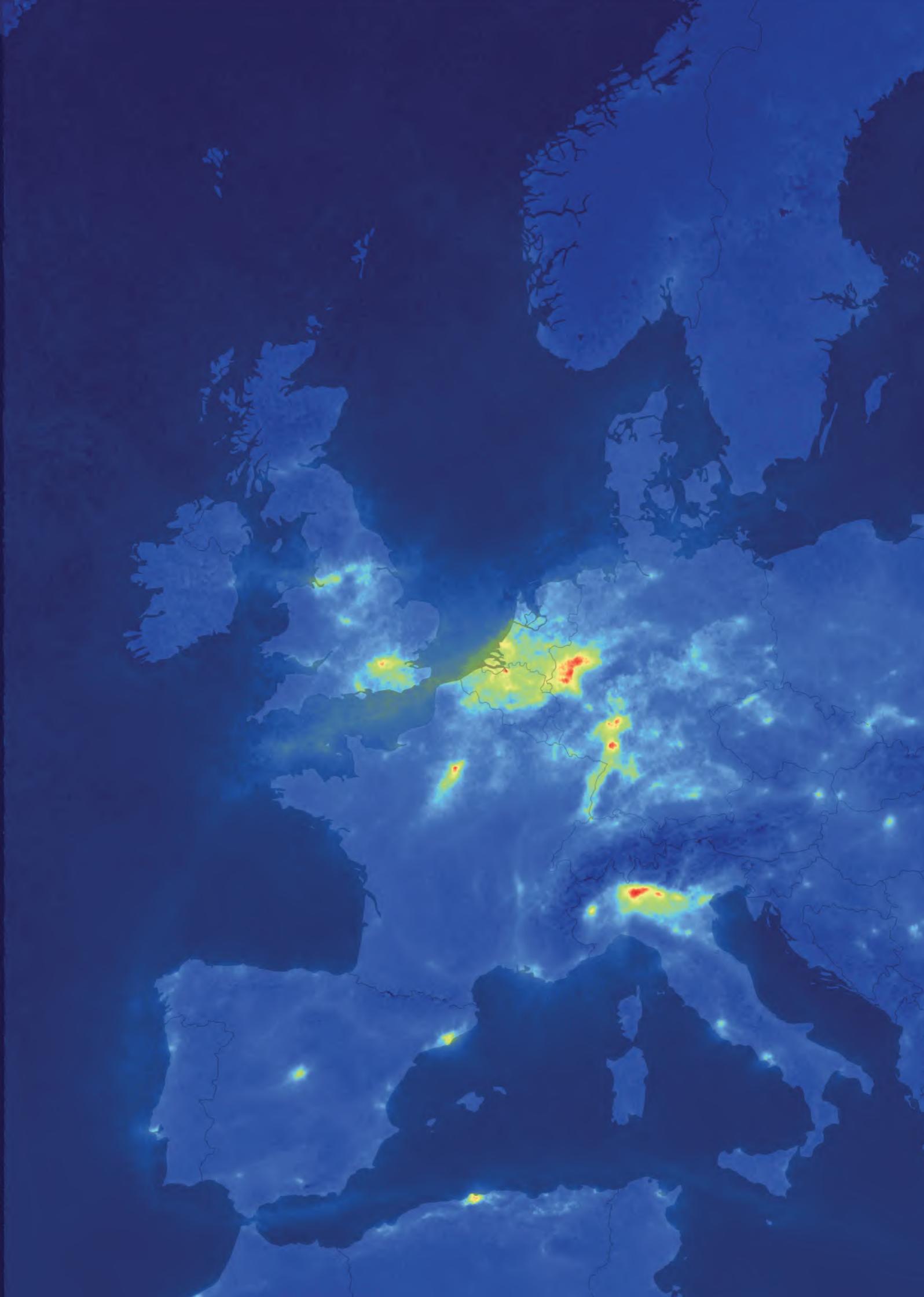
Research at the Atmosphere department is application-oriented and thus characterized by manifold cooperation with partners and stakeholders from science, industry, public administration, and politics. Research concentrates on the following main tasks. In the area of "atmospheric trace gases", the work is focused on characterizing their respective spatio-temporal distribution on a global to regional scale on a respective synoptic grid by combining data with models. The topic of "air quality" and its impact on human health and the relation to economic development is increasingly becoming a department focal point. Consistent estimation of the spatio-temporal distribution of "atmospheric aerosols" and in particular quantification of their long-term development based on data from various satellite-based sensors is being undertaken and also represents a visible contribution to the Copernicus program. Furthermore, aspects of "atmospheric dynamics" are addressed. The variability of large-scale planetary waves as well as small-scale gravity waves are characterized, which can contribute in particular to better understand the evolution of extreme weather events. One focus is on the development of our own measuring instruments for the remote sensing of atmospheric hydroxyl (airglow) and the recording of temperatures at the edge of space where changes (trends, cyclic variation etc.)

become particularly noticeable. This work is part of the international Network for the Detection of Mesospheric Change, NDMC and contributes to the World Climate Research Program. A web-based platform, the World Data Center for Remote Sensing of the Atmosphere (WDC-RSAT), serves as a digital development laboratory and information technology platform for all of the above-mentioned activities and provides tools to support the preparation and operation of new processors. Selected data and information products are also made available to the public via this platform.

We cover a broad spectrum of methodological developments for the generation of novel data, information, and services performed in the context of the above-mentioned topics. For example, in order to link various (extensive) existing data with each other and with complex numerical atmospheric models we apply data assimilation techniques. Powerful mathematical algorithms (e.g. non-linear spectral methods and AI) are also applied. In addition, we work on the further development of novel approaches for passive infrared (IR) atmospheric remote sensing such as tomography to derive 3D information from IR airglow images (temperature, winds, dynamics). By further developing and operating WDC-RSAT, selected data, information products, and user services can be provided also to the broader public. Measures are developed and applied to ensure stable operation, data management, control, and monitoring of DFD's own fleet of IR spectrometers and IR imagers at many different locations around the world.

In this respect, the department operates the only hardware laboratory at DFD where atmospheric instruments are developed to observe the hydroxyl layer in the middle atmosphere. This development line works essentially with off-the-shelf components from commercial vendors. Optimization and engineering for effective use of the two instrument lines GRIPS and FAIM are pursued inde-

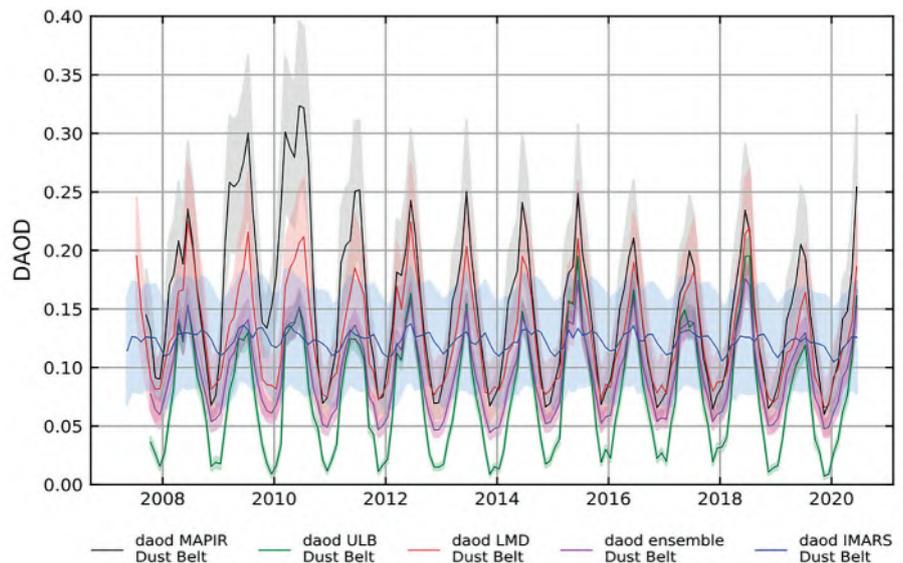
On the right: NO₂ (tropospheric vertical columns) over Europe in March/April 2019.



pendently. The GRIPS instrument line was originally taken over from University of Wuppertal and then further developed.

Beside DLR-internal networking, these focal points include potential cooperation with industrial companies and start-ups from various sectors such as the insurance industry, the automotive industry, medical technology, optics, and the NewSpace sector. There are also numerous cooperation agreements with research and development institutions,

BMBF, BMVI, and Bavarian state ministries. Research is also carried out in cooperation with other DLR institutes. Examples are common projects in the areas of the influence of environmental stressors on health (ME), aerosol monitoring, air quality, and the investigation of gravity waves (PA), as well as the estimation of trace gas distributions (IMF). Mention should be made at this point of the strong commitment to the Bavarian environmental research station (Umweltforschungsstation Schneefern-



Comparison of climate data records 2007 – 2020 of average Dust Aerosol Optical Depth (DAOD) obtained with four algorithms and an uncertainty-weighted ensemble of them for the global dust belt. Propagated uncertainty ranges of each dataset are depicted in paled shadows.

especially abroad. In addition, we contribute to societal tasks in the area of climate change, as formulated in particular in the Europe 2020 Strategy, the European Green Deal, the Kyoto Protocol, the Paris Agreement, and the UN Sustainable Development Goals. The department is also valued at ESA and NASA as a partner and provider of ideas for current and future missions and projects. These aspects will be discussed in more detail below.

Third-party funding comes from a wide range of sources, including European research framework programs, ESA and EUMETSAT, federal ministries such as

erhaus), UFS, on the Zugspitze mountain. There the department operates IR spectrometers for remote sensing of atmospheric airglow, which contributes to projects on behalf of the Free State of Bavaria and other entities. Examples include the development of a tomographic method to retrieve 3D information on atmospheric dynamics from IR-airglow camera data, an approach for IR remote sensing of tsunamis and volcanic activity, estimating the energy content of strong cyclones and validating satellite-based temperature measurements in the alpine atmosphere.

The department has a consistently high number of doctoral, master's and bachelor's students from STEM fields in Germany and abroad. The staff is international; their professional background is predominantly in the fields of physics, mathematics and geography.

Aerosols and Radiation

The focus of this research topic lies on the development of algorithms for the exploitation of satellite data to determine the distribution and properties of atmospheric aerosols and their relevance for questions of climate change, air quality and health, and solar irradiation. This focus is closely linked to the Copernicus services for climate change (C3S) and atmospheric monitoring (CAMS) as well as to ESA's Climate Change Initiative (CCI).

Through being in charge of continuous iteration with pilot users, we contributed significantly to the establishment and user-driven development of the CAMS service, also in the economic domain. Under the scientific leadership of DFD, work on aerosol algorithms in the CCI program led to the establishment of international standards for the production of aerosol climate data records from different satellite sensors with varying information content. The discussion on common standards resulted in the formation of the International Satellite Aerosol Science Network AEROSAT, which DFD co-chairs together with NASA (<https://aero-sat.org/>). Experiments in AEROSAT have shown that regional satellite-based aerosol time series from different instruments have different absolute values depending on sampling and quality filtering, but show great similarity in their temporal sequence and thus can be used for validated trend analyses.

In CCI and AEROSAT studies, the concept of pixel-wise uncertainties through error propagation calculations was successfully demonstrated with significant participation of DFD and subsequently adopted by NASA groups. Complementary to this,

an extension of the error propagation calculation for gridded level-3 data taking into account the correlation structures of errors in measured reflectance data in a case study on aerosols based on AVHRR data was developed in an EU-H2020 project in collaboration with meteorology experts. Accurate knowledge of the vertical distribution of aerosols is necessary for improved analysis of satellite datasets. For this purpose, in a feasibility study at UFS, DFD developed a concept for 3D surveying with drones, which is to be implemented there and at other stations of the WMO-GAW network.

As a basis for climate change research, the consistency of independently produced satellite datasets of various climate variables must be confirmed. DFD therefore coordinated overarching work in the CCI program that led to the first comprehensive definition of "consistency" and the design of its systematic verification. In the DFD-internal TIMELINE project, a novel Level 3 format was developed for rapidly changing cloud parameter monthly means, which sorts the data according to local time of day and thus enables the derivation of consistent time series from data from many sensors, taking the diurnal cycle into account.

Based on the above research, we are in charge of the generation of climate data records of atmospheric composition (ozone, greenhouse gases, aerosols) for the C3S for continuous observation of these essential climate variables. Here we were able to demonstrate that error-weighted ensemble products can combine the best characteristics of several algorithms for the same sensor. A new Bayesian method for analyzing the interaction of aerosols and clouds (the climate radiative forcing with the largest uncertainty in the IPCC reports) from satellite and model datasets was developed in the DLR KliSAW project together with PA and applied in a first case study.

"Under the scientific leadership of DFD, work on aerosol algorithms in the CCI program led to the establishment of international standards"



Trace Gases

This research area focuses on monitoring and analyzing ground-level pollutants, especially nitrogen dioxide, ozone and particulate matter, from the regional down to the urban scale. Satellite observations allow quasi-global coverage, while local observations and modelling enable very high-resolution monitoring at street level where people live. The data are based on satellite measurements from the European systems MetOP and Sentinel, as well as NASA’s AURA, Terra and Aqua missions. The European Sentinel missions currently provide powerful satellite instruments for measuring atmospheric pollutants, namely NO₂ by TropOMI on Sentinel-5P and aerosols by SLSTR on Sentinel-3. As they record tropospheric column densities at fixed local times only (and not during night time), atmospheric modelling and inversion is needed to derive surface concentrations, emissions from specific sources like traffic, and their temporal variations (e.g. diurnal variation). To complement satellite observations and further constrain models, inclusion of other data sources is indispensable. We thus integrate especially ground-based measurements as provided by the European Environment Agency as well as by the Copernicus Atmospheric Monitoring Services and European and national emission registers (e.g. GRETA), e.g. in the EU H2020 projects NextGEOSS and the EuroGEO flagship project e-shape.

Methodologically, numerical chemical transport models (SACADA, POLYPHEMUS, PALM4U, ROSE) in combination with statistical data assimilation of observations (4D-Var and ensemble methods) are further developed and deployed. The weather model WRF (Weather Research and Forecast) is used as meteorological driver.

Corona lockdown effect: mean NO₂ levels in spring 2019, 2020, and 2021. In 2021, a further increased resolution of Sentinel-5P results in greater spatial detail.

As part of DFD’s *terabyte* project, special HPC and HPDA methods are tested and used in collaboration with the Leibniz Supercomputing Centre to enable the assimilation of measurement data into our models in near real-time and to carry out turbulence-resolving large-eddy simulations of urban climate and air pollution.

The research described above forms the basis for answering various research questions and developing applications. For example, using a chemical transport model (POLYPHEMUS/DLR), we calculated the spatio-temporal development of NO₂ pollution against pre-Corona emission levels. Comparison with these former observations revealed a decrease in NO₂ pollution of around 30 to 40 percent across national borders during the Covid19 lockdown. These results were the first evidence of a Corona effect on air pollution levels with weather influences being eliminated. Atmospheric models are also used for trace gas retrieval. We showed that by combining satellite-based retrieval approaches with higher-resolution chemical transport models significant improvements can be achieved. Using this approach, we are able to quantify urban pollution plumes, closing mass balances, and to evaluate urban climate models, as we demonstrate in the German research initiative Urban Climate Under Change [UC]².

Furthermore, the availability of area-wide air pollution information for regions and urban areas combined with a forecast covering a few days allows us to estimate the associated additional health risk due to short-term exposure to a mixture of pollutants (Aggregated Risk Index, ARI). For a given health end-point, e.g. mortality by cardiovascular diseases, the risk calculation is based on incremental relative risk values provided by the World Health Organization WHO. Distinctions can be made according to age classes and specific diseases. Within the framework of a cooperation agreement with the AOK-Baden-Württemberg in cooperation with DLR-ME and within the

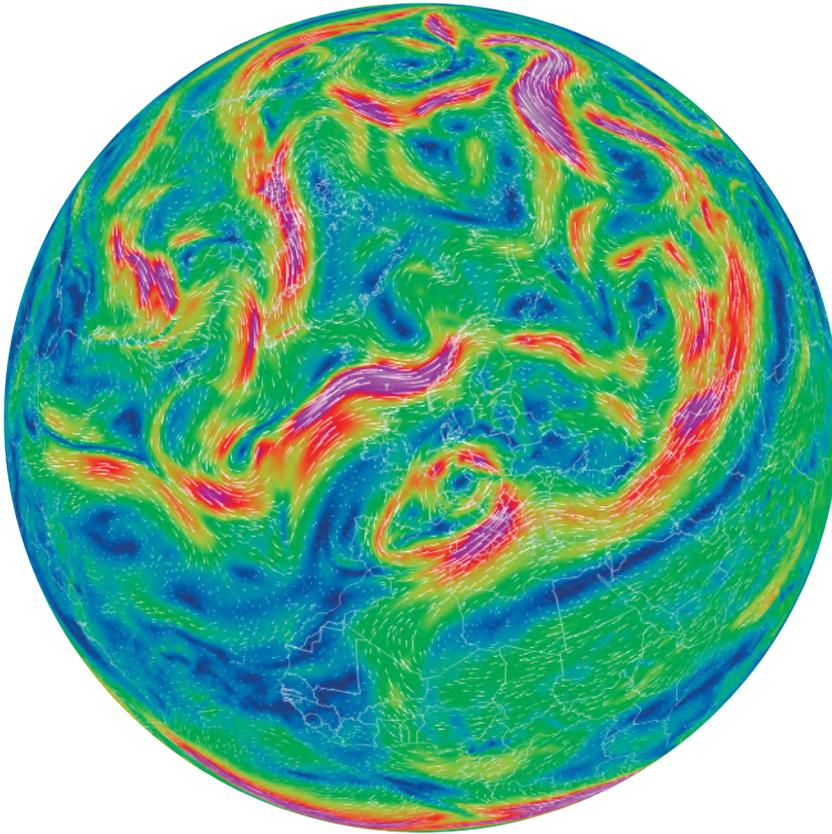


The PALM-4U urban climate model enables an analysis of air pollution down to the street level. The figure shows the NO₂ concentration at one of the pollution hotspots in Germany: Landshuter Allee in Munich.

framework of several third-party-funded projects, a first web-based bioclimatic information system (BioCliS) was established at the district level (see below) and is constantly being expanded. All relevant satellite- and model-based data sources are being combined for integrated health risk assessments in the urban environment, including air pollution and thermal comfort, to strengthen climate resilient urban planning and to improve quality of life. As economic activity is often connected to air quality, an indicator is being

developed allowing the quantitative investigation of the connection between economic development in a region and its air quality. Such an indicator (recently awarded the prize of the DLR Vision Competition), which can be created for any place in the world, can in this way reflect the level of economic development there and is of considerable interest to institutions such as the World Economic Forum, private companies, or the EU's Green and Circular Economy program.

BioCliS provides information about the accumulative health risks caused by air pollution, heat stress and cold stress in the form of daily, color-coded risk maps and forecasts covering two days.



A cyclone cut off from the jet stream over southern Germany caused the flood disaster in July 2021.

Dynamics

Research in this domain concentrates primarily on the area of atmospheric eddy/wave dynamics, i.e. planetary waves, gravity waves, infrasound waves, and turbulence. The focus is on the altitude range of the upper mesosphere and lower thermosphere (UMLT), the transition region to space, where dynamic signals are particularly strong due to the low air pressure. The data basis consists on the one hand of satellite-based measurements (e.g. TIMED-SABER). On the other hand, for IR remote sensing of this altitude range, our own passive ground-based and partly also airborne remote sensing sensors (14 GRound-based Infrared P-branch Spectrometers, GRIPS, and seven Fast Airglow Imagers, FAIM) are deployed at various locations worldwide and further developed with respect to optics, algorithms and control. This enables the detection of spatio-temporally very small-scale structures, such as turbulence, which the satellite cannot monitor. The natural phenomenon of atmospheric airglow is exploited in the process. The work is carried out in close institutional cooperation with the University of Augsburg (in a Collaborative Professorship) and with UFS partners. It is part of the NDMC, which DFD founded in 2008, as well as the Virtual Alpine Observatory (VAO), a European network initiated in 2012. Both programs are coordinated by the department. Re-analysis, radiosonde, and satellite data (e.g. from ADM/AEOLUS, Sentinel-5P) are used to cover the altitude range of the stratosphere and troposphere.

The methods used include mathematical approaches such as linear and non-linear statistical methods as well as complex spectral analysis for spatio-temporal data series (autoregressive and moving-average approaches such as the maximum entropy method, bi-spectral analysis, wavelets, harmonic analysis, empirical decomposition methods, and increasingly also artificial intelligence (AI) approaches) and for numerical atmospheric models

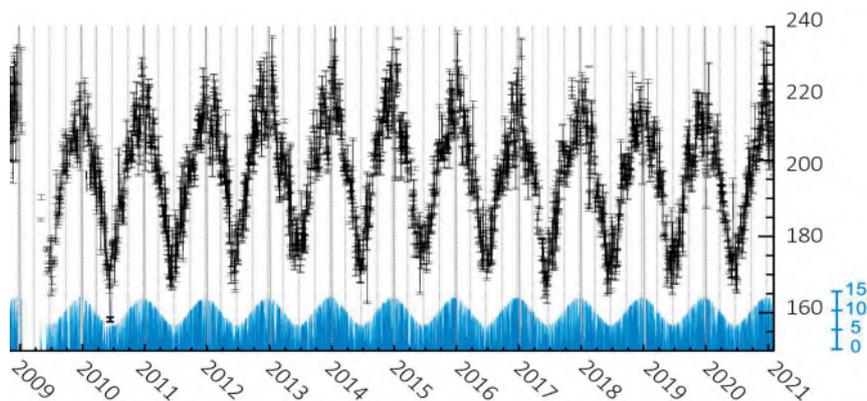
(WRF, as well as the wave propagation models HARPA/DLR and GROGRAT). The large amount of data makes it necessary to apply and adapt efficient algorithms in the field of pattern recognition and meanwhile also AI methods. The use of quantum-accelerated machine learning is being prepared.

The described research contributes to the improvement of climate models, in which especially gravity waves are often only parameterized and the vortex-related redistribution of energy and momentum can only be roughly captured. Thus, with the above-mentioned data basis of GRIPS and FAIM supported by satellite-based measurements, we quantified the amount of energy transported by gravity waves and derived the horizontal direction of energy transport. This was found to strongly vary with season and wave frequency. Even wave-induced turbulence and non-linear wave-wave interaction was identified and it could be shown that heating due to dynamics obviously is of the same order of magnitude as chemical heating.

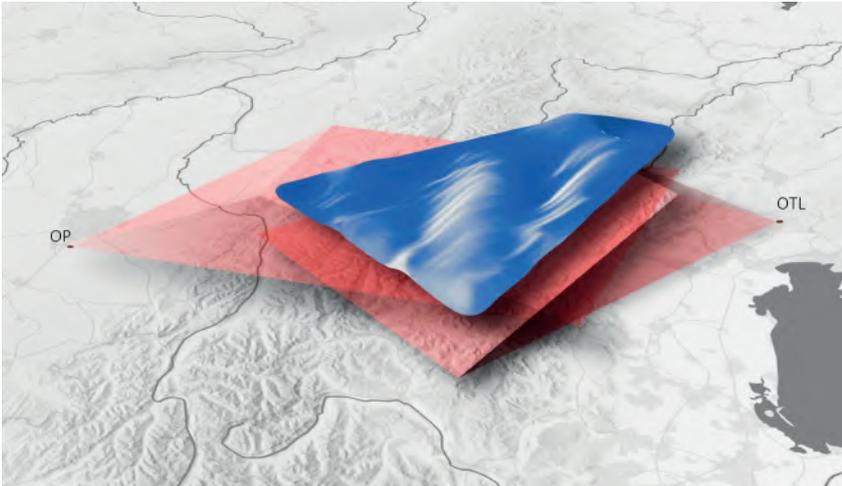
We operate a large number of instruments that are unique worldwide, and we derive much information operationally. The operational estimation of energy transmitted to the background is work in progress and based on AI approaches. Additionally, we succeeded in developing

a tomographic algorithm allowing us to quantify the three-dimensional structure of a gravity wave in the UMLT region for the first time with high spatial (3D) and temporal resolution by using simultaneous measurements from two FAIM instruments located a few hundred kilometers apart from each other and observing the same part of the sky. This technique now also allows us to derive from these measurements the background wind at these altitudes. We are developing plans to put such instruments on a satellite.

Other research questions are linked to planetary waves, which characterize the large-scale dynamics of the whole atmosphere. For example, they are well known to be drivers of weather patterns, especially in the mid-latitudes. Our analysis indicates that planetary wave activity is changing due to climate change. Especially, the so-called "16-day planetary wave" seems to show a tendency to strengthen while the "5-day planetary wave" behaves the opposite way. This can possibly contribute to an increase in the formation of the stationary weather patterns that are frequently associated with extremes, such as the recent 2021 floods in central Europe or the heat waves in 2003 and 2015. As another example we found a hint that the long-term temperature trends in the UMLT



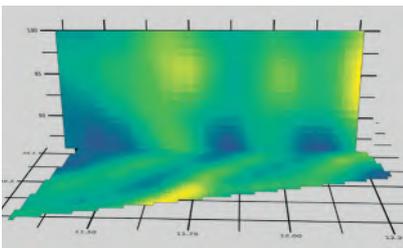
GRIPS measurements: Gapless time series of temperature at 87 km altitude over southern Germany from 2009 to present (black: hydroxide temperature in Kelvin, blue: duration of the measurement in hours)



FAIM measurement from Oberpfaffenhofen (OP) and Otlica (OTL): spatial structure of a gravity wave over the Alps at an altitude of about 90 km

region might be at least partly associated with the meridional planetary wave structure.

Low-pressure areas as well as natural disasters such as tsunamis, volcanoes and earthquakes generate amongst other effects infrasound that propagates very quickly through the atmosphere. This can be used for early warning by measuring it over an epicenter over the ocean using IR remote sensing and modelling its propagation (HARPA/DLR propagation model). This approach was proposed by DFD researchers in 2010 and has since been confirmed by extensive modelling by a U.S. research group. In order to test the approach experimentally, a suitably designed and equipped measurement container was developed containing two FAIM cameras and a GRIPS spectrometer and will be set up at the European Southern Observatory (ESO) in Chile (within the DLR OASIS project) from 2022 onwards. A subduction zone runs off the coast of Chile and the probability of earthquakes and tsunamis is comparatively high there and nearby.



Tomography of the gravity wave shown above in space and time

World Data Center for Remote Sensing of the Atmosphere

WDC-RSAT (<https://wdc.dlr.de>) was founded in 2003 as an atmospheric remote sensing component in the system of so-called "World Data Centers" coordinated by the International Council for Science (ICSU) and the World Meteorological Organization (WMO). It was accredited as a data publication agent at the Technical Information Library Hannover. As of 2020, a formal mandate no longer exists. Nevertheless, DFD continues to contribute to the WDC family as an Associate Member without external obligations. For practical reasons and with the support of ICSU, the WDC-RSAT designation is maintained in external relations. Therefore, the focus of WDC-RSAT has increasingly shifted from archiving, documenting and distributing data within the family of WDCs to a digital development environment for DFD's atmospheric research and projects. WDC today supports many of the department's developments as a technical platform and thus forms its IT backbone and IT-development and -implementation environment. At the same time, selected data and information products and services also remain accessible to the public.

Developments in the WDC focused on the following areas:

Computing-on-Demand: Various numerical models of the atmosphere and complex analysis tools can be configured by researchers who do not have to be experts on the respective model themselves. This supports and accelerates research and development work and is implemented in particular through the use of so-called "dashboard" technologies. The Computing-on-Demand service is only available internally.

Service-on-Demand and Data-on-Demand: The "WDC-Map-Viewer" enables researchers to display complex and large datasets from satellites, models, and in the future also from re-analyses

(2D and soon also 3D in space and for selectable times) without having to deal with time-consuming data handling. For selected spatio-temporal sections, the desired data can be downloaded for the momentary project task. For this particular application, the OGC concept of distributed archives is increasingly used. This service is also open to external access.

Operation-on-Demand: DFD operates a large number of ground-based instruments for remote sensing of the upper atmosphere (NDMC and OASIS). In the future, it should be possible to control these instruments via the WDC platform, e.g. if data are to be recorded simultaneously with the overflight of a satellite for validation purposes, or if an exceptional event occurs, such as the passage of a wave disturbance induced by a tsunami. Procedures and user-friendly interfaces are being developed to enable automatic or individually-needed alignment of instruments to a specific region of the atmosphere and to control the corresponding data flows. This service is available only internally. However, the technology is a potential candidate for transfer to other applications.

NDMC host function: WDC serves also as host of the international Network for the Detection of Mesospheric Change, NDMC, which is a contribution to the UN World Climate Research Program. Quicklooks of datasets from many ground-based instruments for remote sensing of the atmosphere are presented here in near real-time, supplemented by model-based information, such as temporal developments of meteorology (wind, temperature in the lower atmosphere) and refined data products, such as time series of gravity wave potential energy or the Brunt-Vaisala frequency. In the future, matching satellite-based data products (e.g. TIMED-SABER) will also be added (e.g. planetary wave activity for this altitude range, or the spatial distribution of trace gases).



UFS project interface: In addition, WDC has been used in close association with the Leibniz Supercomputing Centre through the UFS-platform "AlpEnDAC" (<https://alpendac.eu>) for more than six years. AlpEnDAC is supported by the Bay-StMUV, and operated and continuously developed within the framework of the VAO. Some WDC services are therefore accessible via AlpEnDAC. One example is the Bioclimatic Information System, BioCliS. This system provides an intuitively easy-to-use web interface on which a county can be selected by mouse click from an overview map of Central Europe, currently covering Germany, the Czech Republic, the Alpine region, and parts of France. For this district, the current and future (two-day forecast) situation with regard to air quality, meteorology, and

"Optical wave radar" for the Alpine region: all-sky observation of atmospheric waves over the Alpine region (diameter of the field of view approx. 500 km)

the resulting additional health risk for various population groups (age, previous illness) is then indicated. The system is also available with significantly higher spatial resolution and more detailed information (expert mode).

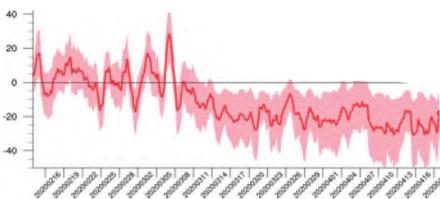
Outlook and Challenges

Building on the developments described above, various goals are to be achieved in the next few years in cooperation with partners from the research, industry, and public administration sectors. For example, and in line with Europe's Destination Earth program, first steps towards building a digital twin will be taken for recording air quality in selected regions and urban areas with high spatio-temporal resolution and high accuracy, which also allows an assessment of an associated additional health risk. The system is to be used both in near real-time and for scenarios (e.g. climate adaptation, construction, and traffic route planning). In this context, a transfer of mathematical methods from atmospheric physics and AI is carried out to further support the development of a numerical epidemic spread model with the aim of being able to even better identify regions with increased vulnerability to infectious diseases (influenza, Covid-19) due to increased pollution. Such information will then also be included in WDC (BioClis). Furthermore, the development of an indicator based on air quality information derived from satellite data for continuously monitoring economic development in any region is to be continued.

In addition, innovative data and information products will be developed to improve the resilience of the economy and society in a changing climate. Examples include optimizing the precision of storm track forecasts for particularly severe cyclones (so-called Vb systems) by incorporating data from DFD's own instrument line GRIPS and FAIM, and improving the estimation of the intensity of extreme weather situations, such as heat waves in Germany, Europe and worldwide, as they

are likely to occur more frequently as a result of changing atmospheric dynamics. Another focus is on further improving the reliability of tsunami early warning by incorporating airglow measurements. In this context, the above-mentioned cooperation with ESO is being carried out, whereby such measurements will be made available in real time by DFD from 2022 in Paranal, Chile, also for Chilean Early Warning authorities (SHOA). The data will also be used subsequently to correct the astronomical observations of ESO with regard to light pollution ("astronomical weather") and will also be used to support NASA's StarShade project ("second Earth"). Building on the OASIS goals (application, research, technology development), the aim is to develop a proposal for a satellite-based mission in the area of cube-sat swarms. ESA and the BayStMUV have expressed interest, and initial talks have been held with the space industry. In another priority area, work is being carried out in cooperation with international partners on the development of new AI algorithms for consistent retrieval of aerosol mixtures (type differentiation) from a combination of several satellite sensors. This research thus contributes to reducing the uncertainty of the overall cooling effect of aerosols on Earth's radiation balance, which according to the IPCC is associated with the greatest uncertainty.

Technology transfer and cooperation potentials lie in various fields, such as medicine (IR tomography methods), the vehicle industry (vehicle data for green routing), the insurance industry (extreme weather), the financial industry (Circular and Green Economy), as well as public administration (urban and transport planning), policy consulting (Bavarian Ministries of Environment and Health), and development and aid organizations (World Bank, UNHCR, German Red Cross).



Difference between NO₂ concentrations measured at 25 ground stations in Lombardy between February 15 and April 20, 2021 using the simulation of the air quality model POLYPHEMUS/DLR. A reduction of NO₂ concentrations is evident from March 8 on.

On the right: NO₂ (tropospheric vertical columns) over Europe during the Corona Lockdown in March/April 2020. Compared to the situation in March/April 2019 (see p. 70), the NO₂ reduction over all of Europe is estimated to be 38 ± 5%, taking into account the impact of long-term trends, population density, and meteorology.



Land Surface Dynamics

Orientation of the Department

Societies' socio-economic transformation, human-induced environmental change, as well as climate change have serious consequences for the livelihoods and ecosystems on our planet. How we face these changes and deal with them is a crucial challenge directly affecting our future. In the context of the Land Surface Dynamics department, DFD studies and quantifies global change as manifested on Earth's land surface, and addresses socio-relevant questions. We develop Earth observation-based geoinformation products for science, industry, stakeholders and decision makers, and for civil society. This work is mainly based on the automated extraction of information from large heterogeneous datasets (big earth data, often referred to as high volume data processing) using machine learning and AI methods deployed on powerful computer clusters (*terabyte* infrastructure, GeoFarm, and DFD's Calvus cluster). We produce research results based on both established and innovative methods, are involved in a wide range of geoinformatics and geoscience data analytics tasks, and employ all types of national and international EO sensors (optical, multispectral, hyperspectral, thermal, SAR) at all spatial scales from local to global. The main sensor "work horses" are the U.S. Landsat, MODIS, and AVHRR missions/sensors, the ESA Sentinel-1, Sentinel-2, and Sentinel-3 missions, the national TerraSAR-X, TanDEM-X, and in the near future EnMAP, DLR's programmatic DESIS and FireBIRD missions, and the Japanese ALOS data archive, for example, as well as the ever-growing archives of former and current high-resolution sensors such as IKONOS, QuickBird, WorldView and PlanetScope.

"By working closely with DFD's ground segment engineering teams and the Information Technology department, we are able to operationally process extensive multi-decadal time series"

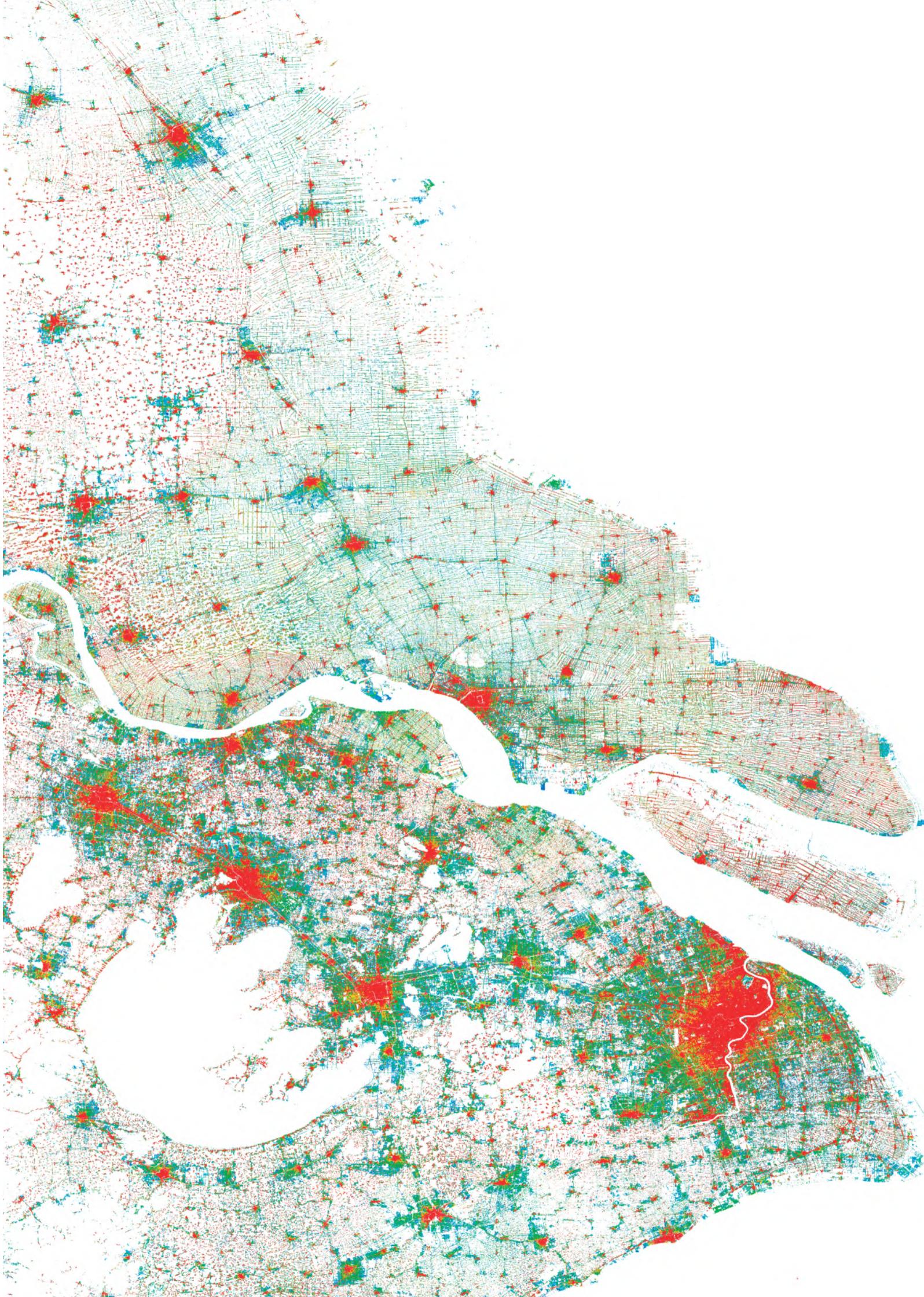
World Settlement Footprint Evolution data for Beijing, China. The WSF Evolution provides unique insights into the annual growth of global settlement area between 1985-2015. To create the WSF Evolution, over seven million images from the US Landsat satellites were analyzed using machine learning approaches.

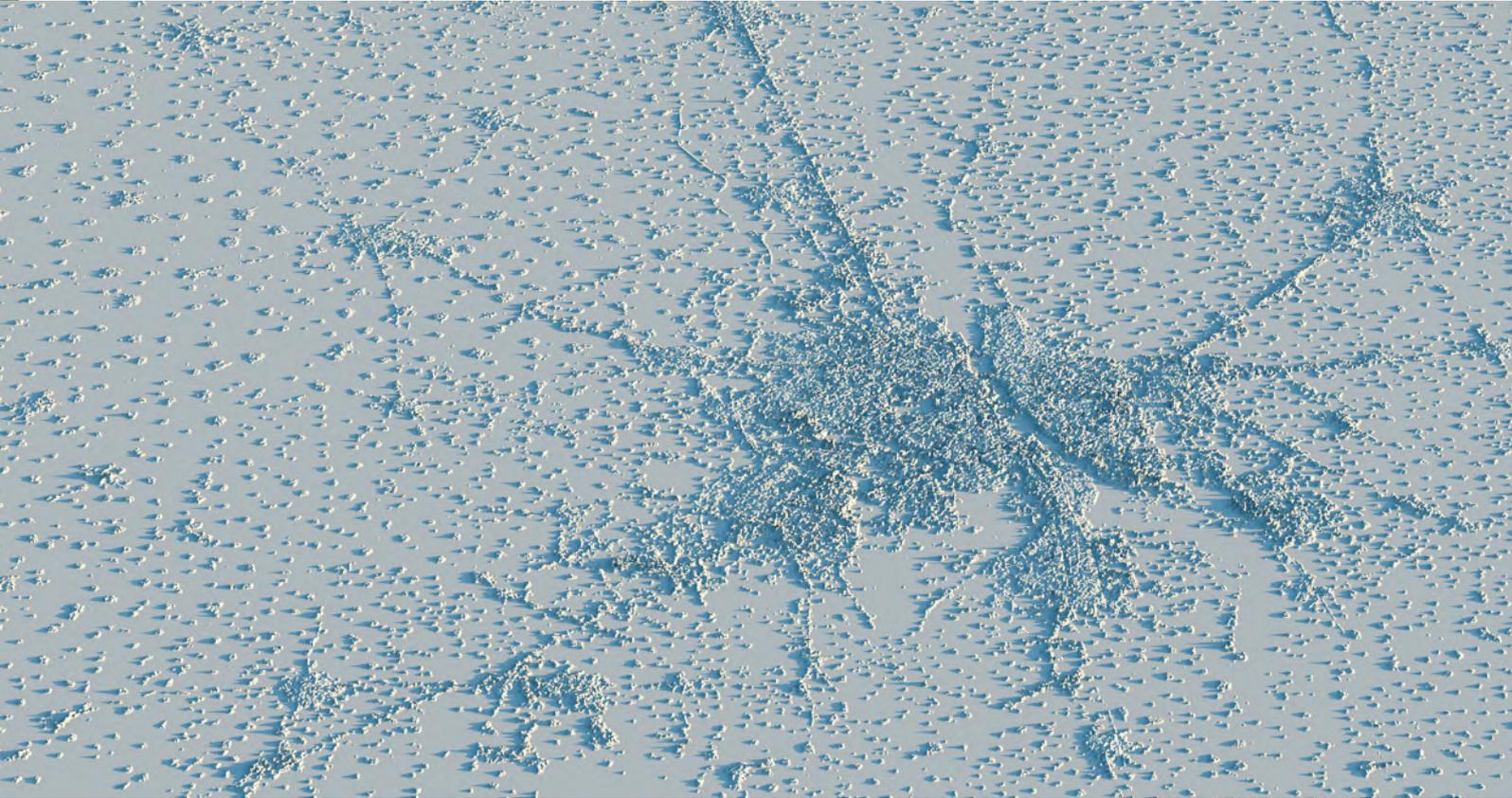
By working closely with DFD's ground segment engineering teams and the Information Technology department, we are able to operationally process extensive multi-decadal time series and associated statistical parameters such as variability, anomalies, and trends. In addition, we have recently begun to explore time-series-based forecasting approaches, as we believe that especially planners and decision makers need knowledge not only of the past dynamics and current state of our land surface, but also on likely future developments.

Our thematic domains for research on land surface dynamics are currently addressed by the following department teams: Smart Cities and Spatial Development, Agroecosystems and Phenology (including forests), Coasts and River Basins, Polar and Cold Regions, and SAR Topography.

At the time of reporting, four teams focus on key livelihood and economic sectors and natural ecosystems. A fifth team has traditionally concentrated on methodological developments for the use of SAR data and is also operationally involved in SAR mission execution, creating products at the end of the value chain (e.g., elevation models). In addition, the groups that focus on application areas have a wide range of methodological expertise, e.g., in hyperspectral and thermal infrared data analysis and AI methods.

Third party funding in the field of land surface dynamics comes from ESA, HGF, BMWK, BMBF, BMEL, BMUV, DFG, DAAD, Airbus, the World Bank, BASF, and others. Additionally, for several years now, DFD's research and development, as well as applied research in this context, also contributes to and directly feeds into the curricula of a larger number of Master of Science and engineering programs in remote sensing, such as in institutional collaboration with University of Würzburg, at the University of Jena, the Hochschule für Technik Stuttgart, the University of Tübingen, and LMU Munich.





Perspective view on Cairo, Egypt, generated on the basis of the World Settlement Footprint 3D. The data set represents the first global and consistent 3D survey of the worldwide building stock.

Smart Cities and Spatial Development

Today, around 7.9 billion people live on Earth, and by 2050 this figure is expected to rise to nine billion. Seventy percent of them will then live in cities. As political, economic and cultural centers, urban agglomerations play a key role. However, providing adequate living conditions and jobs for the growing urban population while maintaining a sustainable ecological footprint is a tremendous challenge that requires a solid planning basis. In this context DFD develops methods and application-oriented geoinformation products for detailed characterization and monitoring of the built environment, from the local level to the global scale. Here, the focus is on the development of operational, high performance processing and analysis frameworks for the provision

of novel data and assessment criteria for global urbanization, smart cities, and sustainable spatial development. The related technical systems solutions include highly automated information extraction from large-volume and heterogeneous datasets (big Earth data). Machine learning, AI, and distributed computing (high performance processing and data analytics) are jointly employed for this purpose. These approaches are supplemented by modern information and communication technologies that allow autonomous control of data access, management and processing (automation).

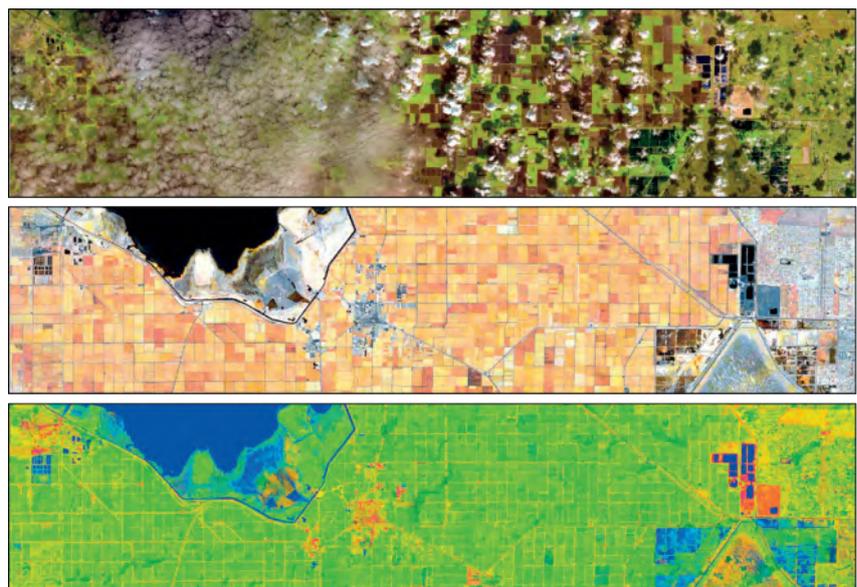
The ability to leverage the use of scalable high performance computing platforms with direct access to full mission archives will become a key factor to ensure the

effective and efficient exploitation of modern Earth observation missions by a wide range of users who do not have direct or performant access to data archives and powerful processing infrastructures. Thus, DFD has implemented the TimeScan methodology and processor, which is a modular workflow tool for the flexible and scalable processing of large image data collections, on a variety of private or public computing clusters. Technically, the TimeScan processor aggregates the information content of thousands of single images into a higher-level information product with significantly reduced data volume. The operational implementation of the TimeScan processing chain has already been used to process several million Landsat, Sentinel-1 and Sentinel-2 scenes with more than 20 petabytes of data at different processing clusters (e.g., DFD GeoFarm, Google Earth Engine, IT4Innovations HPC). The TimeScan technology provides the basis for DLR's key global urban monitoring initiatives such as the Global Urban Footprint (GUF®) and World Settlement Footprint (WSF). In 2018, the cloudeo company was granted a non-exclusive license for the TimeScan software.

In 2016, DFD released the Global Urban Footprint (GUF®), the world's first consistent high-resolution mapping of all settlements on Earth. The GUF® raster dataset showed the global human settlement pattern in urban and rural environments at the so far unprecedented spatial resolution of 12 m per grid cell (<http://www.dlr.de/guf>). It was derived from SAR imagery collected between 2011 and 2013 by TerraSAR-X and TanDEM-X. An exclusive license for the commercial use of GUF® has been granted to Airbus. Regarding non-commercial use cases, more than 800 institutions from over 46 countries have requested and obtained GUF® data so far, including the United Nations, World Bank, Asian Development Bank, OECD, WWF, Human Rights Watch, Google, Meta, ESRI, ESA, and NASA.

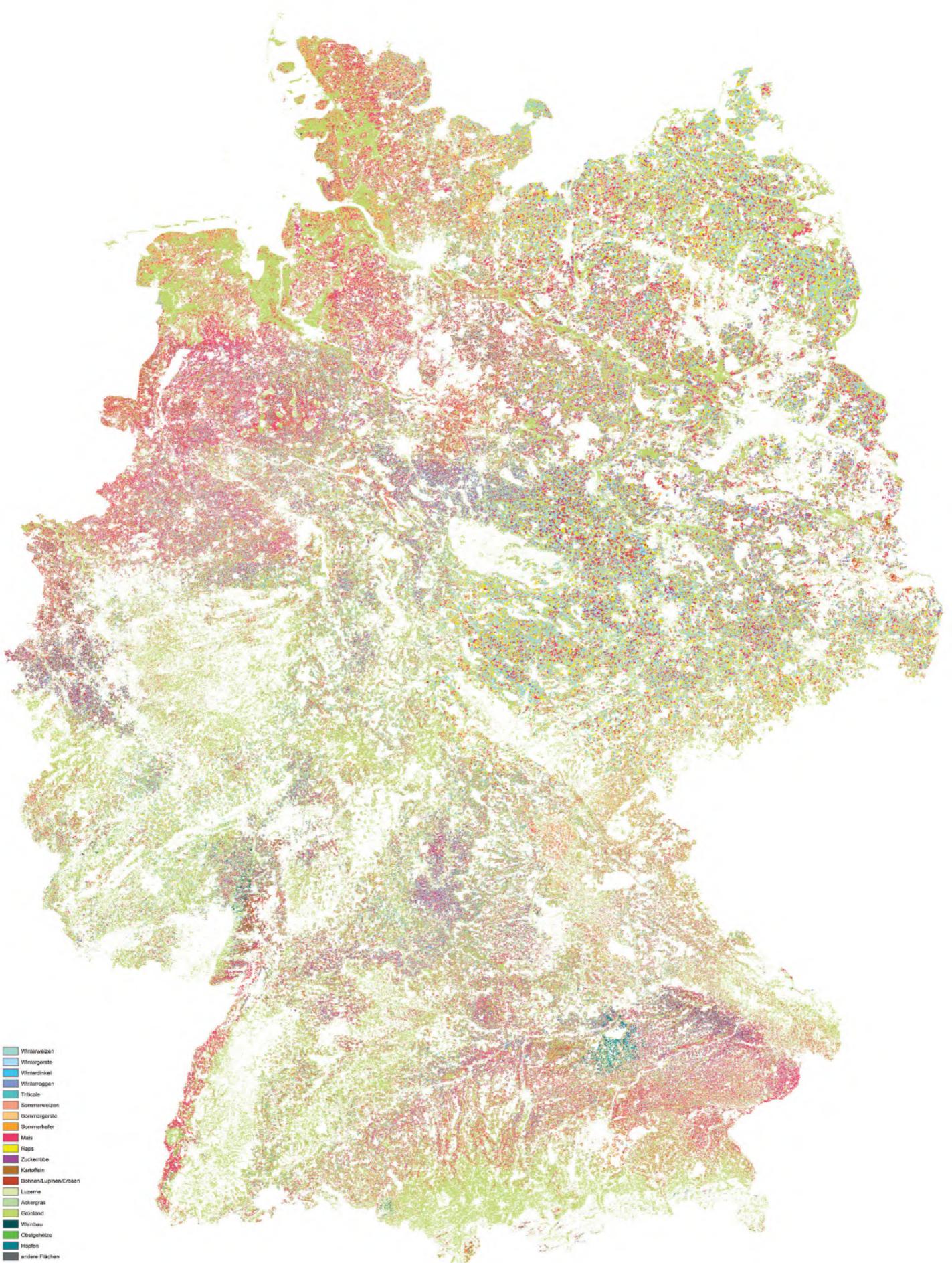
Building on GUF®, the DFD has initiated the WSF as a follow-up development. The WSF initiative aims at comprehensive improvements compared to GUF® and other state-of-the-art datasets and technologies for global urban observation. This includes the use of free and open input data (Sentinel-1, Sentinel-2, Landsat), enhanced spatial and thematic accuracy, a constant global updating capability, and an extended suite of thematic products. The first WSF dataset released in 2018 was WSF 2015, a GUF-like binary human settlement mask with 10 m spatial resolution derived for the target year 2015 through joint analysis of more than 230,000 Sentinel-1 radar images and more than 460,000 multi-spectral Landsat scenes. A first update of this layer for 2019, now based on Sentinel-1 and Sentinel-2 data instead of Landsat, is to be released in 2022. In addition to this capability for future updates of global WSF mapping, DFD has simultaneously developed a methodology and product suite, termed "WSF evolution". It provides annual information on the global development of human settlements from 1985-2019 at a spatial

Single Landsat scene compared with TimeScan products. TimeScan condenses the spectral and temporal information from hundreds or thousands of individual images into a single, cloud-free image, that reflects the temporal behavior of a building, vegetation, and water index.



resolution of 30 m. WSF evolution is based on a multi-petabyte analysis of the entire Landsat archive using a technical framework that has jointly been deployed at the Google Earth Engine by researchers from DFD and Google. WSF 2019 and WSF evolution will soon be complemented by an imperviousness version, specifying the percent impervious surface (or, as an inverse, the urban greenness) for the settlement area outlined by WSF 2019 and WSF evolution, respectively. Parts of the WSF suite are provided via ESA's Urban Thematic Exploitation Platform Project, U-TEP, as well as via DFD's Geoservice. With the World Settlement Footprint 3D (WSF 3D), DFD has recently also generated the first spatially consistent 3D survey of global building stock. WSF 3D estimates the fraction, total area, average height, and total volume of buildings worldwide, based on an analysis of 12 m digital elevation data and radar imagery collected by the TanDEM-X mission in combination with the WSF 2019 imperviousness layer. Finally, the release of a WSF population layer is planned for 2022/23. This dataset will provide a more precise overview of global population distribution. The technology and data of the WSF suite are expected to make an important contribution to the collection of empirical evidence on global urbanization and to the implementation of indicator-based environmental monitoring programs.

At local scale, DFD has pushed technical innovation to support the improvement of urban climate and the quality of life in cities. In this context, a new method has been developed to map green roofs and identify appropriate potential areas for roof greening. Green roofs make cities more livable and help reduce the effects of climate change (e.g., heat waves, flash floods) in urban agglomerations. However, only very few cities have detailed information on the number of green roofs and roofs that can potentially be planted. With the new operational method developed at DFD this knowledge deficit can now be overcome. The approach makes use of high-resolution infrared images combined with cadastral data (building contours, 3D city models) to generate an inventory of all green roofs in a given area of interest. In 2015, DFD researchers received the Green Roof Leadership Award in the category "Green Roof Pioneers" during the 4th International Green Roof Congress held in Istanbul. In 2016, the Roof Greening Project was selected as a lighthouse initiative to be presented at the 2016 Week of the Environment in the park of Bellevue Palace in Berlin. A license for the commercial use of the software to detect green roofs has been granted to EFTAS GmbH.



- Winterweizen
- Wintergerste
- Winterdinkel
- Winterroggen
- Triticale
- Sommerweizen
- Sommergerste
- Sommerhafer
- Mais
- Raps
- Zuckerrübe
- Kartoffeln
- Bohnen/Lupinen/Erbsen
- Lucerne
- Ackergras
- Grünland
- Weinbau
- Obstgehölze
- Hopfen
- andere Flächen

Agroecosystems and Phenology

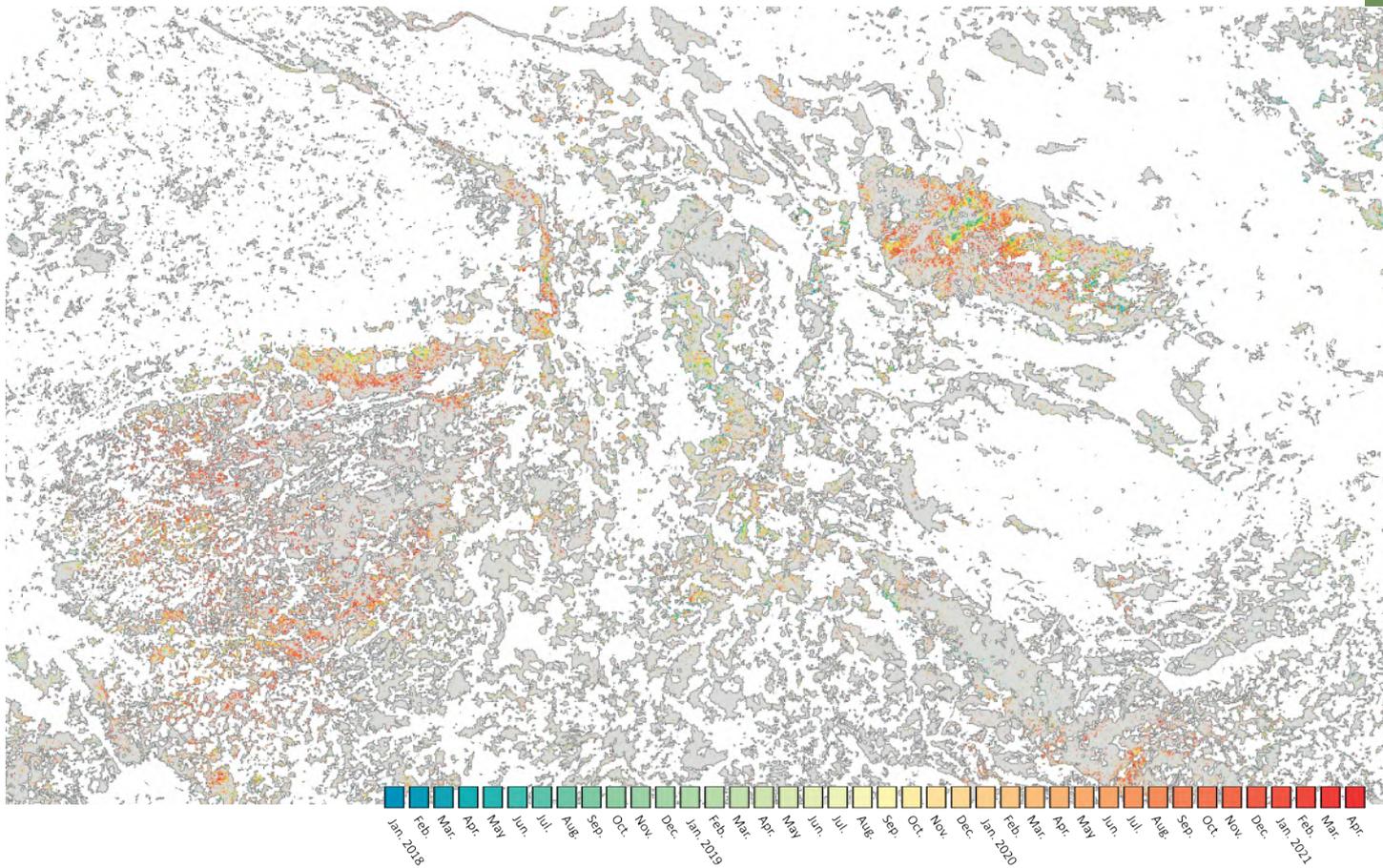
Around 38% of the global land surface is used for agriculture. One third of this agricultural area is cropland, while the remaining two thirds are meadows and pastures for livestock. Depending on environmental conditions and management practices, humans have created a variety of agroecosystems that form the basis for global food security. At the same time, agroecosystems are biodiversity hot spots, as they contain valuable habitats, e.g. for pollinating insects and other species. They also impact the environment and human health by affecting, e.g., water availability, soil erosion, deflection, and the input of chemical and nutrients into our landscapes.

Based on medium- and high-resolution time series from sensors such as MODIS, Landsat-ETM+, Landsat-8, Sentinel-1, and Sentinel-2, DFD has put an emphasis on area-wide mapping and monitoring of croplands from regional down to field scales. In this context, we develop methods and processing chains for mapping crop types over large areas based on phenological metrics, break-point and percentile analyses, and time series segmentation. For example, a map discriminating 18 different crop types for all of Germany at 10 m spatial resolution was produced based on Sentinel-1 and -2 time series within the HGF-funded Climate Initiative Project (HI-CAM). This unique data-set has been requested by national modelling groups (e.g. of UFZ), and national and state environmental agencies (Bayerisches Landesamt für Umwelt, LfU). Further, temporal and spatial transfer of these methods for other years and regions was established. As part of a BMEL-funded project, DFD supports research on the digitization of German agriculture by contributing methods for the EO-based assessment of wheat development and identification of low productivity areas at the sub-parcel scale. In this context, DFD's agricultural field and validation site DEMMIN coordinated by our DFD department in Neustrelitz

plays a relevant role. As part of a long-term validation site network, cooperation with the Helmholtz centers is fostered as well as international cooperation as part of the JECAM initiative.

DFD also quantifies the condition and dynamics of cropland systems outside Europe. Examples include West Africa and Southeast Asia, where DFD has monitored agricultural expansion and crop cycle frequencies using Landsat and Sentinel-2 data in the context of BMBF-funded initiatives (WASCAL, SASSCAL, Agrain, CONCERT). For Burkina Faso in West Africa, processing chains are being developed to monitor current and identify potential rice cropping areas and drought impacts to support climate change adaptation and food security. Several BMBF-funded multidisciplinary cooperation projects also focus on rice cultivation estimates. Sentinel-1 SAR time series were analyzed to develop a transferable methodology to derive rice paddy areas in Asia. In addition, the potential of EO based rice yield estimation in the Mekong Delta of Vietnam was evaluated (WISDOM, CATCH-MEKONG, and IB Riceman projects). With regard to the threats of crop losses and famines, DFD is engaged in monitoring the impact of locust plagues on agricultural areas in Central Asia and exemplary countries in Africa (carried out in the Locust-Tec project). Industry partners interested in our agriculture-related EO-sensor-derived geoinformation products include players like BASF, GAF, SLU, and GREENSPIN, amongst others.

For the study of grassland systems, a relatively new topic at DFD, we rely mainly on exploiting Sentinel-1 and -2 time series, which allows us to assess management-related effects at a higher spatial scale while also providing temporally detailed phenological behavior. By combining multispectral and SAR time series with a spatial resolution of 10-20 m, it was possible for the first time to determine mowing dates and frequencies for the entire German territory. In

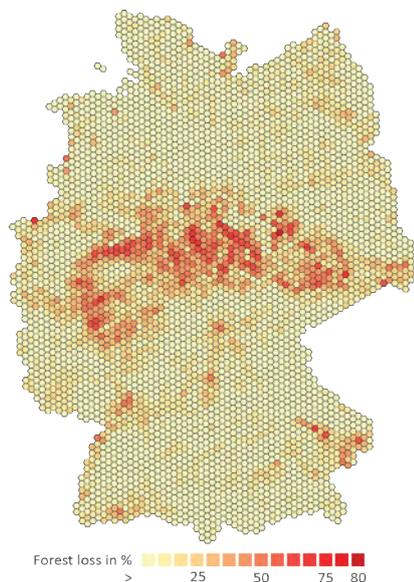


BMZ-funded projects in cooperation with GIZ and WWF, DFD has been working on assessing grassland extents, differentiating grassland types and estimating grassland productivity and carrying capacity in the Caucasus region and in Paraguay. In addition, DFD is analyzing grassland and savanna ecosystems in western and southern Africa in BMBF-funded collaborative projects. Here, phenology and drought effects are mapped based on Sentinel-1, Sentinel-2 and MODIS data to assess land degradation and appropriate adaptation strategies.

DFD is also currently widening its experience in multi-sensor technology for forest activities. Forests cover approximately 31% of the global land area. They are rich in biodiversity, provide a number of

crucial ecosystem services, and are of high economic value. Today, deforestation, non-sustainable forest management and climate change are major threats to forests. Missing carbon sinks in turn have an impact on climatic change and thus on humankind itself. DFD has been exploiting Landsat and Sentinel-2 archives to quantify forest cover loss since the 1980s in a study in Paraguay in joint projects with WWF, financed by BMEL. Several geoinformation products have been produced for national decision makers and stakeholders that examine the effect of forest change on habitat fragmentation. They show how political regulations affect forest loss in Paraguay – the country in Latin America with the highest rates of deforestation due to the expansion of soybean and palm oil plantations

Forest losses in Germany over the course of the dry years 2018-2020 at a spatial resolution of 10 m. The color scale ranges from January 2018 (blue) to April 2021 (red). The subset shows central Germany from the Leipzig region in the east to Düsseldorf in the west and from Fulda in the south to Hannover in the north. Intact forest areas are shown in gray. The Harz Mountains, an area particularly affected by forest loss, are shown in the upper right part of the image.



Forest loss in coniferous forests in Germany, calculated with a spatial resolution of 10 m, aggregated to hexagons with 10 km diameter (ca. 86 km²). Shown is the proportion of coniferous forest that died or was cut down between January 2018 and April 2021 (red).

(the ParLU, SULU and GeoForPy projects). Similar studies have been undertaken in Southeast Asia. In Germany, DFD's forest analyses have focused for many years on experimental analyses of satellite and aerial sensor data, mainly in the area of the Bavarian Forest National Park. Here – in preparation of the EnMAP mission – a number of hyperspectral methods based on airborne AVIRIS and HySpex as well as simulated EnMAP data have been developed to analyze bark beetle damage and advancing succession stages, including analyses of experimental DESIS mon-temporal EO data and Sentinel-2 time series. As the 2018 drought and heat waves in Germany triggered severe forest damage of national relevance, DFD has increased its focus on quantifying forest change at the national scale in Germany. In this context, a detailed time series analysis of Landsat and Sentinel-2 data allowed the mapping of forest losses since 2018 for all of Germany at monthly intervals and 10 m spatial resolution. The results, which are currently being published, are of relevance especially for political stakeholders.

Against the background of climate change, droughts and heat waves will increase worldwide. Germany has also been affected in recent decades, especially in 2003, 2018, and 2019. Therefore, DFD has established a fully automatic processing chain to analyze the effects of droughts on the condition of grassland, cropland, and forests in Germany based on MODIS vegetation index time series. For cropland, where drought effects occur at comparatively fine spatial scales and are highly crop-specific, DFD is currently further developing this approach by integrating high spatial resolution Sentinel-2 vegetation index time series. In general, processing chains in all of the above areas (agroecosystems, forest ecosystems, phenology, and drought) are coded and developed in a way that makes them transferable to the *terabyte* infrastructure operated at LRZ in Garching from 2022 onwards.

Coasts and River Basins

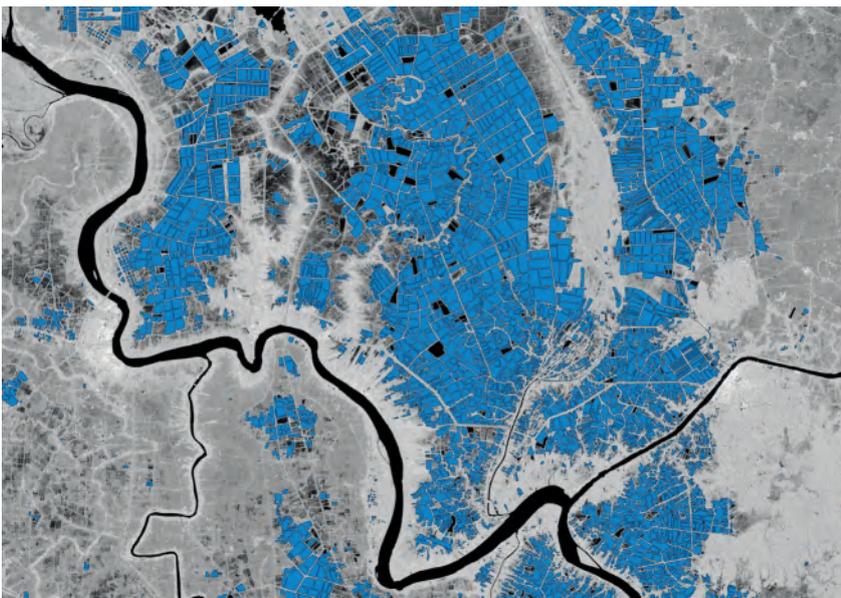
The world's coastal areas are not only very densely populated, but also contribute disproportionately to national GDP. For example, although river deltas and estuaries account for only 5% of the land surface, nearly 10% of the global population lives in these areas. They offer a variety of advantages, including flat topography, fertile alluvial soils, access to marine and freshwater resources, a rich biodiversity of different ecosystems, and often abundant underground resources of hydrocarbons (oil, gas), and salts. At the same time, these highly dynamic, valuable environments face a variety of threats. Increasing habitat loss, water, soil, and air pollution, and sediment compaction from subsurface resource extraction leading to land subsidence all aggravate the already existing threats of storms, floods, sea level rise, and changing climate. Furthermore, coasts and deltas are vulnerable to upstream developments that affect water and sediment supplies. Constant monitoring of these productive but fragile socio-ecological systems is critical to understanding past and current land surface change and anticipating possible future developments.

DFD has a long history in EO-based monitoring of coastal and delta areas and associated river basins. For example, until 2014, DFD coordinated the BMBF WISDOM project (Water related Information System for the Mekong Delta), which was well-funded, enabling a large fleet of researchers to contribute. Five German small and medium sized enterprises were involved in this transdisciplinary project, where not only a complex geoinformation system for the Mekong Delta was developed, but also over 50 PhD students (half of them Germans, half Vietnamese) were educated. Follow-up activities include extending this work to include the entire Mekong Basin with the participation of EO specialists from six countries (Vietnam, Cambodia, Laos, Myanmar, Thailand, and China in the CATCH-MEKONG project), transfer-

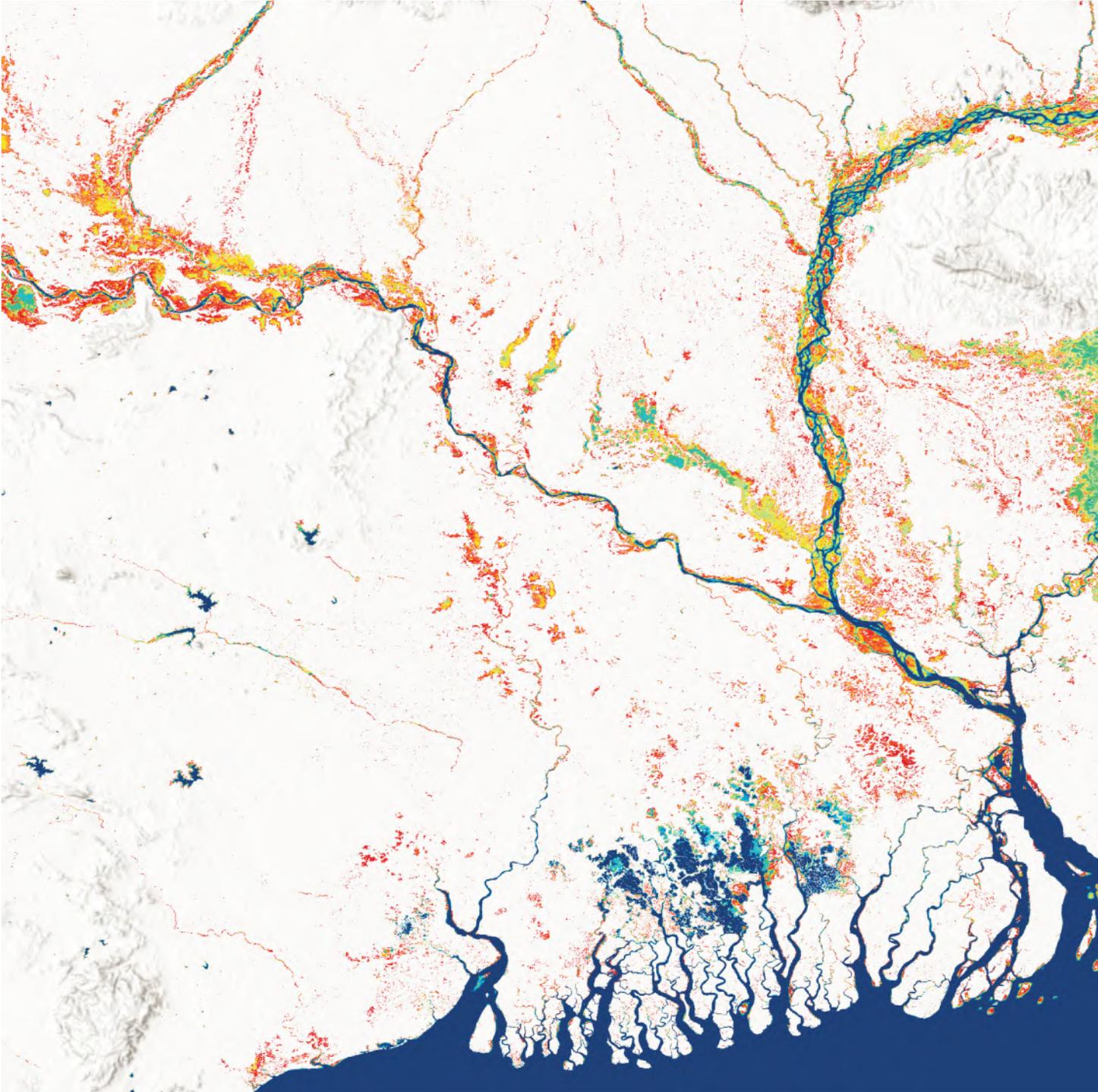
ring approaches in the context of the trans-disciplinary BMBF Sino-German DELIGHT project, and two recently started projects in Vietnam (FloodAdapt and Drought-ADAPT, both running until 2024). Through these projects, DFD not only acquired thematic expertise (DFD was appointed the German Speaker for Future Earth Coasts, an international research project), but above all advanced innovative IT developments for EO-driven information systems, which feed back into DFD's UKIS line (see in the next chapter).

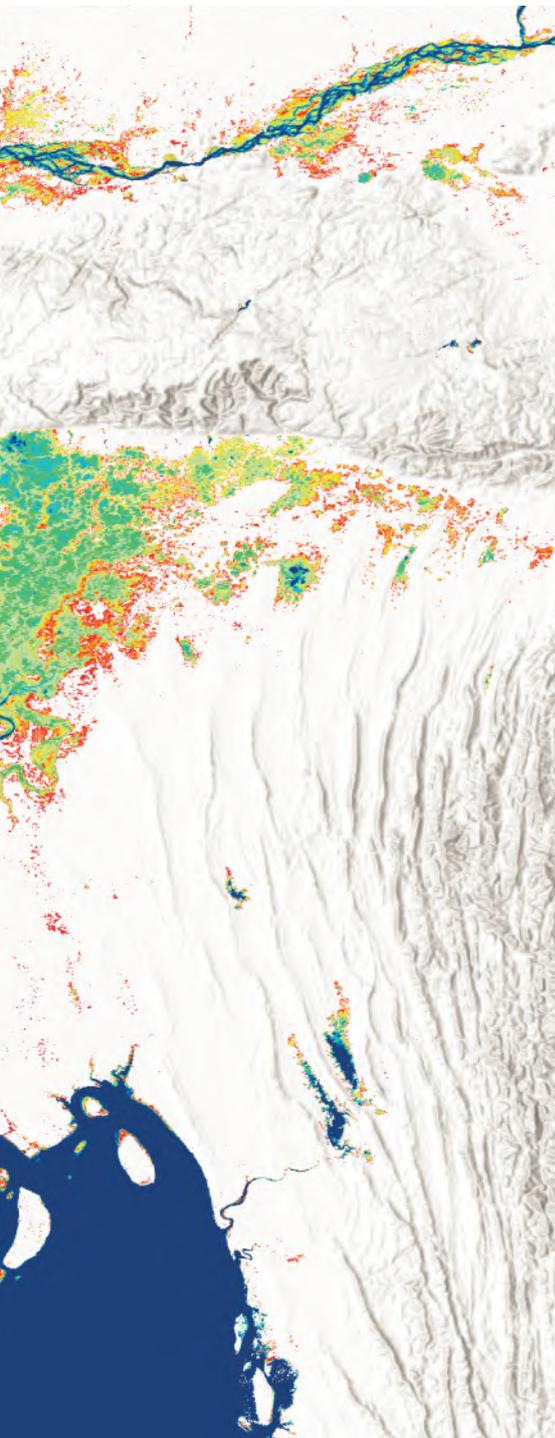
In addition, data analyses were advanced in a variety of new topics, such as large-scale mapping based on multi-sensor data from TerraSAR-X, Landsat, and IKONOS of mangrove forests on the Mekong Delta coast and in Vietnam's famous Can Gio Biosphere Reserve. In parallel, studies on the ecosystem services of mangrove forests in this region were conducted, combined with household surveys in the field, and directly integrated into new management practices of the IUCN-supported reserves of the International Geosphere-Biosphere Program.

A new thematic focus also developed from the river delta projects. Contrary to popular expectations, the fastest growing sector in agricultural production worldwide is not the cultivation of soy or palm oil, but the enormous expansion of coastal aquaculture. Here, cloud-penetrating SAR satellite data from TerraSAR-X, TanDEM-X, and especially Sentinel-1 are particularly suitable for evaluating time series in subtropical and tropical regions. Sentinel-1 time series have been used to detect and map land-based coastal aquaculture areas in Vietnam, China, India, and eventually all of Southeast Asia. We have even succeeded in estimating land-based aquaculture production (i.e., fish and shrimp production in tons) from space. DFD is taking a leading role in this field, including being invited by the European Commission in Brussels, Belgium, in October 2018 to present a keynote speech at the Copernicus for Fisheries and Aquaculture Workshop. Currently, AI-based approaches using convolutional neural networks (CNN) are being developed to detect offshore aquaculture cages and expansion dynamics in oceans and fjords. Other completed algorithm



Coastal pond aquaculture in the Irrawady Delta region, Myanmar, 2019 automatically derived from Sentinel-1 data.

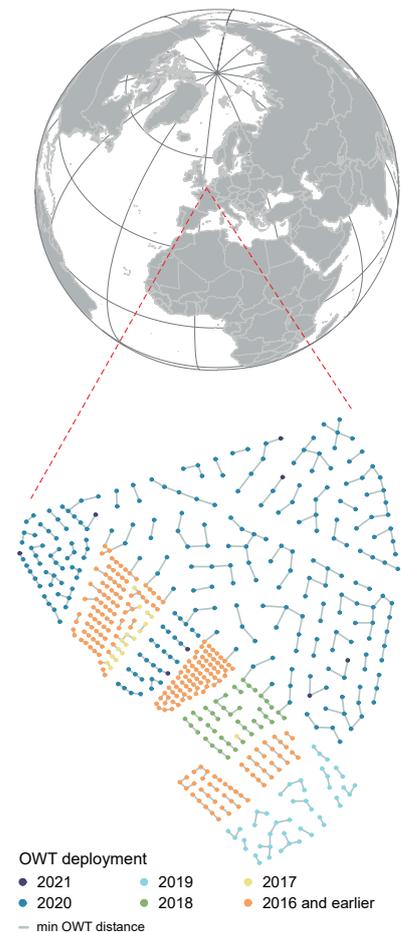




developments for multi-sensor EO data analyses include processing chains to detect morphological processes of coastal accretion and erosion.

For large river basins and generally for investigating global water dynamics, the Global WaterPack has been developed. It is derived from time series of MODIS satellite data with a spatial resolution of 250 m for all years since 2003. The dataset represents the frequency of surface water presence for each pixel worldwide, which is especially relevant for inland water bodies. Thematic studies were conducted to categorize the world's reservoirs and lake types. At the end of each year, the Global WaterPack is reprocessed and updated to include the current year's data in multi-decadal statistical parameters (mean water extent, maximum, minimum, variability, anomalies, and trends). To date, over 6 million satellite datasets have been processed for the entire Global WaterPack. Recently, we fostered the development of comprehensive quality measures for the Global WaterPack, i.e., data quality layers for temporal probability and observational uncertainty. The product is offered in the Geoservice and has already been requested and used by partners such as MPI, other HGF centers (e.g. GFZ, UFZ), international universities, national consortia focusing on hydrological and climate modelling (DFG Global CDA Project), and consortia in the field of hydropower.

An important methodological focus currently under development is AI-based analysis of multi-sensor satellite data. In this context, methods for comprehensive training, data generation, and, in particular, synthetization for deep learning approaches are being developed, followed by thematic processing and classification exercises in the fields of global detection and characterization of offshore wind farms from Sentinel-1 SAR data time series. This allows the differentiation of active turbines versus turbines under construction, and additionally allows a statistical assessment of global offshore



Above: Global recognition of offshore wind farms by a convolutional neural network trained only on synthetic training data using the SyntEO approach. The example shows a detected offshore wind farm complex in the North Sea basin.

Left side: Global WaterPack 2020 for the Ganges-Brahmaputra-Meghna delta (Sundabarns) in Bangladesh. The colors show the duration of surface water cover in days, starting with deep red (0 days) to deep blue (365 days).

windfarm-based energy production. These activities will be expanded to focus on the extraction of coastal and port infrastructure (containers, oil tanks etc.) from high and highest resolution data, such as from Sentinel-2, WorldView, and PlanetScope.

Polar and Cold Regions

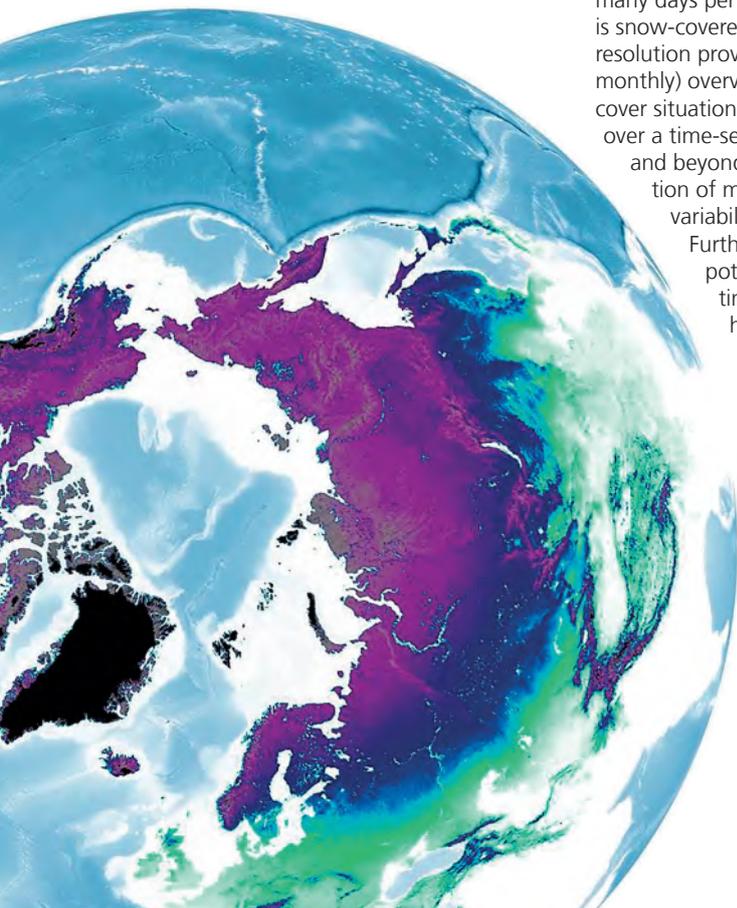
Antarctica, the Arctic, and the highest mountain regions are sparsely populated, if at all, and seem far away. Yet what happens to our cryosphere has a direct impact on our livelihoods. Melting of the great ice caps and glaciers – in addition to the process of thermal water expansion – is contributing to sea level rise and affecting the runoff patterns of major rivers. Alterations in our planet's albedo accelerate global warming. Changing snow seasonality impacts not only flora and fauna habitats, but also the hydropower energy sector, transport, and tourism.

Since 2017, DFD has intensified its focus on this topic area, for example with the Global SnowPack. This MODIS-derived geoinformation product shows for how many days per year a location on Earth is snow-covered. The daily temporal resolution provides a daily (or weekly, or monthly) overview of the current snow cover situation. It has been computed over a time-series from 2000 to today and beyond, allowing the derivation of means, minima, maxima, variability, anomalies, and trends. Furthermore, we explore the potential of Landsat, Sentinel-1 and Sentinel-2 for higher precision snow cover mapping and characterization. A new study is under way to investigate the possibility to forecast snow cover relying on long term time series and statistical methods.

The Global SnowPack was named the best snow cover information product to date at the Eastern Snow Conference, where DFD received the Wiesnet Medal for it. Further honors for this development were the Helmut Rott Prize and the featuring of the Global SnowPack in the "ZDF heute journal" weather forecast. Interested parties can access information on the product and the data itself via the Geoservice. It has already been used in several scientific studies on hydrology, climate change and even animal behavior. For example, the UFZ and the Universities of Bonn and Frankfurt integrate the Global SnowPack into global hydrological and climate models. The Max Planck Institute of Animal Behavior used the data to model habitats of snow-dependent animal species. Industry partners are also showing interest in this geospatial information: For example, the Outdooractive company facilitates near real-time snow cover information for the Alps as part of a routing application for outdoor activities. The link to Outdooractive was established as part of an ESA-funded project.

Another focus is the quantification of environmental and climate change in Antarctica, where DFD operates its data receiving station GARS O'Higgins. Since 2017, several PhD studies have been conducted to quantify the dynamics of the grounding line, the circum-Antarctic position of the ice shelf front, and the amount and dynamics of supraglacial lakes. These studies have used long time series of SAR and multispectral data based on classification and recognition methods using artificial intelligence and machine learning. DFD is currently the only institution in the world extracting the monthly positions of the calving fronts of the major Antarctic ice shelves and deriving the entire circum-Antarctic coastline on an annual basis. The entire daily Sentinel-1 Antarctica archive is used for this deep-learning algorithm-based task. The resulting ice front dynamics data (monthly, seasonal, annual) were further developed for implementation

Global SnowPack: mean duration of snow cover from 2001 to 2021 (white: 0 days, green: 73 days, blue: 146 days, purple: 219 days, gray: 292 days, black: 365 days)



in DFD's Geoservice, available via EOC websites: the IceLines product. This research was awarded the "ASTO Förderpreis", and is recognized internationally, leading to invitations as session leader and keynote speaker at various conferences such as those held by the European Geosciences Union and the American Geosciences Union.

Complementary research is under way to characterize and quantify the extent and dynamics of supraglacial lakes on the Antarctic continent. These thaw lakes, which grow substantially during the Antarctic summer season, not only lower the overall albedo of the continent, but also cause meltwater to percolate, affecting ice stream and glacier runoff into the Antarctic Ocean. The work and the derived geoinformation products are of interest to our HGF partner AWI, to various university partners (e.g. Stanford, Leeds, Lancaster), as well as to international consortia and geopolitical bodies (e.g. Scientific Committee on Antarctic Research).

Based on the Polar and Cold Regions team activities presented above, DLR has been funding the DLR programmatic "Polar Monitor" project since 2020. It combines the polar research expertise of all DLR institutes working with remote sensing data, namely DFD (as lead), IMF, HR, and OS. A flight campaign on the Aletsch glacier in the Swiss Alps was successfully conducted in September 2021 to study the effects of climate change and to support the development of more precise snow cover classification algorithms based on Sentinel-1 and -2 imagery and airborne MACS images collected by OS. In addition, the HGF project Artificial Intelligence for Cold Regions (AI-CORE) was successfully started. Here we cooperate with AWI and Technical University of Dresden to develop AI methods for cryosphere research. Key challenges are the derivation of firn lines, ice shelf front detection in Antarctica and Greenland, and permafrost dynamics, comparing different deep learning algo-



rithms and processing platforms. Permafrost thaw and its impact on e.g. coastal erosion are also the research focus of a currently ongoing PhD thesis at the Chair of Remote Sensing at the University of Würzburg, which is associated with the group.

Calving front time series for Thwaites Eastern ice shelf and ice tongue from February 2015 (dark blue) to October 2021 (white) automatically derived from Sentinel-1 data

SAR Topography

Expertise in 3D SAR topography is based on DFD's decades of experience in the generation, management, and application of Digital Elevation Models (DEMs) from data collected by spaceborne SAR instruments. As mentioned in chapter 2, DLR has generated a global, high-resolution elevation dataset from TanDEM-X mission data. While the data processing was mainly performed by DLR, Airbus holds the exclusive commercial marketing rights for the data and is responsible for adapting the so-called WorldDEM to the needs of commercial users worldwide. DFD was responsible for the calibration and mosaicking of the single interferometrically processed DEMs into a large area. Data acquisition was completed in January 2015 and production of the global TanDEM-X DEM with a 0.4 arcsecond (12 m) posting was finalized in September 2016. The absolute height error is about 1 m, an order of magnitude below the 10 m requirement. DFD is offering a reduced version of the TanDEM-X DEM in 90 m resolution to the user community free of charge. The corresponding 19,389 DEM tiles are available via the Geoservice. The WorldDEM is also the basis for the official Copernicus DEM provided by the EU. It covers 150 million km² – all land masses from pole to pole.

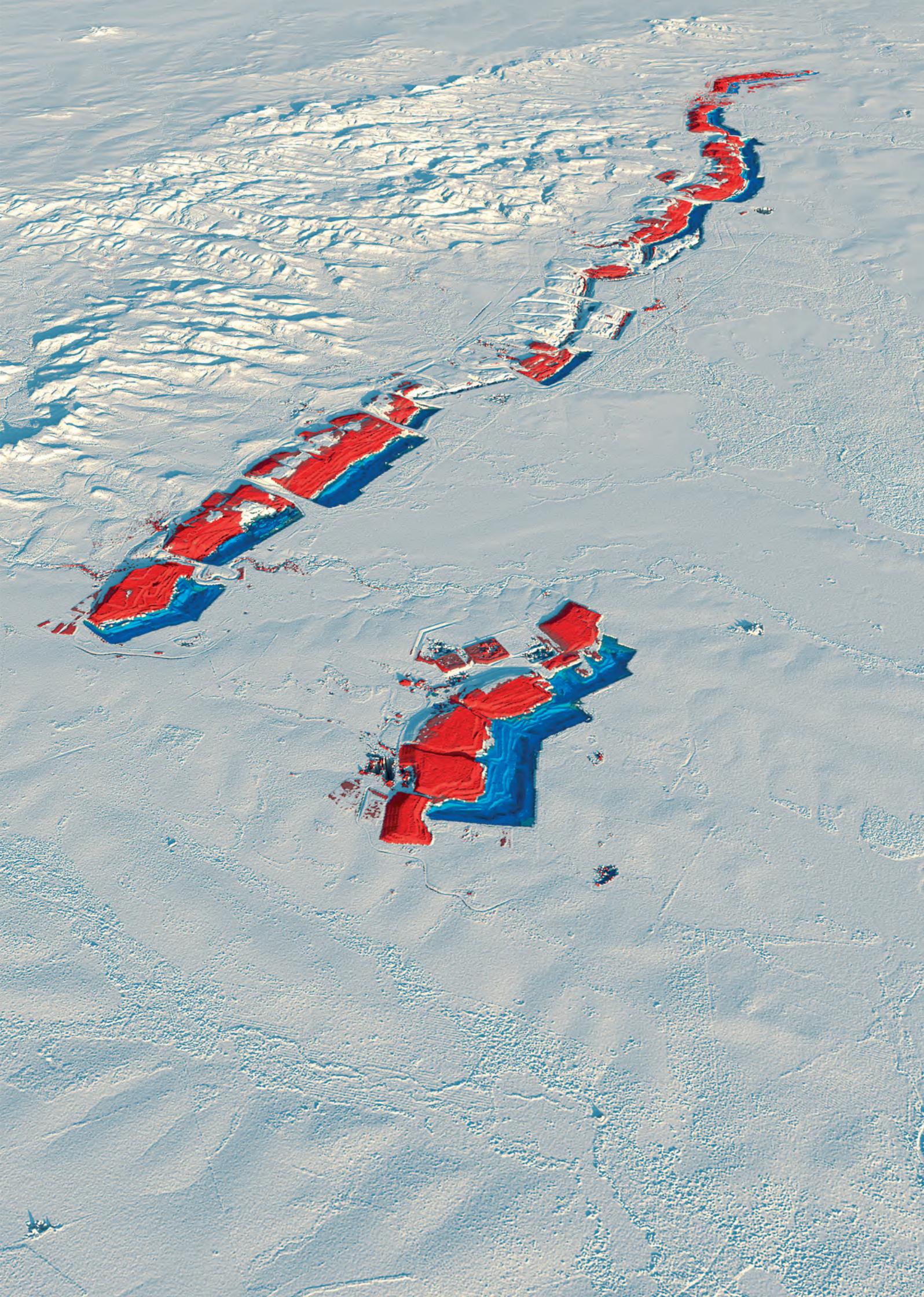
The global TanDEM-X DEM still has some issues that are being investigated and improved, especially for the polar regions. The derivatives that we produce include, e.g., a TanDEM-X PolarDEM consisting of edited, gap-free DEM products in polar stereographic projection, including single-year coverages and penetration bias corrected DEMs. Techniques for application-specific processing of the elevation model are being developed. These include smoothing of rough (=noisy) areas, removal of so-called voids (local disturbances and gaps), reconstruction of coastlines and shorelines, delineation of channels, and replacement of the

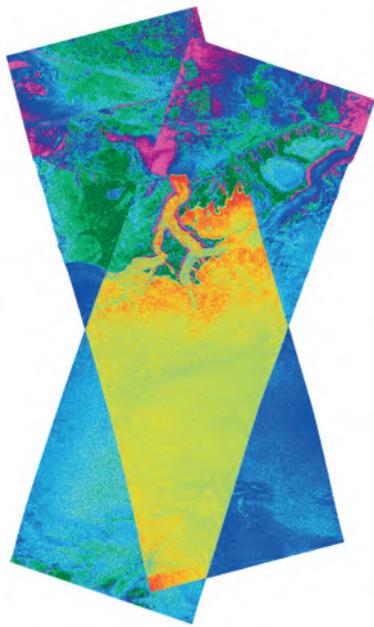
open sea surface and, especially for polar regions, frozen or partially frozen sea ice areas by interpolated geoidal heights.

Another focus of our work is to develop and operate high performance processors for generating analysis ready data and subsequent value-added products from SAR mass data. For this purpose, we designed the Multi-SAR System. Specific processing techniques were developed, improved, evaluated, and also implemented in operational high performance systems. Currently, this includes ortho-rectification to generate images with high location accuracy (geocoding), radiometric corrections (calibration), polarimetric decomposition, and image standardization routines to provide consistent and normalized datasets. The polarimetric decomposition is based on the Kennaugh matrix and enables an improved separation of the different backscattering processes. Consecutive texture analysis and image segmentation further improve image classification and change detection. The Multi-SAR System is currently being integrated into DFD's GeoFarm and is also in preparation for integration into the *terabyte* infrastructure. This system not only allows operational preprocessing of SAR data in general, but also for the derivation of SAR related products that reflect complex filtering operations and decompositions of the SAR signal.

Our many years of experience in creating high-precision DEMs are also the basis for geoscientific contributions, especially in the field of hydrology and cryosphere research. We are currently developing an updated version of the HydroSHEDS dataset. HydroSHEDS is a mapping product that provides hydrographic information for regional and global applications in a consistent format. It was originally based on high-resolution elevation data acquired during a Space Shuttle flight for the SRTM mission. The derivation of river networks, watershed boundaries, drainage directions, and runoff accumulations based on the TanDEM-X DEM will greatly increase the accuracy of this earlier prod-

TanDEM-X change DEM of the Saraji Coal Mine in the Central Queensland region of Australia (blue: losses, red: accumulations)





The penetration depth of radar in snow and ice may vary up to several meters between different acquisitions depending on the acquisition parameters and liquid water content and needed to be corrected for the creation of DFD's PolarDEM.

uct and provide a temporally up-to-date and globally homogeneous representation of large-scale surface hydrological features. In addition, time series of SAR imagery will allow determination of the temporal variation and dynamics of flood events that can be used for calibration and validation of hydrodynamic models.

For the cryosphere, DEMs are used to estimate elevation changes. Arctic ice shields respond rapidly to climate change. Melting results in a loss of ice mass. Height changes are an important indicator of mass change. TanDEM-X DEMs of Greenland acquired at different winter seasons are currently being analyzed to improve understanding of the elevation changes of the world's second largest ice sheet. However, to obtain reliable elevation changes the interferometrically derived height must be corrected for SAR signal penetration into snow and ice. Such novel approaches for estimating the penetration depth are currently being investigated in a DFG-funded project.

Given the long expertise of the team in the field of science coordination of TerraSAR-X and TanDEM-X users, including the bi-annual organization of the TerraSAR-X/TanDEM-X Science User meeting, our colleagues are deeply involved in the mission requirements definition for potential future SAR missions, such as the HRWS mission, which will hopefully be realized. This work includes the preparation of TerraSAR-X and TanDEM-X algorithms, libraries, and code (e.g. Multi-SAR System) to prepare for such a mission.

Outlook and Challenges

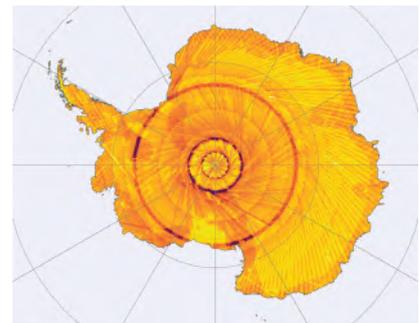
Based on the developments outlined above, a number of ambitious goals are to be achieved in the coming years. Research lines will be expanded in line with urgent societal challenges and according to the demand and needs of the international and national scientific, industrial and stakeholder communities. This includes innovative geoinformation that supports the adaptation of urban areas to climate and societal change, such as 3D information, updated imperviousness layer and novel global population density products, and EO products relevant to the urban microclimate. Quantitative information for adaptation in agriculture and forestry, particularly for Germany, will be developed towards frequent crop type mapping, drought impacts on crop cycles, quantification of forest loss and disturbance, as well as biodiversity parameters. Innovative AI algorithms for coastal infrastructure assessment, such as deriving information on industry, harbors, and coastline retreat, are being developed. Extended datasets for polar and cold region monitoring include assessments for global permafrost thaw risk and for higher-resolution snow cover variability. Novel "change DEM" approaches that enable 3D quantification of the volume loss of forests, mining areas, and ice sheets are under way. We cooperate in many ways with Helmholtz centers, research institutes, and universities that also carry out selected remote sensing work, mostly on a local to regional scale. This cooperation is extremely beneficial for both sides, as our partners benefit from our knowledge in the domain of remote sensing as to pre-processing, special processing techniques, and product generation. In turn, we benefit from their knowledge in various geoscientific research domains. Thus, in numerous collaborations and projects jointly with GFZ, UFZ, AWI, FZJ, etc., we have been able to successfully exploit the potential created by these synergies. Furthermore, we are engaged in long-term, time-series-based forecasting approaches, as we believe

that especially planners and decision makers need knowledge not only about past dynamics and the current state of our land surface, but also about future developments.

The biggest challenge today is the mass data throughput of large EO multi-sensor archives for the creation of time-series-based geoinformation products on a global scale. For many studies, several hundred thousand satellite datasets are processed. Multi-decadal time series need to be reprocessed every month, or at least every year, as all statistical parameters change with each additional data input. This reprocessing means a throughput of hundreds of terabytes, sometimes even up to petabytes. Despite the fact that DFD has powerful processing resources (CPU and GPU) and a large skill-set with agile software development for high volume data processing (including techniques that leverage dockerization, parallelization, and runtime performance optimization for codes), to keep up with the international community we must overcome our dependency on external clouds such as Google Earth Engine and other serverless computing solutions. Therefore, we concentrate on pushing the development of the future *terabyte* system jointly developed by DFD and LRZ, where all workhorse global satellite data archives will be available with global coverage and full satellite life span with frequent, preferably daily, temporal coverage. Another challenge is successful project acquisition in an increasingly competitive third-party funding market.

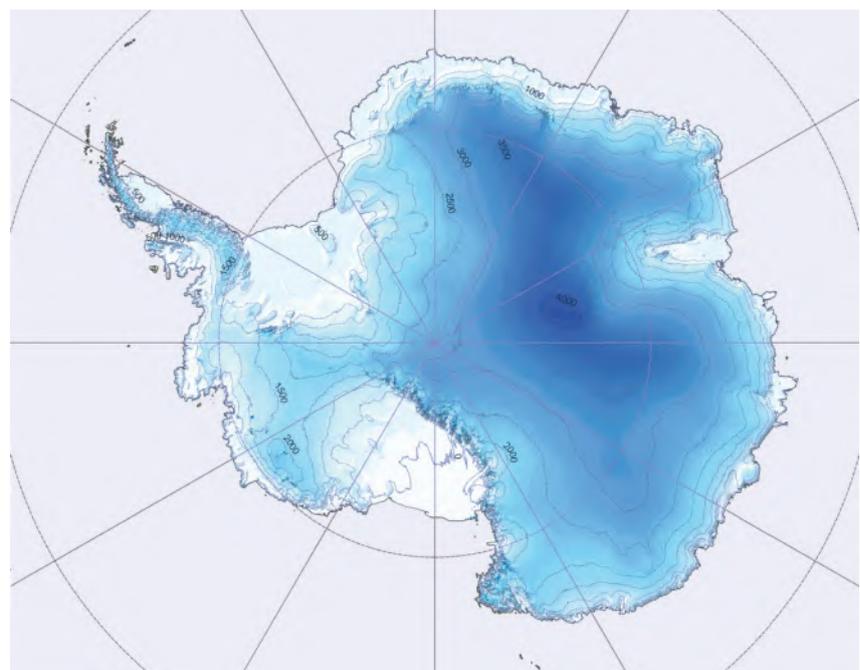
We will continue to support and initiate successful technology transfer with industry, for example in the field of space mission and sensor requirement analyses, mission scientific exploitation (e.g. Airbus, OHB, Teledyne), and the transfer of our high-quality established algorithms and processing chains to German EO companies and small and medium scale enterprises (GAF, Brockmann Consult, EOMAP), as well as support development cooperation via EO

expertise (DLR/GIZ cooperation). We furthermore will strengthen public administration and policy consulting with federal and state agencies, such as BMUV, BMEL, BMZ, BMBF, LfU, NGO aid organizations such as World Bank, UN bodies, WWF, etc., and strengthen our existing close ties to other research units like Helmholtz, MPI, and universities. Especially for the education of future generations and the integration of young and innovative researchers into our field, the Remote Sensing Chair at the University of Würzburg and the international EAGLE Master Program (Earth Observation and Geoinformation for the Living Environment) for chosen excellent students simultaneously functions as a lighthouse, multiplier and incubator.



Number of coversages of TanDEM-X DEM data takes used for PolarDEM (dark red: more than 12 takes)

Gap-filled and edited TanDEM-X PolarDEM 90 m of Antarctica



Geo-Risks and Civil Security

Orientation of the Department

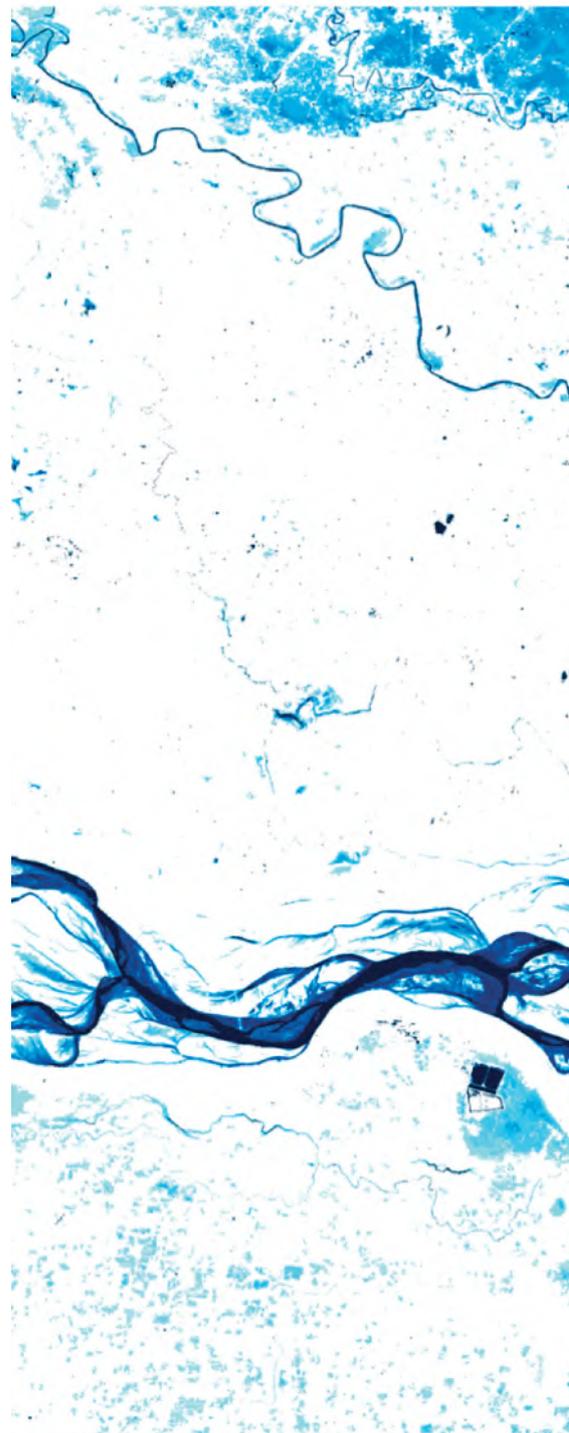
The threats to citizens arising from natural disasters and civil conflicts are increasing worldwide. In addition, global change imposes new challenges with respect to extreme climatological and hydrological events. Therefore, there is an urgent need to address these global threats and provide solutions in order to support disaster risk reduction, adaptation and prevention, effective crisis response, and early warning systems. An important milestone towards these goals is the Sendai Framework for Disaster Risk Reduction, where these challenges have been addressed by the international community and priorities for action and overall targets to be achieved on the local, national, and global level have been agreed.

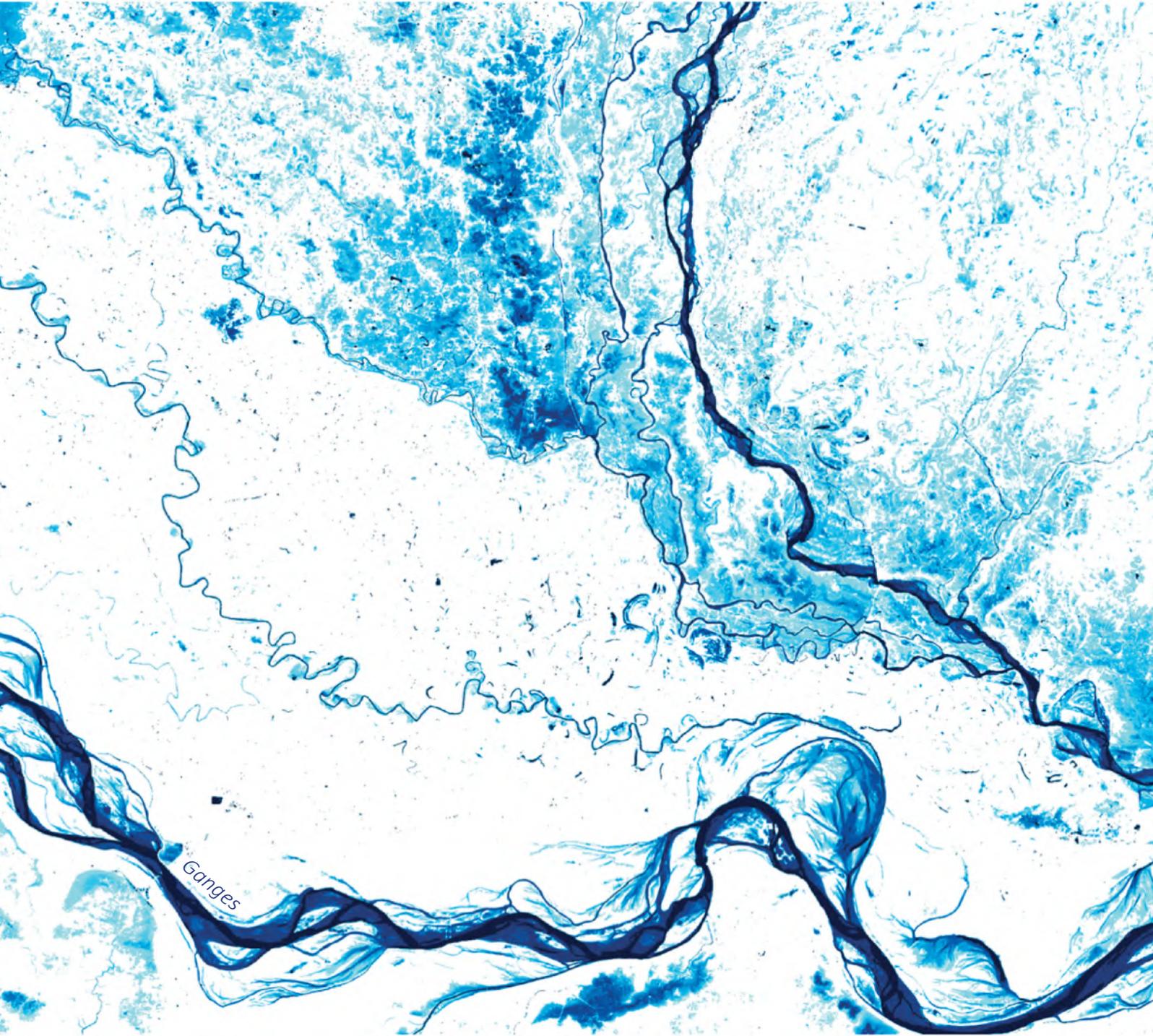
The Geo-Risks and Civil Security department addresses challenges in this domain from a remote sensing perspective. The focus of our research and technical developments is on all phases of disaster management, which includes risk analysis, early warning, emergency response, and post-disaster assessment. We develop innovative methods for information extraction from remote sensing data for applications relating to natural hazards, humanitarian relief, and civil security. Research activities are dedicated to various aspects of urbanization and migration, including the assessment of geo-risks related to people, infrastructures, and assets in exposed areas. We develop and implement thematic processing chains and information systems that enable data visualization and analysis, situation assessment, and decision support.

The overall focus of the department lies on an integrated end-to-end approach. It starts with innovative scientific research, followed by the incorporation of the

“The focus of our research and technical developments is on all phases of disaster management”

Flood duration mapping derived from Sentinel-1/2 (light blue: days of temporary flooding, dark blue: permanent water)





research results into thematic processing chains, the development of products and services, integration in information systems, and technology transfer.

Third-party funding comes from a wide range of sources, from EU and ESA European research programs, from federal ministries such as BMBF, BMI, BMWK and BMVI, as well as from DFG, DBU and similar foundations and alliances. Moreover, the department has close links to many universities and is strongly engaged in teaching and the supervision of students during their internships, Bachelor, Master, and PhD theses.



Volcanic eruption of “Cumbre Vieja” on La Palma: Sentinel-2, September 30, 2021

Natural Hazards

The demand for EO-based crisis information in the context of natural disasters has been growing rapidly for several years. Methodological research on information extraction from remote sensing data aims to improve the prevention of and immediate response to natural hazards. The focus is on natural disasters like floods, storms, fires, earthquakes, volcanism, landslides and droughts. The progress made in the research areas of floods, fires, and volcanoes is described in the following. Moreover, new scientific

results have also been achieved for other hazards and in the area of rapid damage assessment using artificial intelligence methods.

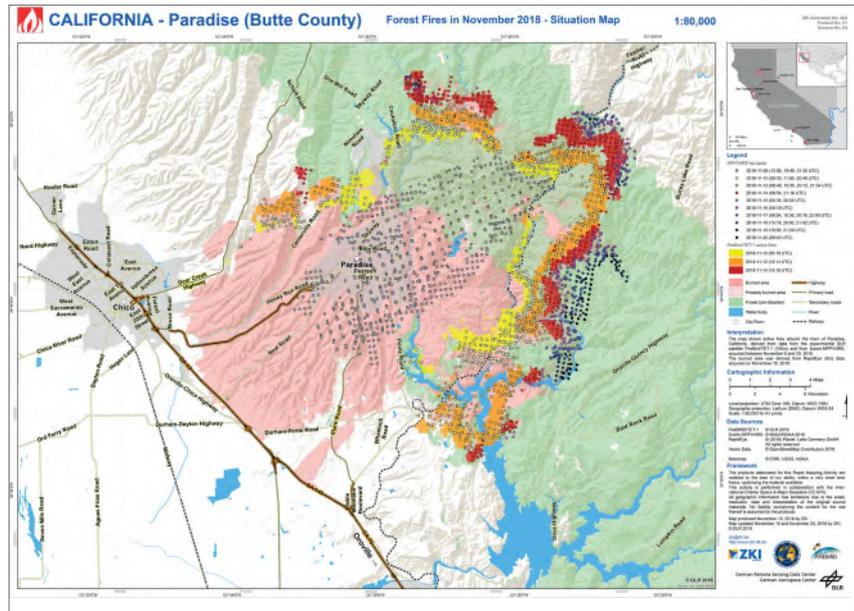
Floods are the most frequent natural disasters worldwide. Therefore, we concentrated our research activities on this topic from the beginning. Optical as well as radar remote sensing data have proven to provide essential crisis information in flood situations. Our research focus of the last few years was on the development of a multi-sensor satellite system for near real-time flood extent mapping. It consists of four automatic processing chains for the extraction of the flood extent from Sentinel-1 and TerraSAR-X radar as well as from optical Sentinel-2 and Landsat data. These flood processing chains encompass automatic EO data ingestion, pre-processing, computation, and adaption of global ancillary data (DEMs, topographic slope information and topographic indices, as well as reference water masks), automatic flood extent mapping, and the dissemination of the crisis information, e.g. via a web-client. The radar-based processing chains make use of an automatic, hierarchical, tile-based thresholding approach in combination with fuzzy-logic-based post-processing for the extraction of the flood extent. The processing chains based on optical data perform water segmentation with a CNN based on U-Net architecture that has been trained, tested and validated on a global reference dataset that is representative of a variety of climatic, atmospheric and land cover conditions. Clouds and cloud shadows are specifically handled by the network to remove potential biases.

Furthermore, information on flood duration can be derived by the flood monitoring system. It is an important parameter for estimating the degree of economic loss and damage to structures. It also provides an indication of the extent of inundation events and allows the comparison of the behavior of different flood events over time.

Further research has focused on flood monitoring in urban areas, under dense vegetation, and in low backscattering water-look-alike areas where flood detection with SAR data is usually unreliable. To reduce overestimations of the latter (e.g. over dry sand, flat and impervious areas) a method based on identifying permanent low backscattering regions in Sentinel-1 time-series analysis data was developed.

Due to the side-looking viewing geometry of SAR sensors and the high variability of the urban landscape, SAR-based flood detection in urban areas is very complex. Therefore, we worked on methods which yield more reliable identification of inundation in these areas by fusing multi-temporal SAR intensity and InSAR coherence through an active self-learning deep CNN and Bayesian Network. Also, the detection of flooding beneath vegetation is usually very complex and reliability strongly depends on various sensor and environmental parameters. In this context we successfully worked on different approaches, e.g. time-series analysis, polarimetric decomposition-based unsupervised Wishart classification in combination with object-based post-classification refinement, as well as probabilistic segmentation with adapted Bayesian CNNs.

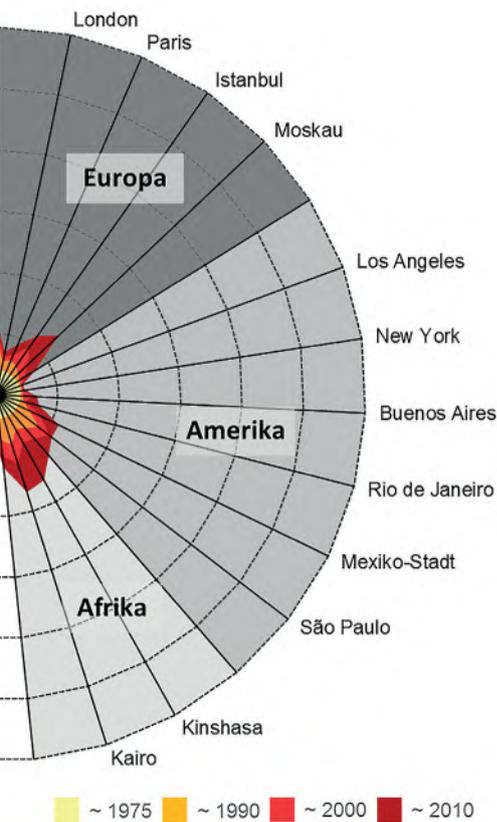
We see ourselves as one of the leading teams in this research field. This was recently confirmed by the successful start of the Global Flood Monitoring project of the European Copernicus program. DFD is part of the European consortium that will provide global flood extent maps in near real-time from the continuous data stream of Sentinel-1 data worldwide. DFD's Sentinel-1 based flood algorithm is implemented in the high performance processing infrastructure and is part of the ensemble approach to provide flood information from more than 1,000 scenes per day. This operational service is part of the Copernicus Emergency Management Service. For systematic global flood monitoring with even higher



California wildfires in November 2018: The ZKI situation map shows the active fires on a daily basis using, among others, data from the DLR FireBIRD mission.

temporal coverage, DFD's processing chains will be further extended to include both Sentinel-1 and Sentinel-2 data.

Forest fires have become one of the most devastating natural hazards worldwide and are likely to increase in the future due to climate change. Large wildfires require immediate attention and reaction to prevent damage to property, life and ecosystems. Within the last few years we focused on the development of several processors to detect fire events ("hotspot detection") and on the analysis of the affected areas ("burnt area mapping" and "fire severity assessment"). For the detection of active fires, we developed a fully automatic fire hotspot detection processor based on AVHRR data. Furthermore, for detailed analysis of actively burning fires, we developed an improved approach for the derivation of Fire Radiative Power (FRP) in data from the experimental DLR FireBIRD mission, including correction of the observed signal for atmospheric influences, detection of fire hotspots, and analysis of FRP. In order to determine the effects of wildfires, we developed and implemented a fully



Left and right side: relative growth of global megacities from 1975 to 2010

automatic processor for large-scale mapping of burnt areas by means of change detection in NIR and RED channel data from the MODIS sensor on board the Terra and Aqua satellites, and from the Ocean and Land Color Instrument OLCI on board the Sentinel-3A/3B satellites. For a detailed analysis, we developed two fully automated processors for burn scar mapping with Sentinel-2 data. The first is based on the analysis of the fire extent in pre- and post-event datasets. The classification is performed by a two-phase algorithm, where the first phase serves to identify seed pixels that have a high probability to be related to burnt areas according to various input parameters selected by discriminant analysis. In the second phase, the selection of the burned areas is refined by examining the neighborhood of the seed pixels by Support Vector Machine based region growing. The second processor is based on a deep neural network approach, which is trained by a representative reference dataset of past fires that captures different types of climatic, atmospheric and land-cover conditions.

All these processors are fully operational and have been applied to large area fire monitoring, e.g. for the forest fires in Eastern Australia in 2019 and 2020. Here we analyzed the fire activity and compared it to the situation over the last 20 years using more than 13,000 Sentinel-3 and MODIS scenes for the analysis of long-term trends. Another example is the monitoring of forest fires in California, where we provided daily situation maps for the fires in November 2018 as well as a systematic analysis of the burnt areas from 2016 to 2020 using more than 5,000 Sentinel-3 scenes.

There are over 1,500 active volcanoes worldwide. Over 29 million people live at a distance of less than 10 km from an active volcano, and over 800 million people, 10% of the world's population, at a distance of less than 100 km. Volcanic hazards include lava flows, pyroclastic density currents, lahars, tephra and ash

fallout, landslides, and tsunamis. Nowadays, volcanic activity is monitored with ground-based, aerial, and satellite measurements. During eruptions volcanoes are often not accessible. Although many volcanoes in the world are located in remote areas, they can also have an impact on inhabited regions. Satellite-based EO provides non-restrictive global monitoring of volcanoes. Therefore, within the last few years, our research focus was on the development of techniques for multi-sensor satellite-based volcano monitoring with the aim to detect and analyze volcanic activity and eruption processes. This approach is based on a joint analysis of thermal, optical and SAR imagery of different temporal and spatial resolutions. This ranges from geostationary thermal sensor data (e.g., MSG SEVIRI and HIMAWARI-8/-9) for detecting and analysis of volcanic thermal anomalies (with an update every 10 to 15 min.) to very high spatial resolution (< 1m) data from polar orbiting satellites, allowing very detailed analysis of changes at the volcano surface. Thereby, we have jointly analyzed data from following satellite sensors: Sentinel-1/2/3, Landsat-5/7/8, TerraSAR-X/TanDEM-X, PAZ, Kompsat-2/3/3A/5, COSMO-SkyMed, WorldView, GeoEye, PlanetScope, AVHRR, MODIS, VIIRS, SEVIRI, HIMAWARI-8/9, DESIS, and FireBIRD. For example, based on multi-sensor satellite data, it was possible to investigate tsunami-genic volcano flank and dome collapses, and to estimate the lava effusion rate and volume from multi-sensor thermal imagery. We have been studying volcanic activity in Indonesia, Papua New Guinea, Hawaii, Iceland, Tonga Islands, Stromboli and Etna, the Andes region, the Aleutian Islands and in the Antarctica. Furthermore, our research activities are closely integrated into international cooperation networks.

City and Society

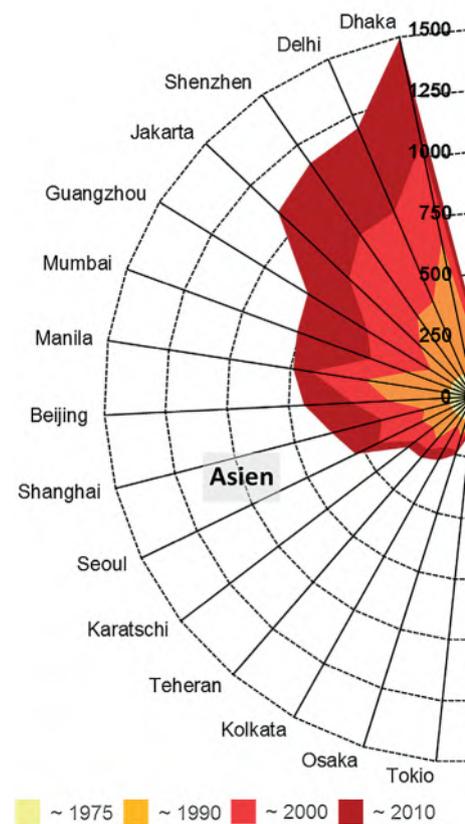
As already addressed in the section “Smart Cities and Spatial Development”, urbanization is one of the central themes of global change. As more and more people settle in ever-expanding urban landscapes, our predominant living environments, our ways of life, and our societies are transforming us into an unprecedented “urban species”. Against this backdrop of global urban developments, the overarching goal of our research is to document the status quo and the change in cities across the world to better understand the habitat in which the majority of humans now live. Therefore, and in complement to the activities of the land surface dynamics department, our activities focus on various aspects of urbanization, including the assessment of geo-risks related to people, infrastructure, and assets in exposed areas.

In order to pursue this goal, remote sensing data have been the central data source. Novel image analysis techniques in the domain of artificial intelligence, i.e. machine learning as well as deep learning techniques were developed, adapted and systematically tested. We designed specific classification schemes precisely tailored to the scientific questions for the particular research questions: two-dimensional land cover information at medium, high and very high spatial resolution as well as three- or even four-dimensional city models from multi-sensorial and multi-temporal Earth observation data were derived. However, a single data source is not sufficient to meet the information needs required to map, monitor, model, and understand the multi-dimensional complexity of urban systems and their changes over time. Thus, heterogeneous (geo) data from a wide variety of sources are made accessible and used for synergistic evaluation together with remote sensing data. For example, datasets are explored from official data such as the census, but they also come from open data sources such as OpenStreetMap, other image data sources from the Internet such as

Google Street View, or they are based on geolocated social network data. This allows the development of applications beyond the physical sphere of cities to map and analyze the social, demographic or economic space of cities.

Our geographic work documented the emergence of new dimensions of urban landscapes on our planet, such as megaregions or urban corridors. New approaches based on global remote sensing products allowed us to question existing global urban statistics. Biases due to non-comparable administrative spatial units could be eliminated, and scientifically comparable units resulted in a more accurate city ranking of the world's largest cities. Further research systematically addressed the intra-urban structuring of cities. Indicators such as building density, the proportion of green spaces, and urban classification schemes of structural types formed the basis for a better understanding of the organization of urban space. For example, in collaboration with IMF we have empirically demonstrated for the first time that cultural regions on our planet do indeed have similar urban structures, in this case based on “local climate zones”. In addition, our research has also addressed urban structures in terms of land consumption, polycentricity, or the definition of centers in general. In this context, we have also conducted initial studies on the relationship between urban structures and quality of life or environmental justice. In addition, we have mapped and analyzed special phenomena such as ghost towns in China.

In analyzing the built urban environment, a particular research focus has been on the structures of poverty. We documented which settlement structures represent poverty in a global comparison. The emphasis was on the settlement structures of slums. With “deep learning” methods we have shown that these complex, often small-scale areas can be extracted with high accuracy in EO image data. In our works we could systematically show in geographic applications that slum





Mapping informal settlements in Dharavi (Mumbai, India), one of Asia's largest slums: estimating population density

inhabitants are disadvantaged among urban residents. Economic disadvantage is reflected in lower light emissions than in richer areas within cities; disadvantage in settlement location is reflected in higher exposure to natural hazards. In combination with other geospatial data, the approaches in this thematic domain were extended beyond the built landscape towards socio-economic and demographic understanding of urban space. For instance, we found urban morphologic parameters to correlate with low-income households derived from census data, making the remote sensing approach a legitimate proxy for slum classification. Another example is social network data showing that residents of these areas are often less likely to use new communication media such as Twitter.

Urbanization is leading to more and more people living in areas at high risk of natural hazards. A comprehensive assessment of geo-risks and their interdependencies is necessary to provide a scientifically sound basis for improved disaster preparedness and mitigation, early warning systems, and rapid damage assessment after emergencies. Here, we have developed new methodological approaches for the classification of exposed objects (buildings, infrastructure) and population, as well as their vulnerabilities. In interdisciplinary collaboration with geologists and landscape architects, we mapped locations of exposure, e.g. landslide prone areas, to support evacuation planning. We also studied the impact of earthquakes and tsunamis on building stability in interdisciplinary work with civil engineers, using a variety of EO and other data.

Key research activities aim at a comprehensive multi-hazard risk assessment. The complex relationships between multiple or consecutive natural hazards, the exposed population, dynamic vulnerability, and critical infrastructures can lead to cascading effects that are often not considered. Therefore, we dedicated substantial research activities to this topic.

As part of the international BMBF-funded RIESGOS research project and its successor RIESGOS 2.0 under our lead, we developed an innovative approach that considers these interdependencies and possible cascading effects on critical infrastructures. An important data basis for this is the characterization of the buildings and urban structures. For this purpose and in addition to the WSF 3D, we developed a method adjusted to the local morphological specifics of the built environment that derives building height and density automatically with high accuracy. The method uses multispectral Sentinel-2 image data and height information from the TanDEM-X mission. Based on machine learning techniques and transfer learning the algorithm was also successfully applied to areas where no elevation data are available. Therefore, global classifications of buildings will be possible in the future.

Information Systems and Geomatics

In the era of "big data" from space, it is important that the processing and analysis of EO data is implemented in a highly operational and efficient way. Therefore, the focus of our activities is the efficient development and implementation of our thematic processing chains and their optimization for integration into suitable IT infrastructures for High Performance Data Analytics. In addition, we develop information systems that enable the combining of various data sources, data visualization and analysis, situation assessment and decision support.

The key to answering many scientific and societal questions, including those in the areas of natural and man-made hazards and related to civil security applications, lies in the systematic analysis of ever-increasing amounts of data. Aspects such as the ability to analyze time series, process near real-time data, and fuse and synthesize Earth observation data with non-EO data in a systematic way are playing an increasingly important role for

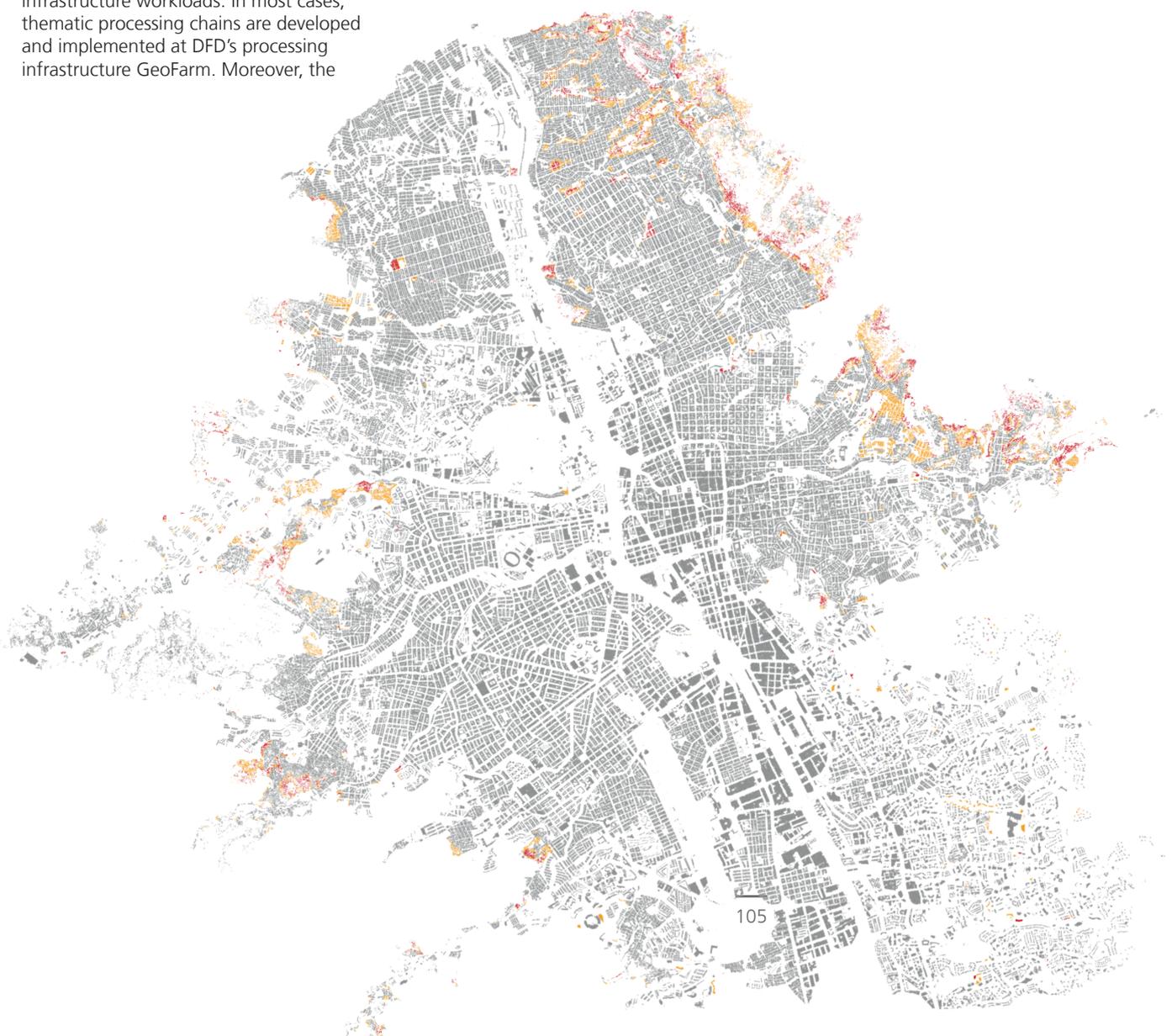
dedicated monitoring applications, e.g. for floods and forest fires using multi-source satellite data.

In order to meet the requirements for both scalability and flexibility in relatively short development cycles, we are following the principle of containerizing applications and processes when developing and optimizing processing chains. In order to be able to efficiently implement our processors in different IT infrastructures, we are focusing on a “cloud native” approach based on the open-source container and microservice platform Kubernetes, that orchestrates computing, networking and storage infrastructure workloads. In most cases, thematic processing chains are developed and implemented at DFD’s processing infrastructure GeoFarm. Moreover, the

transfer of processing chains with a particular need for large-volume processing and analysis of Earth observation data to the *terabyte* infrastructure to be operated at LRZ will be prepared.

These competencies and processing chains are being further developed in the frame of several national and international projects, for instance, in the EU project VESTEC. In this project our processing chains for wildfire analysis have been integrated in a high performance computing infrastructure, which allows the monitoring of the current fire situation as well as the prediction of the fire propagation in realistic scenarios.

Landslide risk exposure for the city of Medellín, Colombia: The combination of EO and ancillary data was used to produce up-to-date and high-quality estimates of areas, people and assets at risk (red: high risk, orange: medium risk, gray: low risk).



Moreover, the integration of heterogeneous and unstructured data into “big data” analytics is an important topic. We developed methods to automatically retrieve information from social media, like Twitter, where we analyze these data streams with respect to defined keywords. In order to support the early detection of critical situations, we analyze the frequency of occurrence and determine the related geographic locations. In addition, we also apply this approach to web news. This analysis in combination with satellite-based information allows us to derive indicators for upcoming crisis situations.

Environmental and crisis information systems are key tools to enable planning, situation analysis, early warning, and decision making in cases of emergencies. Those information systems provide a basis also for a long-term sustainable use of remotely-sensed information products and continuous improvements. Based on its experience in large projects worldwide, DFD therefore initiated the DLR-programmatic system development “Environmental and Crisis Information Systems (UKIS)” almost ten years ago. This includes the development of a software framework for the implementation and provision of modular and reusable

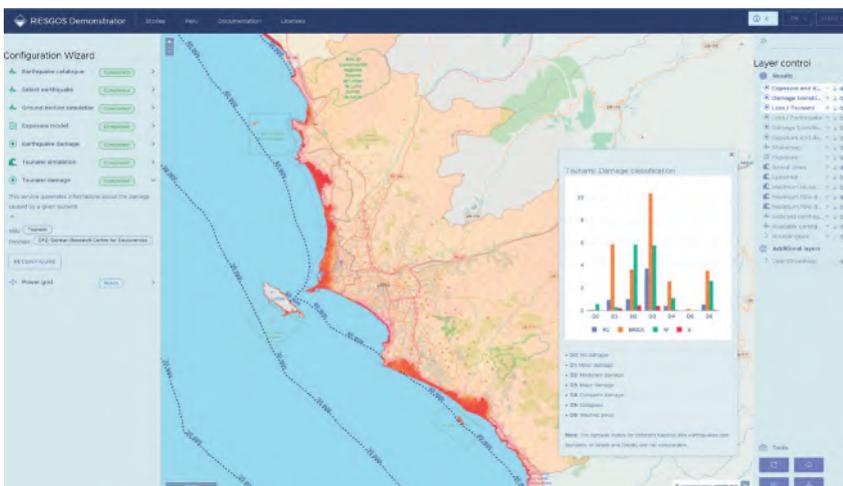
components of web-based geoscientific information systems. The UKIS development, which is described more detailed in chapter 5, is one of the key activities in the department.

The UKIS software modules are being leveraged and further developed in many international projects. For instance, in the EU project HEIMDALL, UKIS-based software tools and a real-time data analysis service were further developed and integrated into the project platform, which addresses the needs of first responders, such as firefighting units, police departments, medical emergency services, civil protection units, and command and control centers.

Another project where UKIS software is intensively used and further developed is RIESGOS, a project funded by the German Federal Ministry of Education and Research, addressing earthquakes, tsunamis, volcanic eruptions, landslides and floods in the Andes region. Here we are developing the web-based components of a multi-risk information system. The service-oriented system architecture is based on a distributed hardware and software infrastructure and web-based services that are integrated via standardized interfaces. The system concept is therefore scalable, easy to expand and reuse, modular, and open. This approach enables authorities and civil protection agencies to integrate RIESGOS developments into their own, already existing information and decision support systems. In RIESGOS the UKIS software provides the basis for an intuitive graphical user interface that enables emergency services, planners and relief organizations to use simulation, modelling and other system components contributed by project partners.

Looking ahead, interactive data analysis in web-based information systems is becoming increasingly important. Using innovative back-end, database, and front-end technologies in our UKIS software development, our goal is to make

The RIESGOS demonstrator enables the simulation, analysis and assessment of multi-risk situations (red: the coastal sections particularly at risk from a tsunami).



the results of the thematic processing described above not only accessible but also analyzable. Consequently, users from different thematic domains, for instance in the context of natural disasters and geo-risks, can perform their own interactive data analyses in a web browser based on our research.

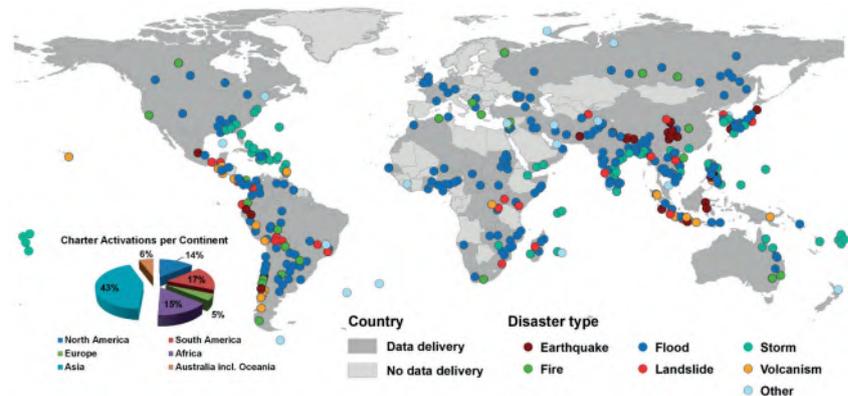
Center for Satellite Based Crisis Information (ZKI)

Since its formal establishment in 2004, the Center for Satellite Based Crisis Information (ZKI) has been a key player in research activities and the development of services for disaster management worldwide. The activities of ZKI contribute to all phases of the disaster management cycle, which include risk assessment, early warning, rapid response, and post disaster monitoring. Earth observation data such as satellite images, aerial images, and other geodata are acquired, analyzed and processed in a user-friendly manner. Moreover, at ZKI a substantial number of its activities is dedicated to scientific research and innovation in order to support the management of natural and environmental disasters, humanitarian relief activities, and civil security issues worldwide.

The activities of ZKI focus on global, European and national levels:

- Global: contributions to the International Charter Space and Major Disasters
- Europe: contributions to the European Copernicus program
- Germany: services and technology transfer for German users

The International Charter Space and Major Disasters is an association of currently 17 space agencies and satellite operators with the aim of providing a unified system of rapid space data acquisition and

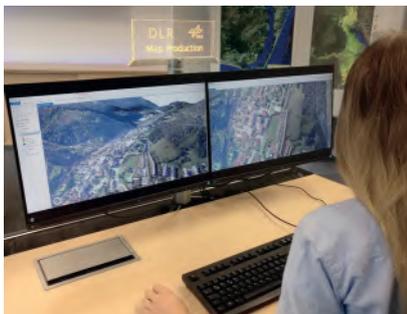


Global distribution of the Charter activations supported by DLR

delivery in cases of natural or man-made disasters. Each member agency has committed resources to support authorized users, such as relief and civil protection organizations, with free of charge satellite data in order to help mitigating the effects of disasters on human life and property.

DLR has been a full member of the Charter since October 2010 and is actively involved in all its activities. The main operational tasks of DLR's contributions to the Charter comprise satellite tasking and delivery of data from German satellite missions, project management and value adding for selected Charter activations, and emergency on-call officer duties for the Charter. Since October 2010 more than 1,400 TerraSAR-X and TanDEM-X datasets as well as more than 1,000 RapidEye data tiles (until 2019) have been delivered to the users of the Charter. In summary, more than 380 activations of the Charter have been supported by DLR.

In the European Copernicus Program, ZKI has been actively engaged from its beginning. We substantially contributed to the development of the Emergency Management Service (EMS) and the Security Service through our involvement in several large European research projects.



DFD's ZKI produces emergency maps for authorities.

Moreover, ZKI was also a member of the consortium that provided the Rapid Mapping Service of EMS. We also developed and contributed services to the European Forest Fire Information System, EFFIS, as part of the EMS Early Warning and Monitoring Service. Finally, as already mentioned, since 2021 we have been a member of the consortium for the Global Flood Monitoring Service, the most recent and innovative service in the framework of Copernicus EMS.

An important milestone for ZKI is the close cooperation with the German Federal Ministry of the Interior and Community (BMI). Under two consecutive framework contracts from 2013 to 2020 the so-called ZKI-DE service enabled governmental authorities and other authorized users access to ZKI services, training, feasibility studies, and pilot projects as well as demand-driven developments and innovations. At the end of the ZKI-DE framework agreement, the operational provision of remote sensing products and services was handed over after training to the Federal Agency for Cartography and Geodesy (BKG).

A new framework agreement with BMI started in 2021. The new cooperation, called IF-Bund, now focuses on the analysis of new Earth observation technologies and the transfer of potential innovations from EOC and – where possible DLR-wide – to federal agencies to support their tasks. In addition, the focus is on supporting German federal authorities in building their capacity to use Earth observation data and analyses for other fields of application, such as spatial planning and statistics.

Activities related to technology transfer to public authorities are described in more detail in a later chapter.

In summary, ZKI is substantially contributing to the development of services and the transfer of research results into practice. User-oriented research and innovation, implementation into services, and technology transfer have always been

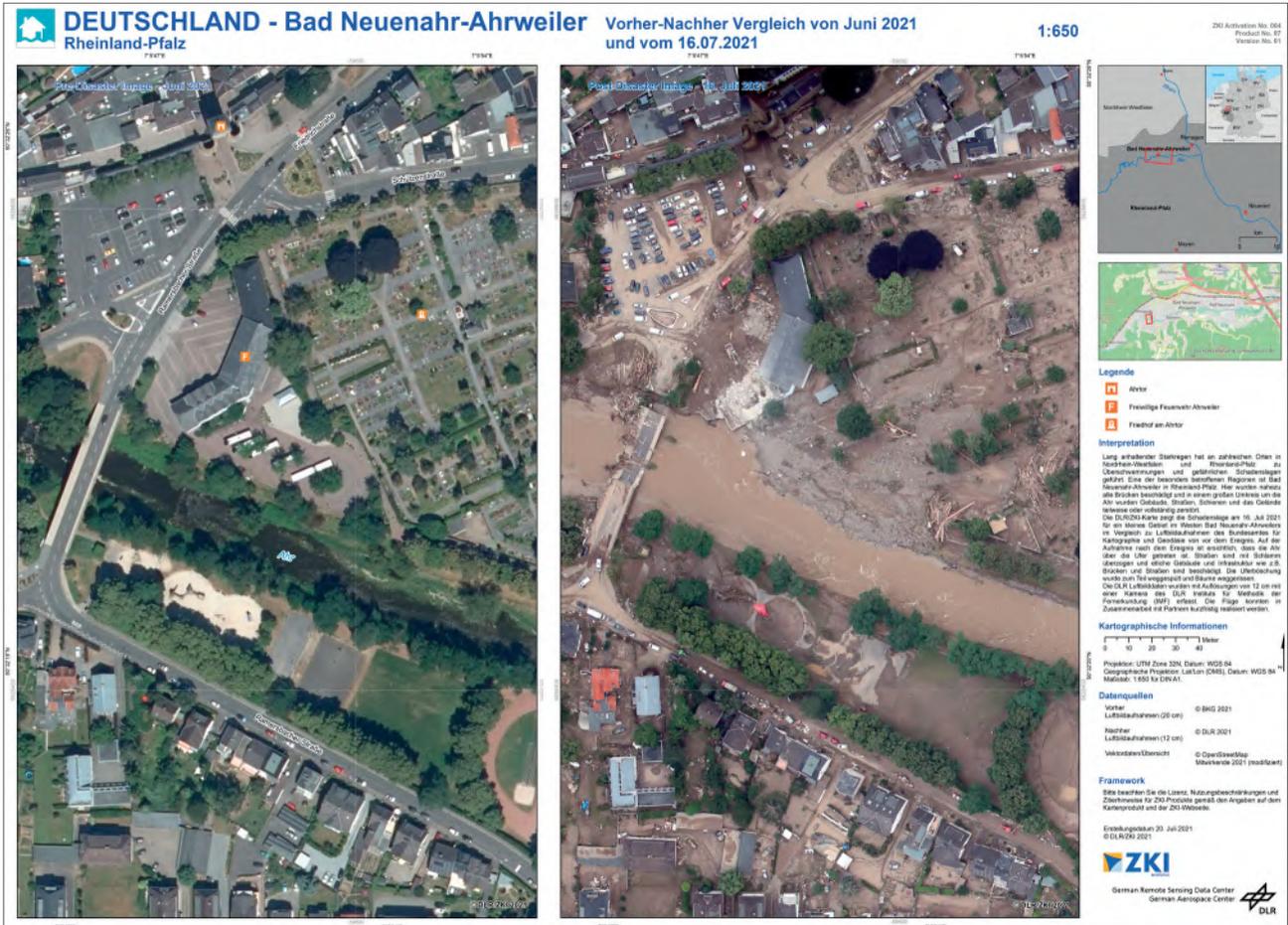
key characteristics of the work of ZKI and stand in many ways for the general attitude of the entire DFD. In recognition of these contributions of ZKI, the German Aerospace Society, DGLR, has awarded the ZKI team the "Ehrendadel der Deutschen Raumfahrt" in August 2021 for the "outstanding achievements of the ZKI team in the use of Earth observation data for worldwide support of crisis management after natural disasters and in humanitarian aid".

Outlook and Challenges

The main orientation of the Georisks and Civil Security department with the described focal topics will be continued and further developed in the future. In terms of scientific research and method development, physically-based algorithms will increasingly be supplemented by methods based on artificial intelligence, especially neural networks and machine learning approaches. This research will be significantly strengthened for all applications in the future.

Another challenge and opportunity at the same time is the topic of "Big Earth Data Analysis". The ability to process and analyze large amounts of data will be further developed and implemented in the high performance computing infrastructure of our *terabyte* system.

The focus here is on the Sentinel missions, since their long-term continuity and data availability is guaranteed within the framework of the Copernicus program. Another important source of Earth observation data will be the current and especially the future national missions EnMAP and HRWS, as well as the new small satellite systems in the area of NewSpace. The capabilities for processing and analyzing big global datasets over long time-spans or in near real-time in combination with other types of data, for example from social media, will be further expanded in the future.



Based on these methodological and technological developments for large-scale data processing and analysis, we will also increasingly focus our research work towards deriving new scientific insights for better disaster management and global change research. This includes research on early crisis detection, on global urbanization with a focus on informal settlements and their dynamic changes, and on complex risk analyses of natural hazards worldwide.

Emergency mapping of the disastrous floods in the Ahr valley in July 2021

Science Communication and Visualization

Orientation of the Department

Earth observation is visual per se. It makes the invisible visible, gradual changes tangible, and provides maps of our atmosphere and Earth's surface. It provides insights, bases for decision-making, and approaches to solutions for socio-politically-relevant issues.

Consequently, DFD has professionalized the visualization of its data for the purpose of interdisciplinary communication of Earth observation, its possibilities, and results. In this way, DFD specifically addresses – beyond scientific publications, projects, and services – a broad lay audience in order to bring its application-oriented research into practice, to inform society, and to inspire young scientists about its topics.

DFD considers science communication to be a genuine part of its tasks and set up a dedicated department at an early stage. Today, this department comprises twelve employees, most of whom have a science background. Their expertise covers the entire spectrum of techniques that can be used for science communication. The Science Communication and Visualization department serves DLR's public relations and intermediary communicators, such as journalists and museums, as an interface to the EOC and as a source of high-quality material.

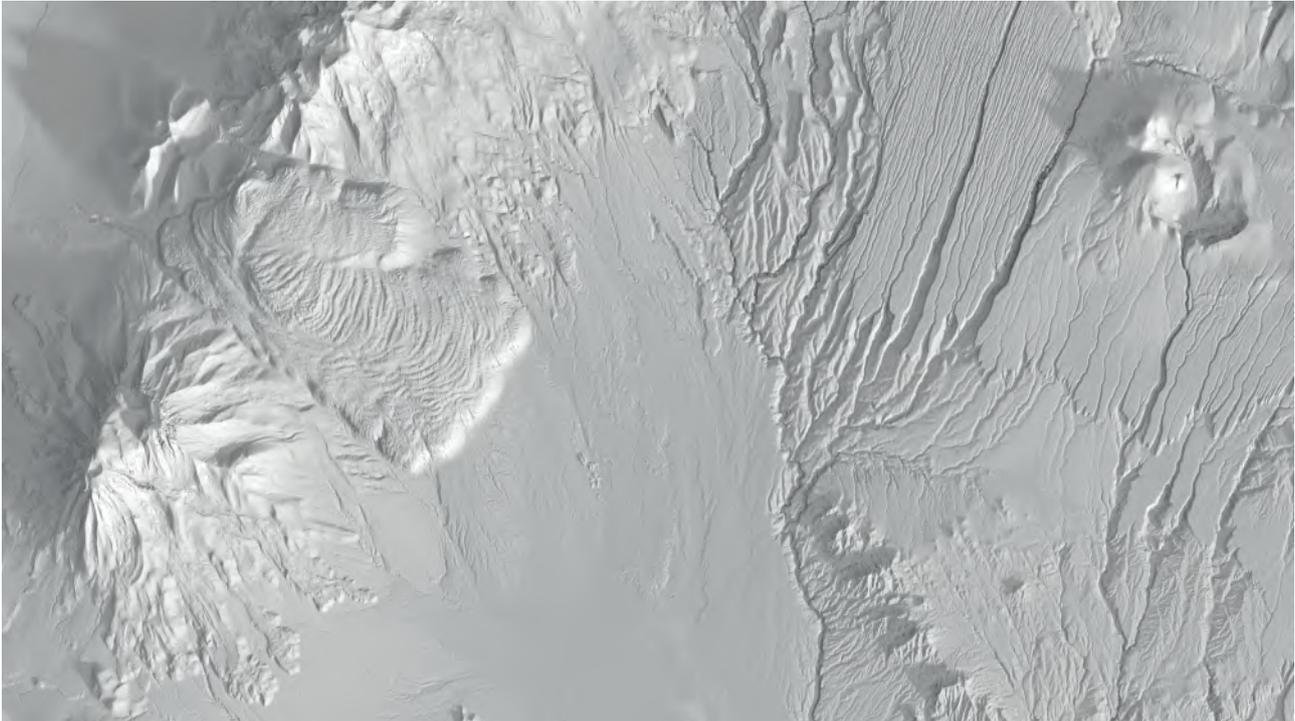
The department focuses on elaborated visualization of complex data and topics. In addition to scientific and data-analysis know-how, professional visualization methods from the film and gaming industries are used for this purpose. The combination of science, data processing, visualization, and aesthetics is unique and cannot be found in this form either

in DLR's PR department or from external providers. For this reason, the department's services are increasingly being used by other institutes in DLR, and by ESA and museums. The products realized in the department include animations, films, and publications that serve the classical communication of knowledge in the sense of the "Public Understanding of Science" as well as exhibits with a high potential for discourse, as is sought in science communication today.

The focus of all products is visual understanding and experience. Images can be used to present complex topics in a comprehensible way to get to the heart of a matter. Above all, however, visualization is the means of choice for generating attention among target groups and arousing interest in a topic. Due to the success of social media channels and the daily flood of information, the need for visually strong material ever increases. In order to become visible in the media noise and still convey science topics, significantly more effort is required today than a few years ago. The department relieves science colleagues and takes over for them the story telling, data preparation, and target-group-oriented visualization of their content in selected domains.

Since the last evaluation period, the department has been able to significantly expand its unique selling proposition and both broaden the portfolio of mastered techniques and further increase the quality of its products. In recent years, the department has managed to gain a number of key personnel. With them, the areas of operational visualization, web and app technologies, film, and virtual reality in particular have been strengthened or newly established.

"DFD considers science communication to be a genuine part of its tasks"



Visualizations, Animations, 3D and Virtual Reality Technologies

The core task of the department was and is the visualization of scientific data and projects. Whether time series, terrain models, simulation data, or even the technology behind Earth observation, the visualization and animation of large and complex datasets is time-consuming and thus cost-intensive. In recent years, we have been able to achieve significant efficiency gains and automate data processing, rendering, and parts of the animation and visualization. Classic time series animations, for example, can now be initiated by the scientist himself via a client. Within minutes, he receives a high-quality visualization that, as footage material, meets the quality requirements of broadcast stations, or with the help of which he can visually test his hypotheses without having to download even one dataset himself beforehand. Only by combining the particular competencies in the department was it possible to

develop methods and techniques that then formed the basis for lighthouse projects with a significant impact, such as the recent Earth and mountain sculpture displayed at the Gasometer Oberhausen exhibition hall.

With virtual reality, the department opened up another field of activity during the evaluation period that fits seamlessly into its previous work. The game engines used in the gaming industry for virtual reality are ideally suited for interactive, immersive science communication. The knowledge built up in recent years makes it possible to circumvent the limitations of game engines in order to integrate, for example, concepts from geodata visualization and techniques from web development.

Graphics rendering with ray tracing: terrain model of the TanDEM-X mission of a region in the Atacama Desert in Chile, west of the Chuquicamata copper mine

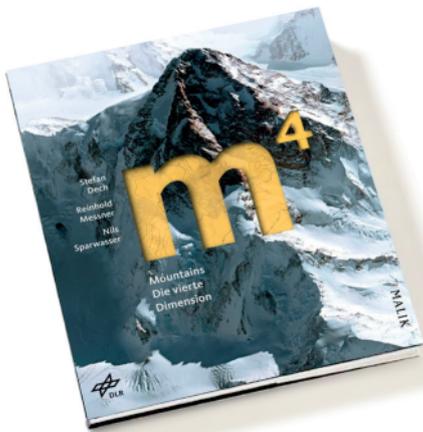
Film and Feature Productions

An elaborate visualization only makes sense if it also succeeds in reaching the desired target group and placing what is presented in a larger context. This is where film comes in. Scientific animations may help to present complex topics in a comprehensible way, but they are hardly suitable for maintaining the audience's interest over a longer period of time. Films, on the other hand, can generate emotions more quickly and offer the chance to credibly convey the scientists behind the projects, their ideas and goals. Emotions help to anchor messages in the memory of recipients. Since the beginning of the current evaluation period, the Science Communication and Visualization department has therefore been making selective use of films in addition to animations. Together, both techniques unfold their full potential. Today, two film school graduates work in the department, and their work and storytelling have contributed significantly to increasing the department's visibility at DLR. The department focuses on micro-documentaries that, despite their brevity, can provide an authentic insight into science. Examples of this are the films for the Rosetta mission or, for example, the documentary on the DFD Antarctic station GARS O'Higgins, which,

like all other work, was created entirely in the department, including story development, animation, postproduction, and sound recording.

Exhibitions and Books

Animations also became the nucleus for new fields of activity. Early on, a publishing house became aware of the institute's work through the department's animations. This encounter led to four internationally released, high-quality illustrated book projects. During the reporting period, the book "m4 Mountains – The Fourth Dimension" was published in collaboration with Reinhold Messner, using computer visualization to create a completely new visual approach to the world's mountain giants. These books in turn led to first exhibitions, museum contacts, lectures, and the first contact with Gasometer Oberhausen. Finally, in 2015, the management of the Gasometer approached the department to realize "Earth Sculpture", an animated projection onto a balloon 20 m in diameter. With 13 projectors, the extremely high-resolution animation created from animated Earth observation data was projected onto the balloon surface.



Above: Photorealistic computer renderings of satellite measurements form the basis for the book project with the exceptional mountaineer Reinhold Messner.

Right: Film complements the department's visualization techniques and opens up new audiences for scientific topics (Scan the QR code to watch the film about GARS O'Higgins).



On the right side: Earth sculpture with a diameter of 20 meters in the exhibition "The Fragile Paradise" in the Oberhausen Gasometer







The exhibition “Das Wunder der Natur” became the Gasometer’s most successful exhibition to date, with over 1.3 million visitors. “Der Berg ruft”, a logical follow-up to the book project with Reinhold Messner, was also extremely successful with over 860,000 visitors. In turn, it led to the development of new technical solutions from which the department subsequently benefits to this day. Together with the most recent exhibition, “Das zerbrechliche Paradies”, which focuses on global change and, among other things, introduces laypersons to the possibilities of Earth observation, DFD has already realized four exhibitions in cooperation with the Gasometer. In this way, it was possible to address a target group that is otherwise difficult for science communication to reach. Even though these projects take up only a small portion of work time, they have a big impact. Further exhibits were and are prepared for the Expo in Astana, the Science Center Experimenta, the Deutsche Museum in Nuremberg, the Oceanographic Museum in Stralsund, the International Astronautical Congress, and ESA. For ESA, several Earth observation exhibits were developed for the visitor center at the Frascati site in Italy. The development of exhibits for museums and trade fairs once again demonstrates the interplay of the department’s various competencies and the successful combination of science, visualization, and aesthetics. One of the resulting developments, a touch table for self-exploration of the topic of Earth observation, was continuously refined during the reporting period and is now being used by DLR institutes, ESA, the Deutsches Museum in Munich, and space museums abroad to bring people closer to Earth observation.

Outlook and Challenges

The department picks up developments in the film and animation industry, the open source community, and consumer electronics, and makes them usable for science communication and scientific visualization. In doing so, it is important to follow trends closely and use resources efficiently in an almost unmanageable market of possibilities, and to ride the wave before it breaks.

The department’s work environment differs from the multi-year science project activities of other DFD departments. Predominantly, this is a small-scale, fast-moving, and dynamic contract business, similar to that of an agency. In order to be successful and at the same time able to drive developments forward, a high level of commitment is demanded of the employees. The success of the department is based on a stable, finely balanced interaction of specialists which has grown over many years. Their expertise will be needed more than ever in the coming years to make science heard and respected. A recently launched initiative by the German Federal Ministry of Education and Research to strengthen and promote science communication underscores this need.



Visualization of flight data for the exhibition "The Fragile Paradise" in the Gasometer Oberhausen. Europe can be seen on the top left, India in the middle and Asia on the right (data source: Flightradar24).

Major Interdepartmental Activities

Major Interdepartmental Activities

High Performance Data Analytics Infrastructure – *terabyte*

Overview

In order to respond to the epochal transformation in Earth observation big data computing and analysis and to fulfill the demands of science at EOC on corresponding vendor-independent and secure platforms, DFD initiated in 2019 a major development jointly with the Leibniz Supercomputing Centre (LRZ) in Garching. This resulted in significant investments on both sides to realize a specific High Performance Data Analytics (HPDA) infrastructure for DLR's EO institutes and Bavarian Universities, including a connection between DFD's D-SDA (German Satellite Data Archive) and LRZ premises and very large fast data storage capability. The installation of the system and its initial operation and optimization is planned in a seven-year (until 2026) Memorandum of Understanding agreement that will be extended in case of a successful first phase. The project is named *terabyte* in allusion to Earth as a research object and to the term terabyte as a data storage unit of measure.

LRZ, an institution of the Bavarian Academy of Sciences and Humanities, is an internationally recognized organization and for us the best possible partner for the implementation of this endeavor. LRZ already operates one of the world's fastest computers. With its focus on computationally intensive applications, there was great interest in jointly with us opening up the field of computationally- and data-intensive Earth observation applications. In return for DLR's contributions, LRZ provides the general infrastructure and expertise for an energy-efficient operation of the resulting high performance data analytics system. Based on

the *terabyte* agreement, DLR can already use the existing structures and exploit considerable synergies by integrating a large part of the planned system facilities at LRZ.

DFD is coordinating the implementation of the *terabyte* system and compiling the requirements of the DLR Earth observation institutes involved.

Approach

terabyte is an infrastructure built on experience in processing EO data for missions as well as in scientific contexts. It combines the engineering and informatics knowledge required for managing data in complex EO missions with the needs of scientists for specific functionality. This discipline of EO informatics strengthens EO science by making available and facilitating the use of state-of-the-art technologies.

All DLR institutes planning to use *terabyte* chose a pilot application – and the respective personnel – to bring in their specific requirements. This way, a team is collaborating not only on establishing a running platform, but also on achieving a scientific goal.

An essential component of the *terabyte* infrastructure is the EO data itself, which requires not only a large data storage capacity of several dozens of petabytes, but also performant data formats as well as seamless integration into the *terabyte* platform services to be offered to scientists.

Hardware

Storage is the focus of the first *terabyte* expansion stage. Thanks to the cooperation agreement, it is possible to draw on LRZ's many years of experience. The data science storage (DSS) concept developed allows the construction of large storage systems that reach the maximum possible speed.



At LRZ, these storage systems have so far been used primarily in high performance computing (HPC) clusters for batch processing. There, the memory is mainly used to hold the processing results for the scientists. Since the LRZ concept scales well, DSS is also suitable for larger databases. However, the volume required for Earth observation data and the type of storage access is a new, innovative application scenario. Indeed, in the case of *terrabyte*, data science storage not only forms the basis of individual calculations, but must also accommodate huge amounts of global datasets, as well as intermediate and final products. This increases the demands on the system and expands the competence of both partners in the area of high performance data analytics.

DLR's major investment in DSS will more than double the online storage at the LRZ data center from 26 PByte to 62 PByte. It will be accessible from all of LRZ's processing environments and thus represent a valuable expansion for the second-largest mainframe in Germany (and ranked 23th globally in January 2021).

The focus of the second stage is the expansion of the number and capabilities of the computing nodes. To ensure optimal tailoring of this hardware and an efficient use of funds, the expansion is being defined by the experience gained from the programmatic DLR project "HPDA User Support" and will accordingly consider the requirements of the participating DLR Earth observation institutes DFD, IMF, PA, and HR. Prior to the second expansion phase, LRZ is already providing us with additional computing power available at LRZ in order to gain initial experience.

Software

The *terrabyte* environment must not be understood as a simple multiplication of computing power. Therefore, a scientist's algorithm cannot simply efficiently use the new environment. To reduce the complexity of the necessary paralleliza-

tion and data management, another layer, practically an operating system for *terrabyte*, is necessary. Only then will it be possible to use the mass of data together with the hardware in such a way that tasks can be solved at a completely new scale.



DLR and LRZ sign the *terrabyte* cooperation agreement © Alessandro Podo, LRZ

Large cloud providers are trying to provide users with an environment in which they no longer have to worry about how their individual tasks are parallelized, and how data is handled and prepared for processing. This allows users to fully concentrate on the actual problem to be solved. The price for users, however, is the loss of their independence. While they gain the ability to process large amounts of data without detailed IT skills, they also lose the freedom to do so with other clouds of their choice, as the means of processing are cloud-provider-specific.

To avoid such a forced binding on *terrabyte*, DLR wants to have control over the software layer or the entire stack on which an application runs. This does not mean that the software has to be developed from scratch. Rather, much of the functionalities similar to those offered by e.g. Google Earth Engine and Amazon Web Services can be provided via an architecture of existing open-source cloud applications. With sovereignty over this stack, it is also possible to switch between providers or operate one's own cloud platform.

An integral part of the software stack developed and customized by DFD is also the resource management, i.e. a fair allocation of computing power and storage volume, load monitoring, consumption of allocated resources by individual users, and the allocation of these resources to projects. This software stack is essential to be able to use an environment of this size. Without it, the *terrabyte* infrastructure would be almost useless, similar to a PC without an operating system. Unlike a PC, the *terrabyte* infrastructure can hardly be “installed” and operated efficiently on one’s own.

Data and Data Management

The initial loading of the infrastructure with satellite data is driven by the requirements of the projects running on *terrabyte*. Data are transferred to *terrabyte* from DFD’s D-SDA or from other locations, such as the Copernicus Sentinel data hubs. As the available satellite data volume is growing continuously, it will not be possible to hold all data online in different product variants; some of the data will have to be evicted. The combination of online platform storage and D-SDA long-term archiving is the particular strength of the *terrabyte* infrastructure. The Online Data Management System (ODMS) developed by DFD is being used and further extended for *terrabyte* with its focus on providing data management mechanisms for data analysis platforms, including data reload from D-SDA, data eviction, and data archiving.

In addition to the initial upload and the storage management, finding the data is the second challenge for the new *terrabyte* infrastructure. Processes have to find the data they need in hundreds of millions of files. Archives have developed corresponding mechanisms. However, these are not always fit for the highly parallelized world of the *terrabyte* environment and are not connected to data analysis tools. A special catalog that combines discovery of and access to data is therefore created so that the required

data can be identified and directly used in data analysis tools, such as data cubes. Making data available as analysis-ready data (ARD), which allows immediate data analysis with no additional pre-processing effort, is also a primary goal according to many user requirements.

***terrabyte* User Support**

To enable users to implement their application for optimal performance on the system, they need to use this software stack correctly. Specifically, the handling and optimal use of highly-scaled computer architecture requires special skills, both in the adaptation of algorithms and in the optimization of process flows.

“*terrabyte* User Support” provides resources for building up this know-how for all DLR users and helps them to further develop their skills in designing and implementing science algorithms to achieve optimal performance on the HPDA platform.

Driven by the science needs of the research departments and made possible by the engineering capabilities of the payload data ground segment, *terrabyte* is a groundbreaking DFD development project for the entire DLR, in which geoscientists with special IT backgrounds and experienced space engineers from PDGS combine their knowledge to find the best possible solution for future global big EO data processing at DLR. Project management is the responsibility of the International Ground Segment department, supported by experts from five other DFD departments as well as additional contributions from the other three DLR EO user institutes. This team is jointly working on the design and development of the *terrabyte* platform.

Environmental and Crisis Information Systems Framework – UKIS

UKIS is DFD's software framework for the development of geoscientific web applications. UKIS has been developed and implemented at DFD since 2012 with the goal of providing a common technical basis for the development and configuration of (geo)information systems to support geoscientific analysis, visualization and situation assessment in environmental and crisis-related applications.

UKIS aims to harness research in Earth observation and related topics with easy-to-use geoscientific visualization and analysis systems. Thus, UKIS is a key component within our DFD-wide end-to-end chain that extends from raw satellite data to the end user. The modular approach of UKIS allows the integration of DLR's latest technological and scientific developments. Internal and external data sources can be connected via standardized interfaces. In addition, the topics of data privacy, IT security, and corporate design are of particular importance in UKIS.

UKIS is characterized by its specific orientation to the needs of DLR and, at the same time, by a very high degree of flexibility. The framework seamlessly integrates into complex system environments developed together with external partners in large-scale research and development projects. Thus, UKIS is designed to be reusable. A large number of thematically different systems can be created on its common technical basis. All UKIS-based systems mutually benefit from innovations in the common software basis. An agile project management model allows short response times to changing thematic or technical

requirements. UKIS software is continuously adapted and extended in iterative development sprints.

Besides, UKIS is open. A selection of UKIS software products is published under an open source license on the Internet. In this way, industry and science benefit from work done at DLR while we in turn benefit from contributions and feedback from external software developers. Hence, UKIS makes us independent of the product and licensing policies of commercial companies. Furthermore, UKIS systems can be passed on to users and partners without bureaucracy.

Organizationally, UKIS is teamwork. UKIS is in charge of the technical system basis, jointly developed and maintained by the Geo-Risks and Civil Security and Land Surface Dynamics departments, while research and development projects and/or other DFD departments are responsible for the implementation and operation of the specific systems.

Examples of past and current developments are natural hazard warning and information systems for floods and fires, environmental information systems for coastal and land cover monitoring, information systems in the fields of civil security and maritime applications, health information systems, and applications in planetary research (for a dedicated DLR institute in Berlin), as well as systems for creating video animations from remote sensing data.

For instance, the Maritime Security Service (MARISS) is a UKIS-based system that visualizes EOC's scientific information products developed by the EOC Maritime Safety and Security Labs, e.g. vessel detections, wind and wave products or sea ice classifications. Input data from radar and optical satellite missions are received directly at DFD ground stations and the data analysis is performed in near real-time on the institute's own processing infrastructure. The results are published



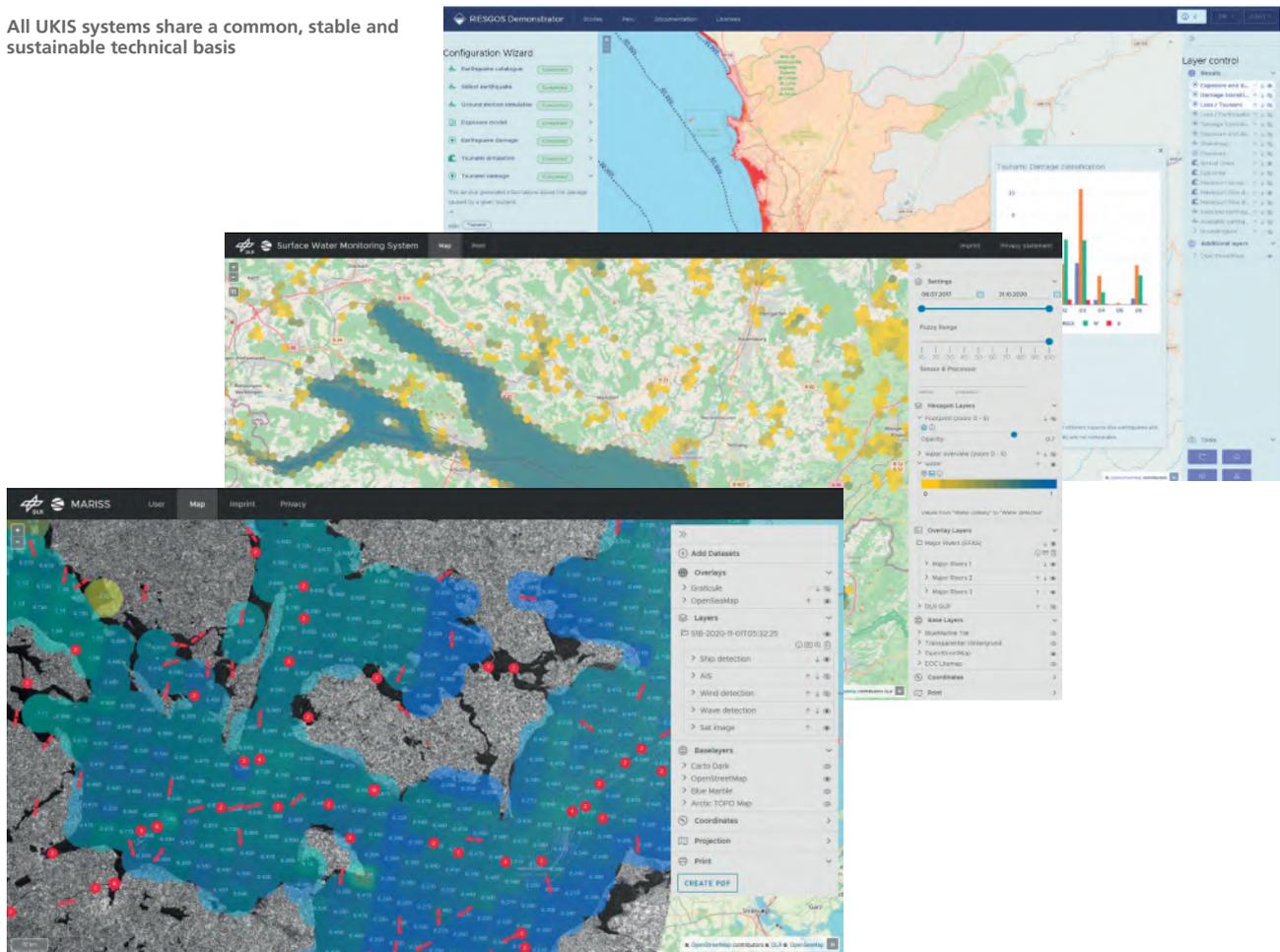
Major Interdepartmental Activities

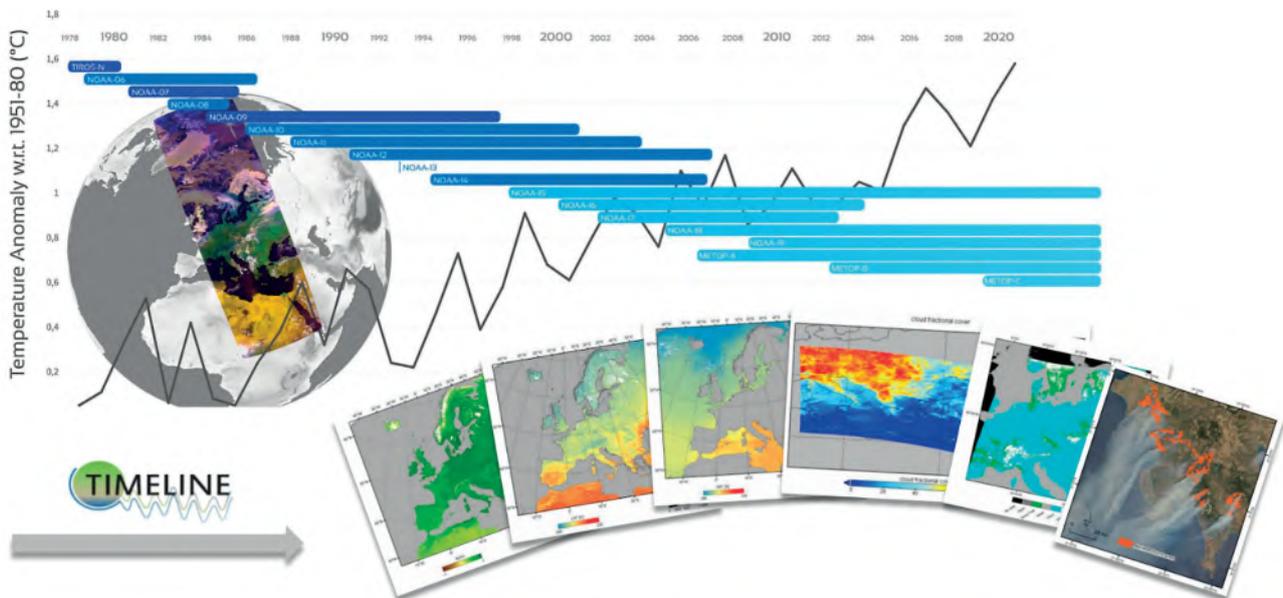
via DFD's Geoservice and finally visualized in the UKIS-based MARISS system in a modern and user-friendly manner.

During the past few years UKIS has proven itself many times over. Up to now, UKIS software components have been used to create more than 30 geoscientific information systems. More than 25 systems are based on the UKIS front-end libraries, which are used for building intuitive graphical user interfaces. More than 15 systems use a variety of back-end components such as geodata postprocessing, storage of analysis-ready

data, or real-time text analysis. Some systems use both back-end and front-end components. Currently, 12 software repositories have been published under an open source license, including all front-end libraries, numerous back-end components, as well as auxiliary tools. Altogether more than 15 third-party-funded projects have been supported by UKIS. All DFD departments use UKIS clients or contribute to UKIS development.

All UKIS systems share a common, stable and sustainable technical basis





Decadal Satellite Series Data Reprocessing Framework – TIMELINE

Since the early 1980s, DFD has been acquiring and processing data from the Advanced Very High Resolution Radiometer (AVHRR) instrument series providing daily datasets with a spatial resolution of ca. 1.1 km. This unique multi-decadal dataset allows us to investigate the long-term impacts of climate change on our environment. The very high temporal resolution of the data series enables the derivation of related statistical parameters such as mean, variability, anomalies, and trends. The challenges to generating a well calibrated and harmonized 40-year-long time series based on the AVHRR series of instruments (three versions exist) operated on 14 different platforms are enormous.

A consistent time series has to be created to make use of this wealth of data. Since no such consolidated dataset exists in Europe, the generation of a homogeneous multi-decadal time series from AVHRR, AVHRR/2 and AVHRR/3 data collected over Europe and North Africa is the main objective of DFD's TIMELINE project. Within TIMELINE, an operational processing and data management environment is being developed to reprocess almost 40 years of NOAA and MetOP AVHRR raw data to Level 1b, Level 2, and Level 3 products based on 1.1 km high-resolution picture transmission and local area coverage. Different remote-sensing-based land and atmosphere geoinformation products with uniform format, map projection, extent, etc. are developed within TIMELINE. The product suite consists of atmospherically corrected surface reflectance, NDVI, snow cover, fire hotspots and burnt area mapping, land surface temperatures, sea surface temperatures, and different cloud-physical properties (e.g., cloud-top temperature).

The TIMELINE products from daily AVHRR coverage over four decades allow the monitoring of climate change effects.

The successful interaction of all DFD departments with their different areas of expertise is what makes TIMELINE possible in the first place. The project is managed by DFD's Land Surface Dynamics department, which also developed some of the Level 1, Level 2, and Level 3 processors. The Geo-Risks and Civil Security and Atmosphere departments are also involved in processor development. These three departments are actively engaged in the scientific evaluation of the TIMELINE products and publication of the results. Public outreach is supported by the Science Communication department. The steps of data curation, data processing and archiving of the TIMELINE products are directed by the two DFD ground segment departments. In addition to in-house activities, Brockmann Consult GmbH is also involved in the contribution of Level 2 processors and validation activities.

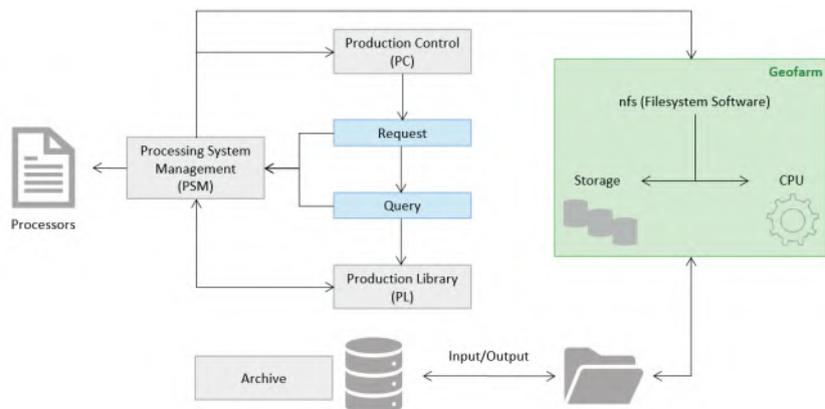
Generating a harmonized and well-calibrated 40-year-long time series based on AVHRR data is extremely challenging if we want to ensure the consistency of reflectance and thermal information. The two major challenges are correction for the satellite orbit drift and the channel calibration drift of the different AVHRR instruments. Thorough data harmonization steps and pre-processing are necessary to eliminate these errors from the

time series. Therefore, a prerequisite for generating a multi-decadal harmonized data base is a well-thought-out framework for big data processing. Hence, a highly automated system composed of a processing, archiving, discovery, and access system was developed as part of the TIMELINE project. This processing system enables (re-)processing of all products in a unified and customizable way, allowing for parallelization of workflows, and ensuring a continuous but flexible input data stream making use of archive tapes from DFD's D-SDA in streaming mode.

Constant monitoring of data quality and regular validation of the different products ensures deep knowledge of the quality of the TIMELINE products. Different remote sensing datasets (e.g. MODIS), pseudo-invariant desert sites, and available continuous measurements over different calibration sites (e.g. DEMMIN) serve as input for the validation process.

Data access and dissemination of the TIMELINE products is implemented using DFD's Geoservice, which provides free and open discovery, visualization, and direct download services to users worldwide.

The TIMELINE processing system



The TIMELINE project enables the analysis of changes as well as the identification of geophysical phenomena and trends in Europe and the Mediterranean area. The very high temporal resolution of long-term time series and the derivation of related statistical parameters such as annual or decadal means and variances serve as inputs for investigating the long-term impacts of climate change on our environment.

Up to now, the fully automated processing chain has handled around 500 TB of data with more than 15 different AVHRR geospatial products from Level 1 to Level 3. The daily, 10-day, and monthly Level 3 products with statistical information for the respective period are being used, for example, to study the long-term dynamics of large-scale land and sea surface temperatures. Concerning land surface temperature (LST), we are currently determining the intensity of the surface urban heat island over Europe for the period 1981–2018 using the TIMELINE L3 LST data.

Technology Transfer to Public Authorities – IF-Bund

The Center for Satellite Based Crisis Information (ZKI) has been implemented and further developed primarily in the Geo-Risks and Civil Security department. However, ZKI activities substantially benefit from the work of other departments, making ZKI a prime example of interdepartmental cooperation within DFD, EOC, and even beyond. For instance, direct access to satellite data from DFD's ground segments has been a key asset that allows fast and flexible near real-time data acquisition in crisis situations. In addition, aerial data have been acquired and analyzed very efficiently in emergency situations using EOC's capa-

bilities. This was e.g. the case during the catastrophic flooding in Germany in July 2021. Moreover, ZKI also benefits from the high performance data processing infrastructure and DFD's Geoservice for the distribution of data.

As mentioned earlier, ZKI is effectively contributing to the transfer of technology to public authorities. This is especially the case within the ZKI-DE and IF-Bund framework agreements with the Federal Ministry of the Interior (BMI), and also takes place in the course of international research and development projects.

Technology Transfer to Federal Authorities

From 2013 to 2020, the ZKI-DE service made it possible for federal authorities to obtain at short notice current geoinformation and analyses, which presented public administrations with new options for action. This innovative collaboration met the need of federal authorities for current, value-added remote sensing data and analyses for crisis situations and to support civil security. The product and service portfolio developed within ZKI-DE has been very successfully adopted by federal agencies, so that between 2016 and 2020 the Federal Agency for Cartography and Geodesy (BKG) was trained by the ZKI team to take over the provision of these operational services to federal authorities. This transfer of comprehensive technical expertise enabled BKG to provide these services from 2021 on.

In the new framework agreement "IF-Bund", which stands for "Innovative Remote Sensing for the Federal Administration", the training and enabling of federal agencies and authorities also plays a key role. The focus is now on innovation and knowledge transfer as well as the extension of the range of applications beyond the core topic areas of natural hazards and civil security. This includes feasibility studies, pilot projects, consulting on new technologies, and service improvements.



IF-Bund - Innovative Remote Sensing for the German Federal Administration: A framework contract concluded between DLR and the Federal Ministry of the Interior, Building and Community (BMI).

A continuous task is to inform government authorities about relevant technological developments in Earth observation and related areas and its potential for practical implementation.

With respect to technology transfer the activities in ZKI-DE and IF-Bund comprise:

- Advising users on the potential of remote sensing technologies,
- Feasibility studies and assessments of new technological developments,
- Training users in the use of remote sensing,
- User-driven further development and adaptation of the product portfolio.

In this context we have organized and conducted 20 training courses and workshops together with users since 2013, which also led to further development of a number of dedicated products and services.

Technology Transfer to European Public Authorities

Within several international projects the development of technologies and their transfer into practice is of high relevance. For instance, in the EU-funded project DRIVER+ (Driving Innovation in Crisis Management for European Resilience) new technologies have been developed that are addressing the operational needs of practitioners dealing with crisis management in Europe.

ZKI not only contributed its experience to the development of the methodological framework. It further provided innovative solutions to be selected by practitioner organizations in specially organized trials. Within the scope of DRIVER+, four trials and a final demonstration were conducted, which enabled various practitioner organizations across Europe to test and validate new solutions for their organizations in realistic environments to meet the challenges of ever more complex crises. ZKI has been able to demonstrate the potential of emerging remote sensing methods to eleven crisis management authorities and affiliated organizations in the Netherlands in the context of large-scale flooding, as well as to additional user groups in a trial in Austria designed around an earthquake scenario. The resulting feedback is incorporated into the further development of the service. With this approach, the project accelerated capability development and innovation through user-adapted solutions and promoted subsequent technology transfer into practice.



EOC Central Functions Provided by DFD

EOC Central Functions Provided by DFD



IT Management

Following a cross-sectoral approach within DLR, each institute has its own dedicated IT staff. IT management for DFD, however, is shared with IMF and is responsible for both institutes, handling numerous operational tasks in the context of reception, processing, archiving, and distributing remote sensing data at EOC. In addition, mass data processing and analysis in platform-based environments has gained importance in recent years. Data integrity, data security, data throughput, data transfer over wide area networks, near real-time response, and system availability are key factors EOC-wide.

EOC is utilizing distributed hybrid environments in order to achieve the data availability and processing power necessary for its experimental and operational tasks. This "ecosystem" comprises in-house IT systems with fast access to the satellite data archive and HPC systems. These are complemented by the *terabyte* infrastructure with massive on-line storage, operated in collaboration with LRZ and further supplemented by infrastructure-as-a-service provided by several public cloud providers, all connected by a 10-100 Gbit/s network bandwidth.

Some specific tasks use infrastructure provided by partners or required by projects. This equipment is usually located in separate network environments with separate network access, which therefore increases the complexity of IT management. An additional challenge arises from our infrastructure located across the globe: receiving stations in Neustrelitz, Oberpfaffenhofen, in the Arctic, and Antarctica that require communication over wide-area networks, including satellite links.

The EOC offices, research, and operational environments require a number of IT infrastructure elements, the most important being:

- Data and computing centers, including air conditioning and an uninterruptable power supply
- Local and wide area networks (LAN and WAN)
- Security systems (e.g. firewalls, anti-virus servers)
- Server farms and virtual machines in the "EOCloud" infrastructure
- Disk storage and a storage area network
- Long-term archiving elements (on/off disk technology, robot libraries, and tape drives)
- Applications (e.g. monitoring, asset management, continuous integration, and deployment)
- Central services (e.g. home service, backup service, print service, license service)
- Communication systems (e.g. phones, video conference systems)
- Personal computers

IT general concepts as well as IT security concepts are defined and implemented by the in-house IT management and engineering team at DFD in communication with DLR's central IT department. The IT activities of the individual departments are coordinated and team up to obtain suitable solutions. Standard administrative services and tasks are procured from service providers, requiring additional guidance and controlling activities.

Approximately every five years the IT management is reviewed by a team of external experts. The last IT audit was performed in late 2021, when the quality and qualifications of the EOC IT team were rated as being "outstanding". The referees stated that DFD was in many

respects a “role model” for other DLR institutes. The evolution and achievements of EOC IT management are outlined in the Information Technology department presentation in chapter 3.

Quality Management

Success and appreciation by our project partners and customers are based on the quality of our processes, projects, and services. DFD was among the first institutes in DLR to implement a quality management system and to establish a dedicated team. This decision was based on the self-image of the institute but also on general working practices and contractual requirements in large satellite PDGS projects, where product assurance and quality management play an important role. With IMF also being committed to the quality concept, and for practical reasons, the quality management system developed at DFD was expanded to the entire EOC, and for that reason our ISO 9001 certificates are issued to EOC.

The EOC quality management system was first certified to ISO 9001 standards in 2007 and has remained without any “nonconformance” since then. It is based on a two-tier management model, consisting of “Business Management” and “Product Realization”. Business Management deals with the management of the two EOC institutes and covers the domains of Top Management, Resource Management, Quality Management, and Project Management.

Project management is the predominant method of conducting business. Management methods and guidelines are defined here, with a focus on satellite ground segment projects. Risk management and product assurance form an integral part.

This is to ensure that the product meets customer requirements and that it is safe, available and reliable.

The principal characteristic of our quality management system is the application of a generic entity model in the domain of “Product Realization”. Entities are self-contained operational units, clearly defined by functionality and specific products and services. They are supported by facilities. Entities are independent of the EOC organization, i.e. they may span across organizational units and different sites. MindMap diagrams are used to identify and document an entity. We have identified two operational areas in which entities are defined, namely “User Services” and “Ground Segment Operations”. Both operational areas are of strategic importance to DFD (see sections 2.1 and 2.3), thus it is of utmost importance to minimize risks in these areas and to ensure that products and services are delivered reliably and in the defined quality.

The evolution and achievements of the EOC quality management system are outlined in the Information Technology department section of chapter 3. At this point, however, attention may be drawn to the fact that due to the deep rootedness of the quality concept and the great commitment of individuals the DLR Quality Award (now the DLR Integrated Management System Award) has already been conferred three times to individuals in EOC.



Projects for Satellite Payload Ground Segments as well as the two operational areas User Services and Ground Segment Operations are ISO 9001 certified with their entities WDC-RSAT, ZKI, OpAiRS, Ground Station Services – Neustrelitz, Ground Station Services – O’ Higgins, Ground Station Services – Inuvik, D-SDA Services and CATENA (status 2021).

Science Communication

In addition to the activities described earlier in chapter 4, the Science Communication and Visualization department performs central tasks for both EOC institutes. For example, the department maintains the EOC web portal, which, excepting the main DLR portal, is the largest and most up-to-date DLR portal, providing more than 50 news items per year. The department takes care of the maintenance and updating of the exten-

sive Internet and Intranet offering, and also manages customized web pages, such as project portals. It also provides advice and support in the realization of special requests. Journalists, publishers, museums, and public authorities, but also private individuals can contact EOC with their questions and material requests via the helpdesk and receive quick assistance. In addition, the department supports all EOC departments not only with respect to the generation of film and animation material, but also in all design aspects and layout tasks that require its tools and expertise. In this way, the entire EOC benefits from the department's portfolio and its further development.



DFD's own touch table development offers an intuitive and simple way to introduce guests to the topics of geodata and earth observation on site or at trade fairs. The software is not only in use at the ESA Visitor Center in Frascati, but also in various museums.

On the right: The Science Communication and Visualization department also provides support for scientific conferences and trade shows and develops exhibits for DFD, such as terrain projections and touch tables.



Appendix

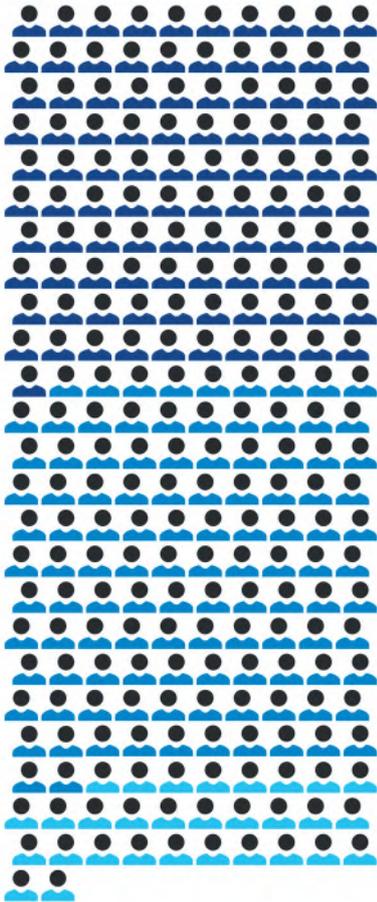
Appendix



Scientific Record Summary

The summary of the documentation part covers the scientific activities of DFD and the associated Department of Remote Sensing at the University of Würzburg in the period between January 1, 2013 and December 31, 2021.

For the full version of the documentation, please scan the QR code on the left or follow the link: https://pub.eoc.dlr.de/eoc-dfd_statusreport_documentation.pdf



256 DFD employees, thereof 212 scientists/engineers (101 in PDGS; 111 in application research, 30 doctoral students)

Academic Degrees

4	professorship appointments, one rejected offer of a professorship
7	habilitations, thereof one ongoing
99	doctoral theses completed or ongoing
280	master theses
134	bachelor theses
11	diploma theses
1	magister thesis

Publications

2579	publications
665	thereof peer-reviewed ISI/SCOPUS publications
244	other peer-reviewed publications
30	open source publications since 2015, including 12 high relevant ones (i.e. actively maintained, citable, popular)
14	books
152	book contributions

Teaching and Education

399	lectures at 17 national and 9 international universities
243	thereof at University Würzburg and University Augsburg
102	invited guest lectures, 76 at 23 national and 26 at 25 international universities

- 112** non-university courses / tutorials at 17 national and 28 international locations
- 9** webinars
- 6** different internal seminar series
- 641** in-house interns and trainees

Scientific Exchange

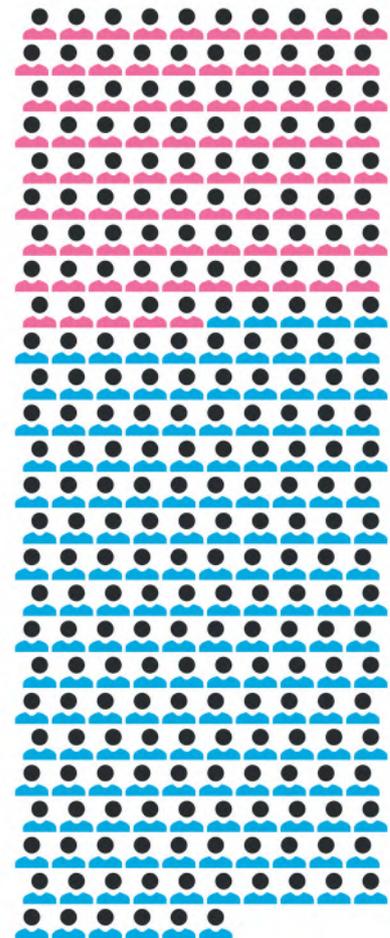
- 68** guest scientists have been hosted by DFD or by the department of Remote Sensing at University of Würzburg (≥ 4 weeks stay)
- 13** DFD scientists spent 15 professional leaves at external institutions
- 52** major conferences, colloquia, workshops (co-)organized by DFD and department of Remote Sensing at University of Würzburg since 2013 (> 40 participants)
- 79** key note speeches at major conferences conducted by 24 scientists

Patents and Awards

- 11** granted patents and 4 filed patent plications
- 52** awards

Memberships

- 83** memberships of 35 scientists in boards of
- 41** different organizations
- 11** scientists are members of 15 different journal editorial boards



256 DFD employees (85 women/171 men)

Abbreviations

3D	Three-dimensional	BMBF	Federal Ministry of Education and Research	CPU	Central Processing Unit
4D-VAR	Four-dimensional Variational Data Assimilation	BMEL	Federal Ministry of Food and Agriculture	DAAD	German Academic Exchange Service
ACE	Advanced Composition Explorer (NASA mission for solar system exploration)	BMI	Federal Ministry of the Interior and Community	DBU	German Federal Environmental Foundation
AC-SAF	EUMETSAT Satellite Application Facility on Atmospheric Composition Monitoring	BMUV (former BMU)	Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection	DELIGHT	Delta Information System for Environmental and Human Habitat Transition (BMBF-funded project in the Delta of the Yellow River)
ADM/AEOLUS	Atmospheric Dynamics Mission Aeolus (ESA Earth Explorer core mission)	BMVI	Federal Ministry for Digital and Transport	DEMMIN	Durable Environmental Multidisciplinary Monitoring Information Network
AEROSAT	International Satellite Aerosol Science Network	BMWK (former BMWi)	Federal Ministry for Economic Affairs and Climate Action	DEM	Digital Elevation Model
AI	Artificial Intelligence	BMZ	Federal Ministry for Economic Cooperation and Development	DESES	DLR Earth Sensing Imaging Spectrometer
AIS	Automatic Identification System	C3S	Copernicus Climate Change Service	DFD	German Remote Sensing Data Center
ALOS	Advanced Land Observing Satellite	CAMS	Copernicus Atmospheric Monitoring Service	DFG	German Research Foundation
AlpEnDAC	Alpine Environmental Data Analysis Center	Cassiope	Cascade, Smallsat and Ionospheric Polar Explorer	DFN	German Scientific and Research Communication Network
AVHRR	Advanced Very High Resolution Radiometer	CATCH-MEKONG	BMBF-funded project for the transboundary Mekong river catchment	DIAS	Data and Information Access Service of Copernicus
AVIRIS	Airborne Visible InfraRed Imaging Spectrometer	CCI	Climate Change Initiative	DIBIAS	Image processing software developed by DFD
AWI	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research	CEOS	Committee on Earth Observation Satellites	DIMS	Data Information and Management System
BayStMUV	Bavarian State Ministry of the Environment and Consumer Protection	CHAMP	Challenging Minisatellite Payload	DSCOV	Deep Space Climate Observatory
BioClimS	BioClimatic information System	CNN	Convolutional Neural Network	D-SDA	German Satellite Data Archive (operated by DFD)
BIROS	Berlin InfraRed Optical System (one of two satellites of the DLR FireBIRD mission)	CODE-DE	Copernicus Data and Exploitation Platform (national project in the context of the Copernicus collaborative ground segment)	DRIVER+	Driving Innovation in Crisis Management for European Resilience (EU FP7 project)
BKG	Federal Agency for Cartography and Geodesy	COSMO-SkyMed	Constellation of small satellites for the Mediterranean basin observation	DSS	Data Science Storage
				DWD	Deutscher Wetterdienst

EAGLE	Earth Observation and Geoinformation for the Living Environment (international Master's study program at Würzburg University)	EvoODAS	Evolution of Online Data Access Services (ESA-funded technology project)	GRETA	Greenhouse Gas Registry for Emissions Trading Arrangements
ECSS	European Cooperation for Space Standardization	FAIM	Fast Airglow Imager	GRIPS	Ground-based Infrared P-branch Spectrometer
EDOS	EOC Data Online Storage (system base for the internal storage solutions IDA and U-Shelf)	FEP	Front-End Processors	GROGRAT	Gravity-wave Regional or Global Ray Tracer
EFFIS	European Forest Fire Information System	FireBIRD	Fire Bi-spectral and Infrared Remote Detection (DLR small satellite constellation)	GSOC	German Space Operations Center
EMS	Emergency Management Service	FZJ	Forschungszentrum Jülich	GUF@	Global Urban Footprint
EMSA	European Maritime Safety Agency	GAIA-X	Initiative for developing an efficient and competitive, secure and trustworthy federation of data infrastructure and service providers for Europe	HAP	High Altitude Platform
EnMAP	Environmental Mapping and Analysis Program (German hyperspectral satellite Earth observation mission)	GARS O'Higgins	German Antarctic Receiving Station O'Higgins	HARPA/DLR	Hamiltonian Ray-Tracing Program for Acoustic Waves in the Atmosphere (improved by DLR-DFD)
ENVISAT	ESA's Environmental Satellite	GDAS	Geospatial Data Access System (software base of the EOC Geoservice)	HEIMDALL	Multi-Hazard Cooperative Management Tool for Data Exchange, Response Planning and Scenario Building (EU-H2020 project)
EO	Earth Observation	GEO	Group on Earth Observations	HGF	Helmholtz Association
EOC	Earth Observation Center	GeoForPy	BMUV-funded project on deforestation in Paraguay	HI-CAM	Helmholtz Climate Change Initiative Project
EOCloud	EOC-wide cloud infrastructure	GEOSS	Global Earth Observation System of Systems	HIMAWARI-8/-9	Geostationary weather satellites operated by the Japan Meteorological Agency
EODC	Earth Observation Data Centre GmbH	GFZ	German Research Center for Geosciences, Helmholtz Centre Potsdam	HPC	High Performance Computing
EO-MARISS	Earth Observation Maritime Surveillance System	GIS	Geographic Information System	HPDA	High Performance Data Analytics
ERS-1/-2	ESA's European Remote Sensing Satellites	GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH	HR	Microwaves and Radar Institute of DLR
ESA	European Space Agency	GOME	Global Ozone Monitoring Experiment	HRWS	High Resolution Wide Swath (planned national radar mission)
EU-H2020	European Union Horizon 2020 program	GOMOS	Global Ozone Monitoring by Occultation of Stars	HySpex	Hyperspectral airborne sensor
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites	GPU	Graphics Processing Unit	HZGM	Helmholtz Centre Munich, German Research Centre for Environmental Health
EuroHPC	European High-Performance Computing	GRACE	Gravity Recovery and Climate Experiment		
		GRACE-FO	GRACE Follow-On		

IDA	Internal Data Access (internal online storage solution providing low-latency access to EO data)	LMU	Ludwig-Maximilians-University of Munich	OASIS	Observations of Airglow with Spectrometer and Imager Systems (DLR programmatic project)
IDN	International Directory Network (international effort coordinated by CEOS to assist researchers in locating Earth science data)	LOOSE	Technologies for the management of long EO data time series (ESA-funded technology project)	ODMS	Online Data Management System
IF-BUND	Innovative Remote Sensing for the Federal Administration (framework agreement with BMI)	LRZ	Leibniz Supercomputing Centre	OECD	Organisation for Economic Co-operation and Development
IMF	Remote Sensing Technology Institute of DLR	LTA	Long-Term Archive	OGC	Open Geospatial Consortium
IMPC	Ionosphere Monitoring and Prediction Center	MACS	Modular Aerial Camera System	OLCI	Ocean and Land Color Instrument
IPCC	Intergovernmental Panel on Climate Change	MARISS	Maritime Security Services	OS	DLR Institute of Optical Sensor Systems
IR	Infrared	ME	DLR Institute of Aerospace Medicine	PA	DLR Institute of Atmospheric Physics
ISM	Image processing software developed by DFD	MetOP	Meteorological Operational Satellite	PAC	Processing and Archiving Center
ISRO	Indian Space Research Organisation	MIPAS	Michelson Interferometer for Passive Atmospheric Sounding	PALM4U	Model for the simulation of urban atmospheric boundary layers
ISSF	Inuvik Satellite Station Facility	MODIS	Moderate Resolution Imaging Spectroradiometer	ParLU	BMUV-funded project on landcover change in Paraguay
IT	Information Technology	MPI	Max Planck Institute	PAZ	Spanish X-band SAR mission
IUCN	International Union for Conservation of Nature	MSG SEVIRI	Spinning Enhanced Visible and Infrared Imager onboard the Meteosat Second Generation satellites	PDGS	Payload Data Ground Segment
JECAM	Joint Experiment for Crop Assessment and Monitoring	NASA	National Aeronautics and Space Administration	PECASUS	Pan-European Consortium for Aviation Space weather User Services
JPL	Jet Propulsion Laboratory (NASA)	NDMC	Network for the Detection of Mesospheric Change	RESA	Rapid-Eye Science Archive
KARI	Korean Space Agency	NFDI4Earth	National consortium for the development of a national research data infrastructure in the field of Earth system sciences	RICOPA	Regional Ionosphere Corrections for Positioning Applications
KliSAW	Klimarelevante Spurengase, Aerosole und Wolken (DLR programmatic project)	NGO	Non-Governmental Organisation	RIESGOS	BMBF-funded project on multi-risk assessment
KOMPSAT	Korea Multi-Purpose Satellite	NOAA	National Oceanic and Atmospheric Administration	prosEO	Processing System for Earth Observation Data
KSAT	Kongsberg Satellite Services	NRT	Near Real-Time	SAR	Synthetic Aperture Radar
LfU	Bavarian Environment Agency				

SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management	TIMED-SABER	Sounding of the Atmosphere using Broadband Emission Radiometry Instrument onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics satellite	WASCAL	West African Science Service Centre for Climate Change and Adaptive Land Management
SatDSiG	German Satellite Data Security Act	TIMELINE	Time series processing of medium resolution Earth observation data assessing long-term dynamics in our natural environment (DFD project)	WCRP	World Climate Research Program of the UN
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography	TropOMI	Tropospheric Monitoring Instrument	WDC-RSAT	World Data Center for Remote Sensing of the Atmosphere
SHOA	Chilean Navy's Hydrographic and Oceanographic Service	UBA	German Environment Agency	WHO	World Health Organization
SLSTR	Sea and Land Surface Temperature Radiometer onboard Sentinel-3	UC2	Urban Climate Under Change (German research initiative)	WISDOM	Water related Information System for the Sustainable Development of the Mekong Delta (BMBF-funded project)
SMCS	Station Monitoring and Control System	UFS	Environmental Research Station Schneefernerhaus	WMO	World Meteorological Organization
SME	Small and Medium sized Enterprises	UFZ	Helmholtz Centre for Environmental Research	WRF	Weather Research and Forecast
So2SAT	DLR project funded by the European Research Council	UKIS	Environmental and Crisis Information Systems	WSF	World Settlement Footprint
SRTM	Shuttle Radar Topography Mission	UMLT	Upper Mesosphere and Lower Thermosphere	WWF	World Wide Fund for Nature
SSA SWE	Space Situational Awareness Space Weather	UMS	User Management System	ZKI	Center for Satellite based Crisis Information
SSC	Swedish Space Corporation	UN	United Nations	SASSCAL	Southern African Science Service Centre for Climate Change and Adaptive Land Management
STEM	Science, Technology, Engineering and Mathematics	UPSTAIRS	Image processing software developed by DFD	SatDSiG	German Satellite Data Security Act
SULU	BMUV-funded project on land degradation in Paraguay	USGS	United States Geological Survey	SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
TanDEM-L	Proposed national L-band SAR mission	U-TEP	Urban Thematic Exploitation Platform (ESA project)	SHOA	Chilean Navy's Hydrographic and Oceanographic Service
TanDEM-X	TerraSAR-X add-on for Digital Elevation Measurement (national X-band SAR mission)	U-Shelf	Internal online storage solution serving EOC researchers	SLSTR	Sea and Land Surface Temperature Radiometer onboard Sentinel-3
TerraSAR-X	Terra Synthetic Aperture Radar-X (national X-band SAR mission)	VAO	Virtual Alpine Observatory	SMCS	Station Monitoring and Control System
TET-1	Technologie-Erprobungsträger (one of two satellites of the DLR FireBIRD mission)	VHR	Very High-Resolution	SME	Small and Medium sized Enterprises
		VIIRS	Visible Infrared Imaging Radiometer Suite	So2SAT	DLR project funded by the European Research Council
		VLBI	Very Long Baseline Interferometry		

Appendix

SRTM	Shuttle Radar Topography Mission	UKIS	Environmental and Crisis Information Systems	WWF	World Wide Fund for Nature
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TET-1	Technologie-Erprobungsträger (one of two satellites of the DLR FireBIRD mission)	VAO	Virtual Alpine Observatory		
TIMED-SABER	Sounding of the Atmosphere using Broadband Emission Radiometry Instrument onboard the Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics satellite	VHR	Very High-Resolution		
TIMELINE	Time series processing of medium resolution Earth observation data assessing long-term dynamics in our natural environment (DFD project)	VIIRS	Visible Infrared Imaging Radiometer Suite		
TropOMI	Tropospheric Monitoring Instrument	VLBI	Very Long Baseline Interferometry		
UBA	German Environment Agency	WASCAL	West African Science Service Centre for Climate Change and Adaptive Land Management		
UC2	Urban Climate Under Change (German research initiative)	WCRP	World Climate Research Program of the UN		
UFS	Environmental Research Station Schneefernerhaus	WDC-RSAT	World Data Center for Remote Sensing of the Atmosphere		
UFZ	Helmholtz Centre for Environmental Research	WHO	World Health Organization		
		WISDOM	Water related Information System for the Sustainable Development of the Mekong Delta (BMBF-funded project)		
		WMO	World Meteorological Organization		
		WRF	Weather Research and Forecast		
		WSF	World Settlement Footprint		

DLR at a glance

DLR is the Federal Republic of Germany's research centre for aeronautics and space. We conduct research and development activities in the fields of aeronautics, space, energy, transport, security and digitalisation. The German Space Agency at DLR plans and implements the national space programme on behalf of the federal government. Two DLR project management agencies oversee funding programmes and support knowledge transfer.

Climate, mobility and technology are changing globally. DLR uses the expertise of its 55 research institutes and facilities to develop solutions to these challenges. Our 10,000 employees share a mission – to explore Earth and space and develop technologies for a sustainable future. In doing so, DLR contributes to strengthening Germany's position as a prime location for research and industry.

The German Remote Sensing Data Center

The German Remote Sensing Data Center (DFD) is an institute of the German Aerospace Center (DLR) with facilities in Oberpfaffenhofen near Munich and in Neustrelitz north of Berlin. DFD and DLR's Remote Sensing Technology Institute (IMF) together comprise the Earth Observation Center (EOC), which has become a center of competence for Earth observation in Germany.

DFD supports science and industry as well as the general public. With its national and international receiving stations, DFD offers direct access to data from Earth observation missions, derives information products from raw data, partly in near real-time. It disseminates these products to users, and safeguards all data in the German Satellite Data Archive (D-SDA) for long-term use. In geoscientific research on the atmosphere, land surface and in the field of geohazards and civil security, DFD develops remote sensing based products and approaches for use in scientific and commercial domains. At the same time, it develops informatics solutions for the efficient analysis of large heterogeneous Earth observation data sets on high performance data analytics platforms. With the Center for Satellite Based Crisis Information (ZKI), DFD operates a service for the International Charter Space and Major Disasters and supports federal agencies in establishing remote sensing based applications for governmental tasks.



DLR

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