DANISH USES OF COPERNICUS

50 USER STORIES BASED ON EARTH OBSERVATION

Copernicus
Framework Partnership Agreement
for Copernicus User Uptake

This joint publication is created in a collaboration between the Danish Agency for Data Supply and Efficiency – under the Danish Ministry of Energy, Utilities and Climate – and the Municipality of Copenhagen. The Danish National Copernicus Committee, which is a sub-committee under the Interministerial Space Committee, has contributed to the coordination of the publication.

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Cover: Mapping of submerged aquatic vegetation in Denmark. The map is produced by DHI GRAS under the Velux Foundation funded project "Mapping aquatic vegetation in Denmark from space" using machine learning and Sentinel-2 data from the Copernicus program. © DHI GRAS A/S.

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The Baltic Sea

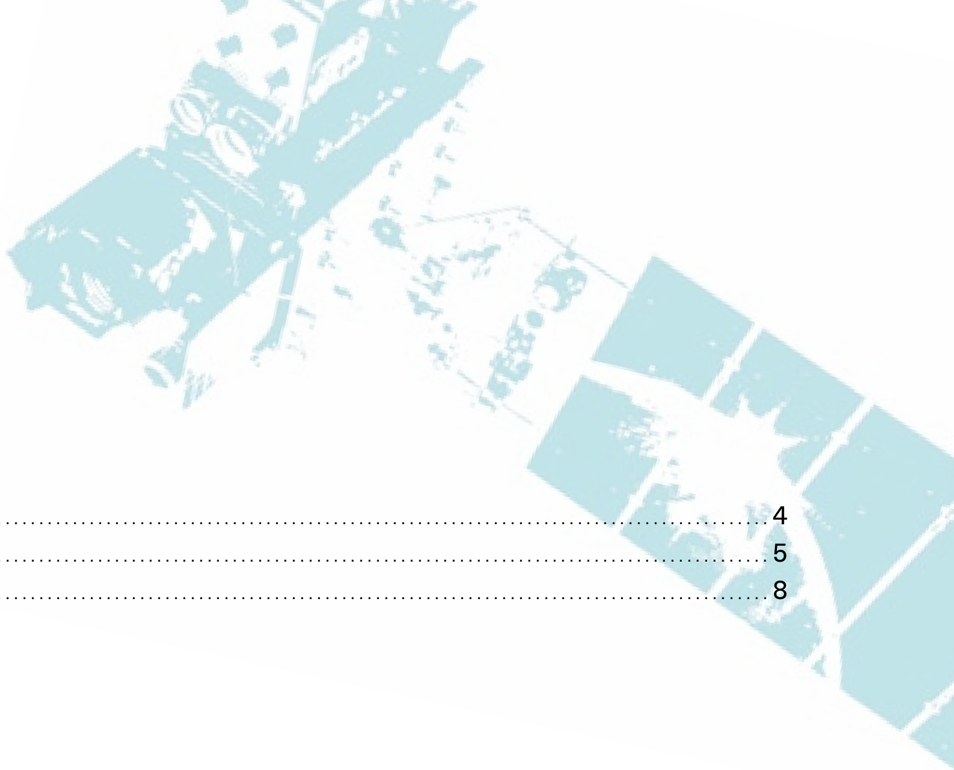
The Baltic Sea is a semi-enclosed sea bordered by eight EU Member States (Denmark, Germany, Poland, Lithuania, Latvia, Estonia, Finland, Sweden) and Russia.

Every summer, colourful blooms of phytoplankton can be observed in the shallow water of the Baltic Sea They have intensified as a result of increased nutrient runoff from land around the sea (mainly because of agricultural fertilisers and sewage). Algal Harmful Blooms are also one of the issues that affect the Baltic Sea. Biodiversity loss, climate change, eutrophication, overfishing, plastic waste, are other examples of environmental problems that impact the health of the Baltic.

This image, acquired by one of the Copernicus Sentinel-3 satellites on 27. July 2019 shows a very large algal bloom in the southern part of the Baltic Sea. Thanks to its ability to monitor ocean colour, the Copernicus Sentinel-3 satellites allow us to better understand marine life, survey biological constituents and their activity.

Credit: Copernicus Sentinel-3 imagery.


Copernicus



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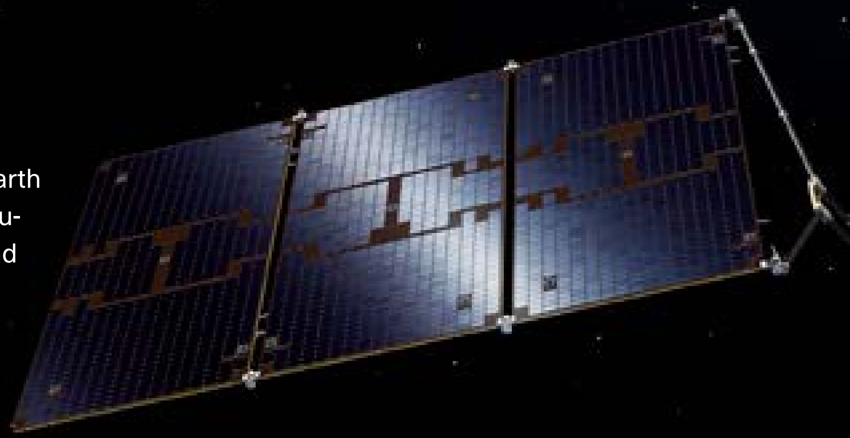


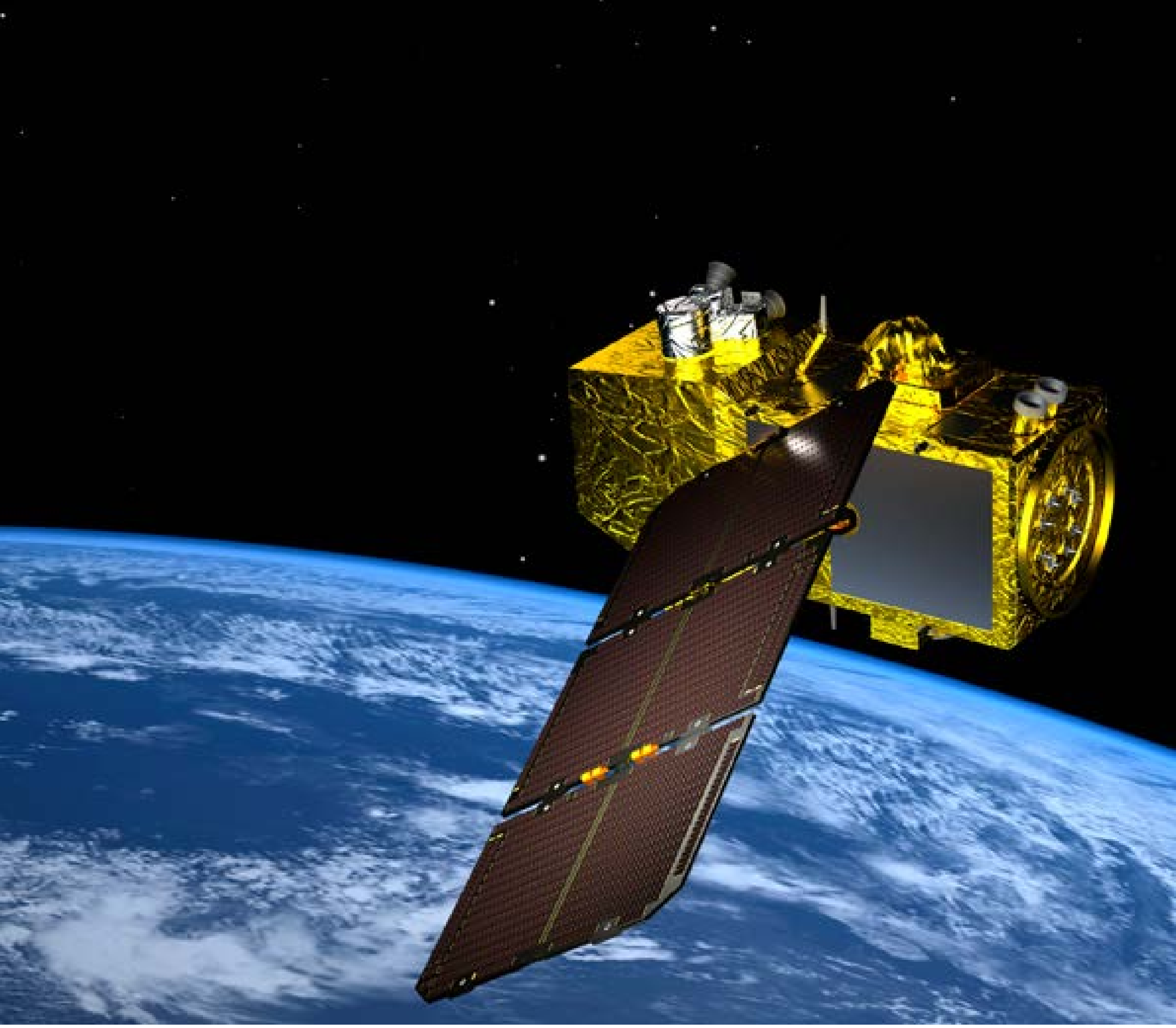
We are pleased to present the publication Danish Uses of Copernicus – 50 User Stories based on Earth Observation. It is a collection of short articles documenting, for a non-specialist audience, the use and benefits of Copernicus. The Realm of Denmark has highly varied landscapes, from its numerous agricultural fields and islands of the southern regions to the grassy-sloped Faroe Islands and the icy and mountainous Greenland in the north. With such vastly spread and large areas to cover, the use of Earth Observation becomes evidently beneficial. Denmark ranks among the most digitized and data-driven countries in the world and has a relatively long tradition of free and open data policies, which also encompasses the geospatial domain.

Over the past years, EU's Copernicus programme with its dedicated Sentinel satellites as workhorses has completely changed the availability of Earth Observation data globally. A suite of satellites is already in operation, and the planning of future missions is well underway. The contribution of the Earth Observation programme in modernising public authorities and enabling them to deliver services that are more efficient is evident, and new usages are continually emerging. The collection of user stories illustrates both the variety and increasing importance of satellite usage in the public and the private sectors, and how Earth Observation satellites are valued at the national, regional and local level.

The 50 user stories have been collected from authors across the scientific, public and private domains in Denmark and Greenland in order to showcase the continuously growing usage and application of Copernicus, the Sentinels and Copernicus Contributing Missions throughout the Kingdom of Denmark - and internationally. The diversity of the user stories, both thematically and geographically is vast, demonstrating practices from monitoring and mapping of Arctic sea ice and the Greenland ice cap, over governmental use in support of agriculture, open land and city planning, to exploitation of artificial intelligence for detection of trees in Africa's Sahel region. The publication also includes examples of nationwide data sets to monitor infrastructure movements and ground motion, use of optical imagery to detect submerged aquatic vegetation and urban dynamics. Furthermore, examples are shown on measuring wind resources from space, seasonal surface water on fields and monitoring of atmospheric conditions.

The following have contributed

Aarhus University
Alexandra Institute
Joint Arctic Command
Asiaq Greenland Survey
COWI
Danish Hydraulic Institute
DHI GRAS
Technical University of Denmark
Danish Meteorological Institute
European Space Agency
EMD International
Energinet
FieldSense
Gamma Remote Sensing
Gas Storage Denmark
GEO
Danish Geodata Agency
Joint GeoMETOC Support Centre
Geopartner Inspections A/S
Geological Survey of Denmark and Greenland
Institute of Agrifood Research and Technology
Institute for Electromagnetic Sensing of the Environment
Ministry of Climate, Energy and Utilities
Danish Coastal Authority
Copenhagen Municipality
University of Copenhagen
Danish Agricultural Agency
Lemvig Vand og Spildevand A/S
Ministry of Environment and Food
The Danish Environmental Protection Agency
Network of European Regions Using Space Technologies
NIRAS
City of Odense
University of Oslo
University of Zurich
Sandholt Aps
Agency for Data Supply and Efficiency
SEGES
Defence Command Denmark
Vattenfall
Vejle Municipality
Vestas



proven valuable over a period - in the process from data capture to application, supporting planning, services and solutions throughout society. In order to provide an overview of the maturity of the user stories, a 'level of maturity' has been added to each story along with an overview of the satellites used.

The Copernicus services have matured and along with the in-situ and contributing mission data, they support a constantly growing number of public services. The EU's Earth Observation programme is unique in that it constantly improves our global understanding of the planet and the environment, and supports a wide range of national initiatives ranging from economic growth, over science and development, to the Sustainable Development Goals and the green agenda. The programme supports national mandatory EU directives by providing relevant information, e.g. on agriculture, land use, regional development and environmental management. The collection of user stories also illustrates the value of Copernicus as a strategic tool for informed decision-making and planning, whether it relates to land-, sea- or air-based projects.

Satellite Earth Observation has like no other technology, the ability to inform, facilitate and monitor national, regional and international developments in a consistent manner. Particularly in remote and

scarcely populated regions like Greenland and the Arctic remote sensing is often the only way to address and support challenges concerning overview, accessibility, environment and climate change.

This joint publication is produced as a collaboration between the Danish Agency for Data Supply and Efficiency – under the Danish Ministry of Energy, Utilities and Climate – and the Municipality of Copenhagen. The Danish National Copernicus Committee, which is a sub-committee under the Interministerial Space Committee chaired by the Danish Agency for Science and Higher Education, Division for Space, coordinated the process. The publication was funded by the Framework Partnership Agreement on Copernicus User Uptake and the Danish Agency for Data Supply and Efficiency.

The overall aim of the publication is to present a variety of Copernicus uses and inspire new users. We welcome you to a world of Danish satellite uses – enjoy your reading!

The Usage Maturity Levels

Level 1	Level 2	Level 3	Level 4	Level 5
Explorer	**Ad-hoc**	**Experimentiel Tester**	**Early Adopter**	**Operational User**
1 Explorer. Has never really made use of the Copernicus-based solution but it has planned ad-hoc tests to assess its potential benefits (e.g. as a project user).	2 Ad-hoc user has used the Copernicus-based solution ad hoc in some specific cases but without an explicit interest to trial repeated usage, (e.g. the test followed the initiative of single individuals within the organisation).	3 Pilot/ Experimental tester has already used the Copernicus-based solution in one or more trials and is concretely considering its integration within its standard practices.	4 Early Adopter has confidently used the Copernicus-based solution and is working to incorporate it as part of its processes (e.g. update of internal procedures, staffing, training...).	5 Operational user is using the Copernicus-based solution and it has integrated it within its standard processes. The related resources (i.e. staff, budget, facilities) are allocated or readily deployable.

Source: The Ever Growing Use of Copernicus across Europe's Regions by the Network of European Regions Using Space Technologies (NEREUS), the European Space Agency and the European Union.

Danish Uses

Title	Satellites	Development
National Monitoring of Ground Motion and Infrastructure using Sentinel-1	Sentinel-1, VHR	5
Effective Screening for Risk of Settlement in Construction Work	Sentinel-1	4
Using Sentinel-1 to locate Subsidence and for Climate Mitigation in Odense Municipality	Sentinel-1, VHR	3
Satellite Based Surveillance of Natural Gas Storage in Lille Torup	Sentinel-1	4
Satellite Based Surveillance of Sewer Systems	Sentinel-1	4
Satellite Based Change Detection of Buildings	Sentinel-1, Sentinel-2	3
Optical Satellite Imagery as Tools for Decision Support	Sentinel-2, Landsat	4
Enabling Earth Observation Methods for Environmental Monitoring in Urban Landscapes	Sentinel-2, HR	4
Nationwide Sentinel-2 Mosaic in Support of Airborne Data Collection and Planning	Sentinel-2, LIDAR	3
Validation of Tree Detection with Sentinel	Sentinel-2, VHR	4
Enabling Earth Observation for Climate Mitigation and Adaptation in Urban Areas	Sentinel, LSTM	4
Municipal Applications of NDVI Analysis	Sentinel-2	3
A Satellite View on Urban Dynamics	Sentinel-1, Sentinel-2, VHR	3
Agricultural Control Using Sentinel	Sentinel-1, Sentinel-2	5
Classification of Invasive Plant Species	Sentinel-2	4
Using Earth Observation to Develop Intelligent Agricultural Solutions	Sentinel-2, Landsat-8	5
Satellite-based Mapping of Water in Fields	Sentinel-1, Sentinel-2	4
Flood Mapping with Satellite Data	Sentinel-1	4
Mapping of Wet Areas in Denmark using Sentinel-1 and Sentinel-2	Sentinel-1, Sentinel-2	3
Monitoring and Mapping Flooding Events from Space	Sentinel-1	4
Utilizing Sentinel-2 data for the Evaluation of Coastal Development	Sentinel-2	4
Satellite-based Monitoring of Coastal Dynamics	Sentinel-1, Sentinel-2	4
Measuring Water Depths in Shallow Water Areas using Satellite Imagery	Sentinel-2, VHR	4
Mapping Submerged Aquatic Vegetation from Space	Sentinel-2	5
Copernicus Maritime Surveillance Helps Denmark Battle Illegal Activities	Sentinel-1, Sentinel-2, CCM	5
Wind Farm Construction on Land	Sentinel-1, Sentinel-2	5
Offshore Wind Farm Planning from Space	Envisat ASAR, Sentinel-1	5

Greenland Uses

Title	Satellites	Development
Landslide Screening in Greenland	Sentinel-1, Sentinel-2	5
Satellite Data for Mapping Remote Regions of the Arctic	Sentinel-2 , SPOT, WorldView, TanDEM-X	4
Detection of Drastic Changes in Nature	Sentinel-1	3
Mapping Greenland's Ice Marginal Lakes	Sentinel-1, Sentinel-2	4
How Fast does the Greenland Ice Sheet Flow?	Sentinel-1	5
Present-day Greenland Ice Sheet Volume Change	Sentinel-3, Cryosat-2 , ERS-1, ERS-2, ENVISAT	5
Ice Reports to Ships Operating near Shore	Sentinel-1, TerraSAR-X , PAZ	5
Mapping Coastal Areas is Important for Safe Navigation in the Arctic	Sentinel-1, Sentinel-2	5
Routine Mapping of Sea Ice to Shipping around Greenland	Sentinel-1, Sentinel-2, CCM	5
Sea Ice Charting from Multisensor Data Fusion	Sentinel-1, AMSR-2	4
Satellite Images for Tactical Navigation in Ice-covered Waters	Sentinel-1, Radarsat TerraSAR-X, Cosmo Skymed	4
Iceberg Detection in Greenland Waters	Sentinel-1, SAR	5
Evolving Production of North Atlantic Iceberg Limit based on Satellites	Sentinel-1, (ROSE-L)	4
The Danish Joint Arctic Command uses Copernicus daily	Sentinel-1, Sentinel-2, CCM	5

International Uses

Title	Satellites	Development
Suporting Financial Inclusion	Sentinel 1, Sentinel 2, VIIRS	4
Satellite-based Warning System for Vector-borne Diseases	Sentinel-1, Sentinel-2, Sentinel-3, LSTM	4
Large-scale Wetland Mapping and Monitoring	Sentinel	5
Irrigation management	Sentinel-2, Sentinel-3	4
Mapping of Grass Fallow Systems from Sentinel-2 Data	Sentinel-2	4
Mapping of Individual Trees in Savannas from Copernicus Data	Sentinel-1, Sentinel-2	4
Earth Observation for Sustainable Development	Sentinel (1-6)	4
Satellite Derived Ocean Current Information for Ship Route Optimization	Sentinel-3, Sentinel-6, JasonCS	4
MOIST – Managing and Optimizing Irrigation by Satellite Tools	Sentinel-1, Sentinel-2, Sentinel-3	4
Global Monitoring of Atmospheric Humidity	Galileo, C3S	5

VHR: Very High Resolution Optical
HR: High Resolution Optical
CCM: Copernicus Contributing Missions
C3S: Copernicus Climate Change Service
LSTM: Copernicus Land Surface Temperature Monitoring

Danish Uses

National Monitoring of Ground Motion and Infrastructure using Sentinel-1

InSAR data have proven extremely useful for locating and monitoring deformations of ground instability and infrastructure. In support of the growing needs for such measurements in Denmark, work is on-going to develop a national monitoring program.

Joanna Balasis-Levinsen [A], Martin Nissen [A], Kristian Keller [A], John Peter Merryman Boncori [B], Mark Falkenberg [A], Per Knudsen [B], Niels H. Broge [C]

A: Agency for Data Supply and Efficiency B: DTU Space C: Geopartner

The challenge

Although most land areas in Denmark are still rising as a result of the post-glacial rebound after the last glacial period, this is not the case everywhere. Locally, land areas and infrastructure are undergoing subsidence depending on soil type and stability, changing ground water levels, foundation, etc. Moreover, more than 850 km^2 land areas are reclaimed low-lying land, most of which is protected by dikes and maintained by pumping and adjusting water levels. Along the 8,750 km Danish coastline, more than 1000 km of dikes play a vital role in relation to coastal dynamics and future climate mitigation. Cities, infrastructure and agriculture located on reclaimed or subsiding ground often experience a variety of costly challenges – along with being expensive to repair and maintain.

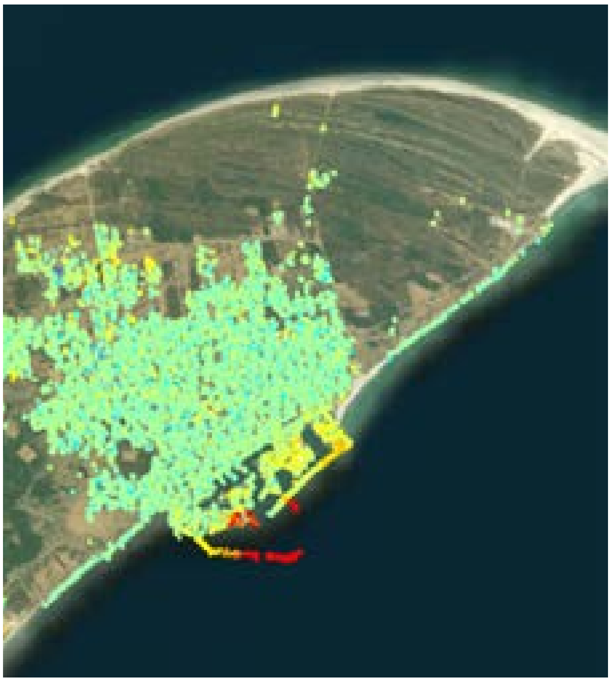
Over the past decades, the means for measuring ground deformations from space have gradually improved and now allow for an independent, uniform and systematic processing. As of 2014, synthetic aperture radar (SAR) data from the Sentinel-1 satellite have been freely available. This has been a game changer for the Earth observation community. For the first time, wide-area processing on e.g. countrywide scale is now possible using free and open data.

Sentinel-1 data allows for estimating e.g. terrain subsidence or uplift and deformations of just about everything man-made. This can be done with millimeter precision. This knowledge may be used in a wide range of areas, from urban studies and planning, over estimating the structural health of infrastructure to providing a second opinion in geotechnical analyses and investigations.

> **Denmark has a coastline of 8,750 km, of which almost 1,800 km are protected by dikes or other permanent technical installations.**
>
> *Ministry of Environment and Food of Denmark*

The goal of the monitoring programme is to deliver operational deformations of ground instability and infrastructure in Denmark and to improve accessibility of data and analysis tools for public and commercial users. An additional goal is to explore and optimize the use of Interferometric SAR (InSAR) data for maintaining the Danish geodetic height network. This includes testing and assessing the value of establishing a nationwide network of compact active SAR transponders (C-band at 5,4GHz) complementary to corner reflectors. The corner reflectors used in support of the nation-wide dataset

The first nationwide deformation map of Denmark was produced from Sentinel-1 data in 2018 in order to support a wide variety of different uses. The map was updated in 2019 and in 2020.



In Denmark, millions of point scatterers have allowed for estimating the deformations of e.g. houses, railways and harbours. Here, the town of Skagen is displayed in a simple colour code. Ref.: TRE Altamira (2019).

are able to reflect signals from both ascending and descending Sentinel-1 orbits.

The space-based solution

The launch of Sentinel-1 carrying its dedicated Terrain Observation with Progressive Scan (TOPS) radar designed specifically for ground deformation monitoring was a huge step forward for wide-area processing. From so-called interferograms, mapped from the phase of the radar signal, interferometry allows for the monitoring of ground deformations with a consistent and high spatio-temporal resolution and coverage. Multi-temporal InSAR methods, such as Persistent Scatterer Interferometry (PSI), are powerful remote-sensing techniques able to measure and monitor deformations of the Earth's surface over time. The nationwide dataset is provided by the Agency for Data Supply and Efficiency (SDFE) after processing the entire Sentinel-1 archive over Denmark, from both ascending and descending orbits. The deformation estimates have been calibrated with GNSS data and a nationwide uplift model in order to open for more uses. The measurement points are displayed in an online web interface that includes tools for data analysis and download.

Benefits to citizens

The millions of measurement points over Denmark hold great potential for geologists, urban and rural planners, road and railway authorities, and in relation to the design phases of infrastructure, climate mitigation, pipeline and wastepipe management, underground gas storage, harbors, bridges and highway extensions. Also as a reference dataset for big data analysis, insurance, real estate, structural engineering and geotechnical issues. Through user consultations in a wide range of user communities, it has become evident that InSAR data is of broad interest not only for public and commercial entities but also for citizens; we have therefore decided to provide all the data at full resolution, freely and open to everyone.

Outlook to the future

Apart from supporting users such as municipalities, road authorities, railroad authorities, city planners, real estate, insurance, transport and structural engineering, the service also holds important potential for creating the basis for further downstream commercial and public use. SDFE plan to maintain and update the data sets at regular intervals, hereby creating predictability for long-term users.

Effective Screening for Risk of Settlement in Construction Work

Ground motion is calculated from satellites as line-of-sight (LOS). LOS provides the movement of a point on the ground along a line towards the satellite. As radar satellites have a tilted viewing angle to the ground, the LOS data need correction and calibration in order to provide reliable estimates of ground movement.

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A: Geopartner Inspections A/S B: Geo C: DTU Space D: Danish Coastal Authority

The Challenge

In urban areas, activities on new construction sites may affect surrounding infrastructure and buildings. The risk of inadvertent damage on and subsidence of adjacent structures can arise, e.g. when building deep parking basements. In such cases, it may be necessary to lower the groundwater head for longer periods during the construction phase, while permanent retaining structures for excavation, baseplates and possibly buoyancy anchors are built.

To avoid unpleasant surprises and contingencies, this risk should be investigated at the earliest possible time in a project – preferably already during the screening phase. Existing geological data, models and methods of analysis can be utilized for this purpose to minimise the costs.

Data

In Denmark, geologic as well as geotechnical borings constitute a multitude of point information of our subsurface and underground conditions. GeoAtlas Live is a web-based solution that provides the information of all boring activity in Denmark, adding up to more than 650,000 borings. Additionally, using GeoAtlas Live, it is possible to perform so-called virtual borings, horizontally and vertically, showing the geological conditions in a point, face or along a line. It is thereby possible to screen a project area for geological, geotechnical, hydrological and environmental data.

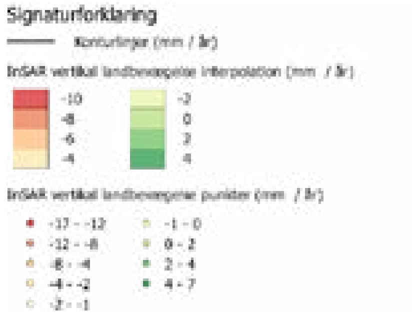
Information of vertical surface movement can be applied as a proxy for the thickness of so-called soft geological layers that recede when surface pressure is added as a consequence of e.g. urban development. Today, measurements of vertical movements can be calculated from satellite data, for instance from the Copernicus Sentinel-1 radar satellite. These measurements can be used as documentation for subsidence in urban areas, but currently this requires in-depth and sophisticated data interpretation.

Interpreting satellite data

The Agency for Data Supply and Efficiency's LOS (line-of-sight) products have a spatial resolution of 5x20 meters and are corrected for viewing angle and post-glacial uplift. This provides a qualified estimate of absolute vertical land movement (figure 1). However, substantial differences sometimes occur between vertical movement rates calculated using data from different scenes in the satellite data series. These discrepancies are typically caused by differences in the geometric relations

Figure 1. Vertical movement calculated from calibrated Sentinel-1 LOS data for ascending track LOS-146A (top) and LOS-66D (middle). The vertical movement is shown as a 2D product (bottom).

Contains modified Copernicus Sentinel data (2014 –2019). Agency for Data Supply and Efficiency /TRE Altamira (2019).



(geometry of viewing versus geometry of movement), gaps in the time series of satellite data, or singular structures in the area moving individually and differently. The Agency for Data Supply and Efficiency also provides data on an 80-meter grid in which the vertical movement is calculated by combining ascending and descending satellite scenes, but the product is not sufficiently detailed to study singular structures.

Benefits

Screening analysis based on geological data combined with data on vertical land movement is a relatively inexpensive method to screen for risks of subsidence in relation to construction work. Investigations during the screening phase can also be applied at a later stage for efficient prioritisation of focused and comprehensive geotechnical, environmental technical and hydrological examinations, which are often costly.

Future perspective

During 2020 and 2021, Geo, Geopartner and DTU Space collaborates on the completion of a European Space Agency co-funded project focusing on the integration of geotechnical and ground motion data. The project develops methods for optimizing the use of the satellite-derived measurements of ground motion that are currently provided by the Agency for Data Supply and Efficiency with an annual update. Further, the project develops a new and improved version of GeoAtlas Live utilizing a true 3D vox¬el-based geological model, fed by geological data and satellite-based ground motion data.

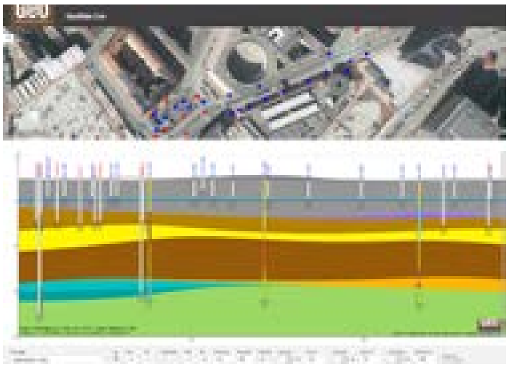


Figure 2: GeoAtlas Live is a web-based platform containing sub-surface information. InSAR satellite data wil be integrated into GeoAtlas.

Ground motion determined from radar satellite images is calculated as line-of-sight (LOS), expressing the movement of an object on the ground relative to the position of the satellite. As the viewing angle of radar satellites is oblique, the LOS data need to be corrected and calibrated to provide estimates of vertical ground movement.

Using Sentinel-1 to Locate Subsidence and for Climate Mitigation in Odense Municipality

For Odense Municipality, InSAR data has been a valuable tool to assess low-lying areas undergoing subsidence and to determine the effects of the building activity and excavations in the city centre.

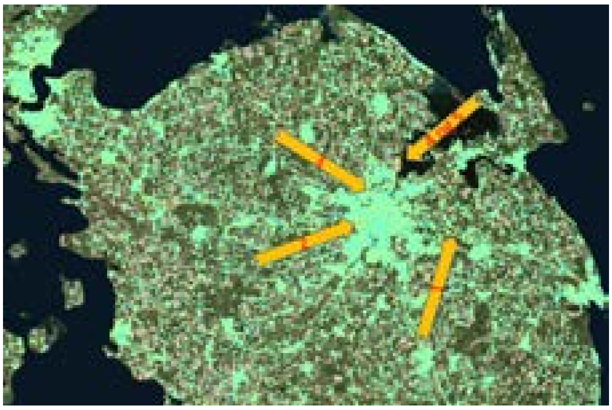
Gert Michael Laursen [A], Martin Nissen [B], Joanna Balasis-Levinsen [B]

A: Odense Municipality B: Agency for Data Supply and Efficiency

The Challenge

Large land areas in and around Odense are reclaimed land. Consequently, there is a risk of subsidence. In order to estimate the rate and extent of the ground movements along the water channel and around the small coastal town of Seden Strandby, the municipality used the ground motion data sets from the Danish governmental Agency for Data Supply and Efficiency.

Areas north of Odense facing the fjord are challenged by storm surges and a rising sea level, and the region was recently included in the list of the 10 most high-risk flooding areas in Denmark, based on the EU Floods Directive. Consequently, Odense faces ongoing climate change challenges in relation to adapting and protecting the physical landscape and the future role and sizing of the dikes.

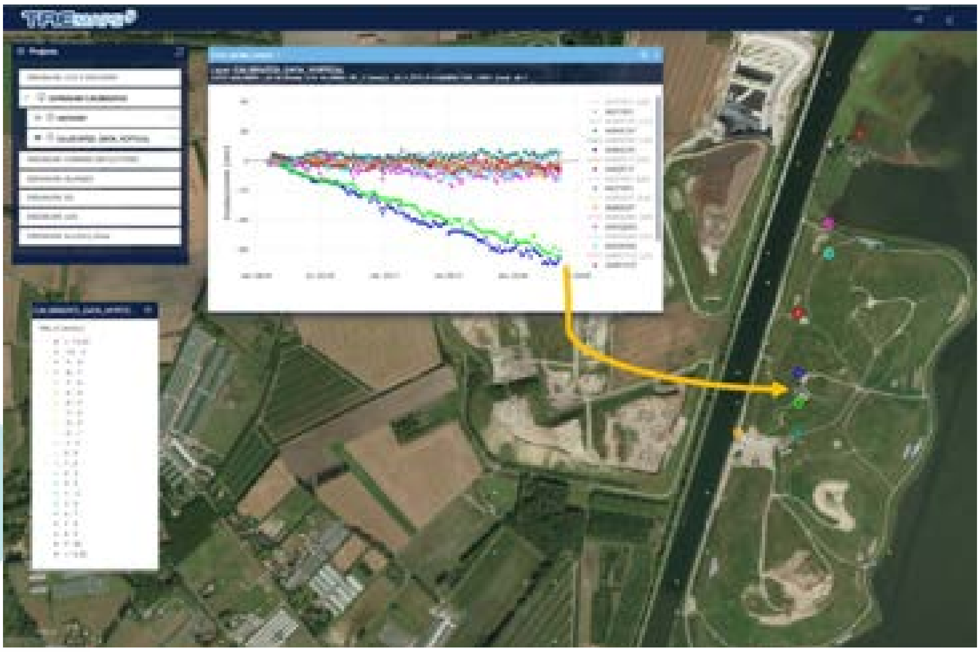


A desktop study pinpointed a number of hotspots around Odense, where subsidence occurs. Particularly the diked areas facing Odense Fjord are at risk and require thorough planning in relation to climate mitigation.

The space-based solution

For Odense Municipality, the work with adaption requires a variety of data and multidisciplinary collaboration, and the nation-wide inSAR data set containing vertical and horizontal ground movements has proven highly valuable in support of this process. The data sets were processed from Sentinel-1, a radar satellite of the EU Copernicus earth observation programme. Funded by the European Commission Copernicus and its dedicated operational sentinel satellites have provided continuous global coverage from the launch in 2014 and will continue to do so well beyond 2030.

Besides estimating the subsidence that the dikes are undergoing, which in some places has exceeded 30-40 cm since they were built, the municipality has used the inSAR data to confirm and disprove that the extensive building and digging activity in the heart of the city may have caused cracks and settlement damage to surrounding buildings and foundations. This is a well-known issue facing



The inSAR measurement points on Stige Ø north of Odense supported the presumption that the area was subsiding and enabled the municipality to estimate the rate and total level locally.

entrepreneurs and constructors of infrastructure – particularly in dense settlement where causality is hard to prove. For instance, it is often difficult to prove if a large construction site or ground motions from the digging of a tunnel are the direct or indirect cause of cracks in neighboring buildings or infrastructure. For this purpose, inSAR data from space provided an important source of independent measurements in the city center. The fact that the processed Sentinel-1 data are provided as a continuous timeline of nearly weekly measurements enables the user to monitor likely causes, which can prove very valuable during the construction phase and in the end support legal and insurance matters.

> **Climate mitigation is a real challenge for many Danish municipalities and it is important to have access to the best data to face the changes.**
>
> *Minister of Energy, Utilities and Climate - Lars Chr. Lilleholt*

Benefits to citizens

By use of the ground motion dataset, a desktop analysis of the region revealed both new and well-known areas of subsidence and enabled the municipality to focus the attention and fieldwork to selected areas of interest where there were valid measurement points. Ground motion data can not only support existing knowledge but can also supply further movement details and seasonal behaviour to support models of future climate scenarios, thereby serving as a tool in risk assessments and aiding economic priorities. In other situations, as was the case with the city centre construction site, inSAR data disproved the presence of ground motion, which was just as valuable for Odense Municipality.

Outlook to the future

Experiences from Odense show that data from Sentinel-1 may be able to serve as an independent measurement tool in other regions of Denmark where local areas undergo subsidence. Subsidence poses a threat to infrastructure, pipelines, railways, roads, foundations, etc. and may well prove vulnerable in a future climate. Mitigation will be challenging particularly if the subsidence coincides with rising ground water, sea level rise, storm surges or other changing weather patterns.

Satellite-based Surveillance of Natural Gas Storage in Lille Torup

The satellite-based monitoring enables frequent measurements and calculations, providing a better timeliness of the monitoring

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A: Geopartner Inspections A/S B: Gas Storage Denmark C: DTU Space D: Geo E: Danish Coastal Authority

The challenge

The usage of gas in Denmark varies with the seasons. It reaches approximately 30-33 million Nm^3 (Normal cubic meters) per day during winter. The maximum supply of natural gas from the North Sea is about 22-24 million Nm^3, which necessitates the storage of gas during the summer months when the consumption is low.

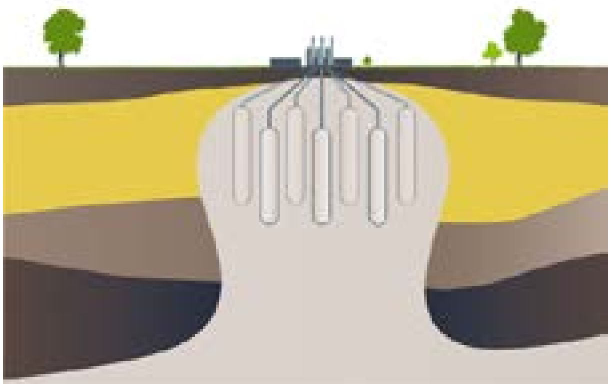


Figure 1. Sketch of the salt dome and caverns used as a gas storage facility.

One of the storage facilities, owned by Gas Storage Denmark, is situated near the village of Lille Torup in Jutland. Here, the gas is stored in subterranean caverns, which are large cavities in a salt dome. The caverns are located approximately 1,000 – 1,700 meters underground, and their dimensions are 200-300 m in height and 40-60 m in diameter.

Salt domes are geological formations formed by evaporated seawater. They occur as a response to the low density of salt in the pressure of surrounding heavier rock formations. The salt is pushed upward and can thereby rise through many kilometers of the overlying geological layers.

Caverns in salt domes are very suitable for the storage of gas because they are virtually impenetrable and act as an efficient seal.

Since 1981, Gas Storage Denmark has performed height measurements of the surface above the storage facility in Lille Torup every couple of years to monitor ground movement and contribute to a common sense of safety in the local community.

Between 1981 and 1992, the height measurements were performed by levelling between height elevation benchmarks in the area of the cavern and control points in the surrounding villages of Ulbjerg, Fjelsø, Tostrup and Møldrup. Since then, the measurements have been performed by complete precision geometric levelling monitoring to ensure an accurate and even basis for comparison through time.

The long-term series of measurements are used to map deformations in and around the salt dome area.

> **Future surveillance of the deformation of the Lille Torup salt dome will improve from satellite-derived deformation rates with more frequent updates than today. This will create a greater sense of safety for the citizens in the area**
>
> *Jørgen Lund, Head of Department, Gas Storage Denmark*

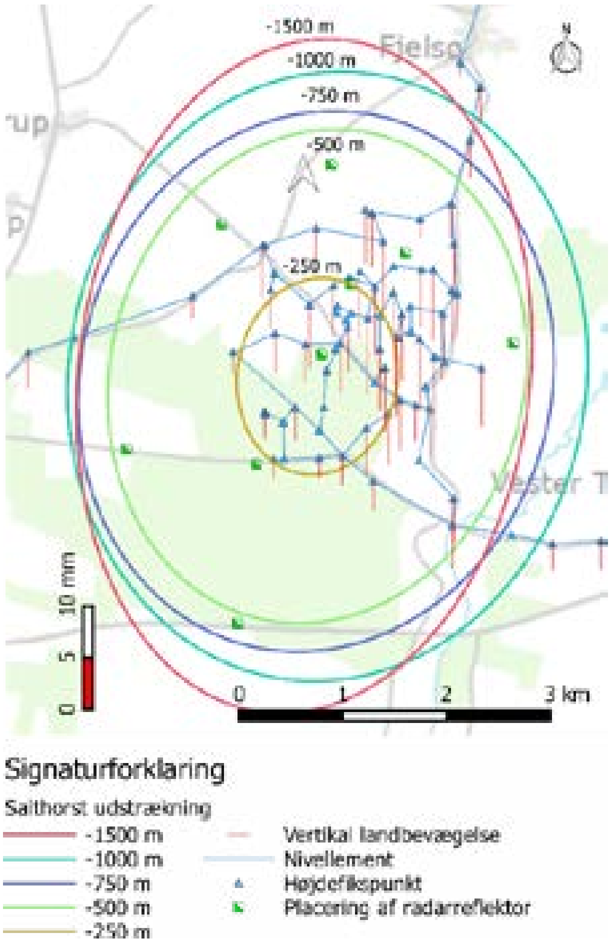


Figure 2. The salt dome at Lille Torup. Fixed points and calculated deformation rates for the period 2013 - 2018 are superimposed.

Future satellite-based surveillance

In the future, Gas Storage Denmark will monitor the salt dome deformation using data from the Sentinel-1 satellite as well. The satellite has gathered radar data every six days since 2014 and will continue to do so until well beyond 2030. Using the InSAR technique in combination with solid in-situ reference data, surface vertical velocity, which is descriptive of the salt dome's deformation dynamics, can be estimated.

The Agency for Data Supply and Efficiency (SDFE) has recently released the second calculation of surface height movement based on the time series of Sentinel-1 data over Denmark and is expected to perform an annual nationwide calculation.

Geopartner Inspections has, in collaboration with the company Kynde & Toft, developed and produced radar reflectors and multi-adjustable innovative radar reflector foundations. Eight radar reflectors have been manufactured and deployed on selected locations above the salt dome. The reflectors have been connected to existing height benchmarks with precision levelling and will serve as the future basis for satellite-based surveillance of the salt dome. Initially, the calculations offered by SDFE will be applied, and from 2021, calculations from the coming Copernicus European Ground Motion Service (EGMS) may be applied.

Benefits

Using the satellite-based surveillance, Gas Storage Denmark will be able to update deformation rate calculations above the salt dome by Lille Torup more frequently. The satellite-based surveillance will also provide greater detail, i.e. more data points collected at a higher measurement frequency. This will lead to better cartography and mapping of the salt dome deformation. Better mapping capability will assist Gas Storage Denmark in their aim of creating the greatest possible sense of security among the residents in the area surrounding the gas storage facility.

Satellite-based Surveillance of Sewer Systems

Sentinel-1 data extends the lifespan of submerged pipelines, providing significant savings for the utility company.

Niels H. Broge [A], Henrik Brændskov Larsen [A], Karsten Vognsen [A], Lars Nørgaard Holmegaard [B], Carlo Sørensen [C], Per Knudsen [D], Mads Robenhagen Mølgaard [E]

A: Geopartner Inspections A/S B: Lemvig Utility C: Danish Coastal Authority D: DTU Space E: Geo

The challenge

Previous investigations in the town of Thyborøn have revealed that the town is subsiding, and that this movement is mirrored in the underground infrastructure. The local vertical ground movements amplify the climate change impacts from rising sea and groundwater levels. As some areas are subsiding more than others, the sewer system is subjected to displacement stress, which reduces the lifespan of the pipes.

Detailed knowledge of ground movement is therefore of significant importance to low-lying towns such as Thyborøn for optimizing investments and maintenance of the sewer system. In addition, this information provides important input on subsidence for climate adaptation activities. Extensive surveys over the past decade have documented the subsidence in the Thyborøn area, which have been implemented in climate adaptation measures by Lemvig Municipality.

Figure 1. Surveyor stage with adapter placed in the middle of the manhole cover defined as the "measuring point" on all covers.

Determination of the rates of subsidence in Thyborøn

In 2018, Geopartner Inspections A/S, in collaboration with the local Lemvig Utility, undertook extensive height measurements (levelling) to benchmarks as well as to 1,158 manhole covers in the town. Furthermore, measurements from the cover to the sewer bottoms were performed to determine their elevation. Thus, a detailed digital record of the level of all wells, inlets, and outlets in the town is available.

Thyborøn excels by having a substantial network of height benchmarks established with a distance of 200-300 meters between them. Most benchmarks have been measured by precision levelling since 2003 in a three-year repetition frequency setup. In a Danish context, this provides a unique possibility to calculate the change in elevation, i.e. the vertical movement over time.

Future satellite-based surveillance

Previous studies have shown a correspondence between vertical movements of the surface calculated from satellite data and the movements that the underground infrastructure (sewers and wells) have undergone. On this basis, Lemvig Utility has

Figure 2. The bench mark measuring campaign in Thyborøn showing how the levelling to each manhole cover is tied to the benchmark network.

decided to move towards full implementation of satellite-based surveillance of the underground infrastructure.

Since 2018, the Agency for Data Supply and Efficiency has offered annual calculations of vertical and horizontal ground movement in Denmark based on Sentinel-1 satellite data from the EU's Earth Observation programme, Copernicus. These calculations are freely available for unrestricted use. SDFE is expected to undertake and provide a new calculation every year, including the newest satellite data. The most recent calculation from the agency was released in 2019. The Copernicus European Ground Motion Service (EGMS) is expected to become operational during 2021. This service will deliver similar calculations at least until 2030. A sustainable satellite-based source of data has thus been established, securing current and future calculations of vertical ground movement.

> **"Subsidence calculations from the Sentinel-1 satellite provide a solid foundation from which to consider replacement and renovation of our sewer system. By utilizing the Sentinel-1 data, we expect a significant rise in the lifespan of our sewer system and savings of up to 400,000 EUR per year accordingly.**
>
> *Lars Nørgaard Holmegaard, CEO, Lemvig Utility.*

Benefit

With the results from the levelling of the sewer system as baseline for the situation anno 2018 as well as the satellite-based mapping of the vertical movements in the area it is now possible to predict the changes in elevation for the entire sewer system. This information can be used for prognoses of future capacity and needs for renovation. Thus, it is expected to become an important tool for planning with a significant potential for increasing efficiency of maintenance and renovation of the underground infrastructure.

The sustainable satellite coverage also provides the option of continuously updating the calculations and monitoring the sewer system with any chosen time interval.

The method is scalable and can be implemented in other urban areas where subsidence plays a role in terms of maintenance of subterranean infrastructure.

Satellite-based Detection of Changes of Buildings

NIRAS has developed a satellite-based method for detecting changes of buildings with the goal of automating the labour-intensive process of updating national topographic data.

Søren Buch [A], Casper Fibæk [A], Peter Gelsbo [A], Mikkel Skovgaard [A], Victor Olsen [A]

A: NIRAS

The challenge

In Denmark, vectorised topographic data is used throughout the public and private sector for a range of services directed towards citizens, governmental institutions and businesses.

Maintaining a high quality topographic dataset, with national coverage, requires continuous updates. Currently, this process is conducted manually by the municipalities, thus putting pressure on public sector resources. An automatic system for topographic change detection is therefore in demand.

At NIRAS we have addressed this problem by testing a satellite-based method for change detection, hence applying Copernicus data to the pressing need for automated monitoring of buildings and other infrastructure.

The space-based solution

The method is based on a wide array of data which combined provides the basis for change detection of buildings. Satellite data from the Copernicus programme comprises the most important data sources. Additionally, national address registries and agricultural field data are integrated to achieve adequate classification accuracy. A brief description of this data integration process will follow.

Detection of a demolished building.

The RADAR signal from Sentinel-1 is used to identify surfaces that display a stable signal across time and have a high reflection. This combination is characteristic of artificial surfaces – including buildings.

Subsequently, structural changes can be identified through a comparison of these results from two periods, with a significant difference indicating changes.

Furthermore, both Sentinel-1 and Sentinel-2 are used to calculate annual temporal profiles (or time-series). These profiles comprise a characteristic pattern that adds valuable information to the subsequent classification.

> **This application of Sentinel data has some very interesting prospects.**
>
> *Bjarke Skjødt, The Danish Agency for Data Supply and Efficiency*

Moreover, selected georeferenced address-points and agricultural field polygons are integrated in the workflow. The address-points contain attribute information that can identify newly constructed or demolished buildings, and the field polygons are used as a filter for noise reduction.

Finally, a neural network is trained on a dataset of manually detected changes in combination with the inputs mentioned above. The process results in detection of building changes occurring within a chosen timeframe.

Satellite data is thereby used in combination with topographic data to achieve a higher classification accuracy. This proved necessary due to the low spatial resolution of the imagery, relative to the buildings observed. Consequently, the method showcases how the high temporal resolution can be utilized in combination with other supporting data sources, despite these limitations.

Benefits to citizens

The main advantage of an automatic change detection system for monitoring structural changes is the reduction of public sector costs. Eventually, the system may even reduce omission errors that are inherent to the current manual process.

Furthermore, a satellite-based monitoring system can deliver timely information to the utility sector, thus enabling earlier and better planning.

Finally, timely updates of the national topographic dataset enable municipalities to respond quicker to building violations and to facilitate better case management.

Time series from Sentinel-1.

Outlook to the future

A fully operational system will require further development but could eventually provide a practical tool for satellite-based monitoring of buildings. Furthermore, the method exemplifies the possibilities of combining data from vastly different sources through neural networks.

The current limiting factor is the spatial resolution in relation to the size of observed buildings. However, the method indicates the advantages of the high temporal resolution of Sentinel-1 and -2 and shows how this temporal information can be utilized despite the limited spatial resolution.

At NIRAS, we see a large potential in data from the Copernicus programme that, as exemplified in this use case, opens up new opportunities for monitoring buildings and infrastructure.

Optical Satellite Imagery as Tools for Decision Support

The usage of optical satellite imagery to observe changes within the city.

Emil Møller Rasmussen, Copenhagen Municipality

The challenge

In a municipality such as Copenhagen, there is an implicit need to see and show the physical changes the city undergoes. This can be hard to do with "traditional" data sources.

For this purpose, satellite imagery is ideal as only few options for showing snapshots of cities exist. As more suppliers and public offers of satellite data have come to market, satellite imagery have become a cost-efficient source of this type of insight and data.

The space-based solution

As information can be recorded in several bands besides the purely optical, a plethora of information can be captured. Proper utilization of this data requires a high level of technical competencies. But by using the purely optical bands of Sentinel-2 satellites, it is possible to gain an overview of phenomena of the Earth's surface without these advanced skills. The optical bands on Sentinel-2 have a spatial resolution of 10x10 meters, which is enough to directly observe some of the larger elements that exist in a city.

Most people can relate to a regular RGB image, and given the size of area a satellite image can capture, these images can provide overview of entire cities at once. This, combined with the relatively short repeat cycle of satellites, enables monitoring of temporal evolution in a city.

One of the limitations of satellite-based data sources is that you cannot observe changes on a shorter

The southern part of Copenhagen before and after the drought in 2018. The color change in the large green areas clearly illustrates the drought's effect on the city.

The center of Copenhagen before and after the drought in 2018. The images illustrate how the city's parks have been affected.

time scale than the repeat cycle of the satellite – in addition to the fact that phenomena have to be uninfluenced by the time of day, as most satellites return at the same time of day. Furthermore, the spatial resolution acts as a barrier for how small phenomena can be observed. Atmospheric disturbances such as clouds or smog will also disrupt some applications or usages of optical data.

For the citizen of Copenhagen

Denmark, and large parts of Europe, experienced record high temperatures and drought in the summer of 2018. To provide citizens and politicians with an impression of the effect this had on Copenhagen, Sentinel-2 satellite imagery was used to display the actual condition before and after the drought. These images provided a dramatic illustration of the effect the drought had on the major green areas of the city.

Time series can be used to show how a major city expands and develops over time. This can be combined with other sources, such as Landsat imagery, so the development of cities can be followed on an even longer time scale. Afterwards, particular areas can be delved into – such as new developments - where the progress can be monitored. After construction, the imagery can be used as archive material for city planners and can serve as the foundation for future projects in or around the given area.

Outlook for the future

As planners and other relevant personnel in local government gain insight and understanding of the possibilities with satellite imagery, more demands and thereby more applications will turn up.

Additionally, the purely optical imagery is good at providing users with an understanding of the capabilities and potential of satellite imagery and can be used as a jumping-off point for more advanced uses and analyses. As such, there are possibilities of getting started using satellite imagery in a local government context by starting by using purely optical satellite imagery – and then later introducing the more advanced capabilities of satellite analysis based on other spectral bands.

Enabling EO Methods for Environmental Monitoring in Urban Landscapes

Earth observation methods provide an objective and synoptic means to monitor urban dynamics, and EO-derived products can be used as crucial tools to measure and estimate environmental parameters.

Mads Christensen [A], Emil Møller Rasmussen [B]

A: DHI GRAS B: Copenhagen Municipality

The challenge

Water pollution is a severe problem worldwide and a great concern to city planners aiming to make cities cleaner, smarter and more sustainable. The ability to meet environmental objectives and stringent commitments imposed by legal obligations is hindered by the ability to consistently monitor and measure water resources and pollutants entering waterways.

Impervious areas are one of the most critical parameters affecting the quality of water resources, and urbanization processes have caused a significant increase of impervious surfaces. Roads, rooftops, parking lots, sidewalks, etc. prevent water infiltration and consequently cause rapid runoff in response to rainfall, thus altering the hydrological balance, structure of critical habitats, water quality, and biodiversity of aquatic ecosystems.

The space-based solution

The ability to consistently and comprehensively monitor impervious surfaces in urban landscapes as well as the composition of these surfaces is critical in order to strengthen the ability of city councils to sustainably manage urban water infrastructure.

Sentinel-2 data (10m) can effectively be used to monitor and map impervious surfaces in urban landscapes and thus provides an objective means to monitor and assess the extent of impermeable areas. Based on a highly automated object-based approach, satellite data can be turned into actionable and seamless information on surface types and degree of permeability, which can be used to assess pollution effects in waterways. These maps can be used to calculate quantities of water and pollutant loading of water coming from the impervious areas

> **Up to date and accurate maps of surface permeability are one of the most important components of rainfall runoff modelling, and satellites provide the most efficient and objective means to consistently map and monitor impervious surfaces.**
>
> *Sten Lindberg, Danish Hydraulic Institute (DHI)*

Deep learning approaches can be used to further analyze high-resolution satellite images to map rooftop segments and distinguish between material types (i.e. green roofs, asphalt shingles, copper roofing, clay tiles) as well as other objects of interest, e.g. solar cells. The ability to identify and map material types in rooftop segments provides critical information that can be used to monitor the concentration of pollutants entering waterways, i.e.

Impervious surface map of Copenhagen, Denmark indicating the coverage of non-permeable surfaces and green areas.

monitoring the concentration of dissolved copper ions in waterways from copper roof sheeting.

Benefits to citizens

Local governments and national authorities need standardized, high-quality spatial information to aid water management policies and strategies for infrastructure planning. Satellite-based approaches to monitor environmental parameters in urban landscapes provide an objective, consistent and cost-efficient means to measure and monitor the condition of water resources.

Data and information on the degree of permeability and information about rooftop material type can aid local authorities to:

1. better understand stormwater pollutant loading in order to identify best management practices;
2. inform sustainable urban spatial planning strategies and regreening activities;

Deep learning approach to automatically segment solar cells on rooftops from very high-resolution satellite imagery.

3. aid city planners in determining where and how storm pipes drain and how it impacts the environment.

Outlook to the future

Urban landscapes will continue to expand to accommodate a growing population, resulting in significant alterations to natural processes and environmental quality. Information from advanced satellite-based analysis is paramount in order to address this challenge. The Sentinel missions have been a game changer when assessing the dynamics in urban environments, and next generation sentinels and other high-resolution sensors will continue to improve the accuracy and precision of satellite-based environmental assessments. The frequent revisit time of the Sentinels will allow city planners to gain insight into the dynamics and environmental condition of urban environments by facilitating the production of recurrently updated information on urban structures. This will allow authorities to make decisions based on near-real time data, rather than on data updated once every 2-3 years. Furthermore, satellite-based mapping of impervious surfaces is an objective and consistent source of information, independent of subjective human interpretation.

Acknowledgements

We thank the European Commission and the European Space Agency for providing Sentinel data through the Copernicus Open Access Hub.

Nationwide Sentinel-2 Mosaic in Support of Airborne Data Collection and Planning

Earth observation methods provide an objective and synoptic means to monitor urban dynamics, and Earth observation derived products can be used as crucial tools to measure and estimate environmental parameters.

Thorbjørn Kjærshøj Nielsen [A], Regin Mark Møller-Sørensen [A], Andrew Flatman [A]

A: Agency for Data Supply and Efficiency

The challenge

Every year Denmark is photographed from the air in 10 cm resolution. The images are used for orthophotos and photogrammetric updates of the GeoDanmark vector map database. Furthermore, 1/5th of the country is scanned with LiDAR every year. The work is tendered to private companies of which most are situated outside Denmark. Good and precise information between customer and producer is essential for a good workflow satisfying both parties.

The aerial data acquisition missions are highly dependent on reliable data when evaluating flight conditions. Some of these data are: Meteorological data, military/aeronautical areas that are closed for aerial operations, as well as astronomical data to determine solar angle and solar eruptions affecting GNSS. Production managers require access to all compiled data in an easy-to-use interface.

The right conditions for aerial data capture are essential for ensuring the optimal final products. There are many factors determining the quality of the acquired data, for instance solar angle, cloud shadows, snow coverage and surface water. For the latter, the Agency for Data Supply and Efficiency has developed a method to determine if an area is ready to be surveyed, even before the acquisition aircraft leaves the ground.

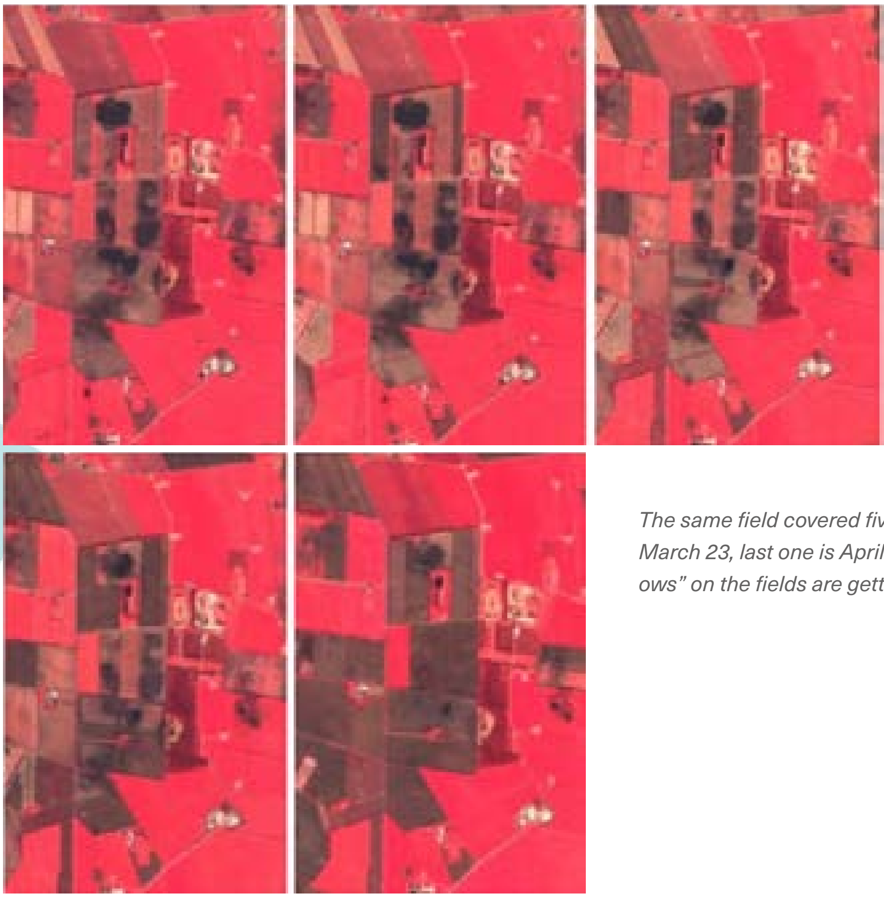
Sentinel-2 imagery excels in temporal resolution. The same area is being covered multiple times per month, even taking cloud coverage into account. Sentinel-2 provides decision-makers (i.e. the project managers in charge of the customer side of the data acquisition) with the best tools and data to base their decisions on. The use of Sentinel-2 imagery has established a near real time overview.

The space-based solution

The Agency for Data Supply and Efficiency has automated the process of downloading and assembling relevant satellite imagery mosaics on a regular basis. The project managers use the mosaics in their dialogue with the agency's suppliers of aerially acquired data. The Sentinel-2 color and infrared imagery are easy to interpret for the project managers who are used to this data type.

Benefits to citizens

The citizens encounter the agency's data either by using the visual products (e.g. viewing their property using an orthophoto), or derived products



The same field covered five times in a month. First image is from March 23, last one is April 23. Note how the surface water "shadows" on the fields are getting progressively smaller.

(e.g. vector/topographic maps), or through derived analysis (e.g. hydrological products on basis of LiDAR scans or taxation authorities advanced analysis of property value where geographical data is one of the most determining factors). It is self-evident that better tools for optimizing the data acquisition lead to better data in the entire supply chain, from low end easy-to-use products to the high end advanced analysis.

The data acquisition companies delivering to the Agency for Data Supply and Efficiency also benefit from a higher level of transparency when a go or no-go decision is being made. When the near real-time satellite images are presented, a common understanding is often reached. Project managers are able to prioritize the data acquisition and foresee the output quality even before aerial data is captured. This reduces the need to re-fly areas helping the agency to reduce the expenses and its carbon footprint.

Outlook to the future

As the Agency for Data Supply and Efficiency gains further experience with satellite imagery acquired close to real-time data, other types of data are relevant to take into consideration. At present, RGB and Colour-Infrared imagery is sufficient for human interpretation, but a more automated decision process could be obtained by using SAR data and machine learning techniques.

Validation of Tree Detection with Sentinel

Karsten Østergaard Noe, Alexandra Institute

The challenge

Deep learning, or other machine learning techniques, can be used to develop robust methods for recognizing objects in images.

The use of deep learning is dependent on large amounts of training data, and unless you already have usable data for the required object types (polygon data for clipping training imagery from the dataset), it is very time-consuming and expensive to create a training dataset.

In this use case, we aimed to develop a tool capable of mapping the wanted object types, without having to create training data in advance. The tool takes its starting point in the technology used for Geovisual Search – another Alexandra Institute project.

The space-based solution

By using orthophotos from planes or VHR satellite photos it will be possible to perform the previously mentioned mapping/counting or segmentation of different object types. This is done by splitting the dataset into a series of smaller cutouts, each of which is run through a so-called resnet network. This has been trained to recognize 1000 different objects in a dataset called ImageNet. Instead of using the final classification, we take out a description from the network – which consists of 2048 numbers. To save memory and reduce the needed computing power we have trained a so-called autoencoder. This is a neural network that can compress the 2048 numbers to 512 bits. After this is done, 48 million cutouts from an orthophoto can be compared with a new cutout in under 80 milliseconds.

Based on the search technology, we have developed a prototype of a user interface, which enables the search results to be refined interactively based on the results from several searches. Afterwards the search results can be converted into polygon layers, showing a mapping of the wanted object types. This mapping has been tested in Copenhagen, looking for the presence of trees – see figure 1.

The suggested method can be used to quickly annotate ground truth segmentation maps for machine learning on Sentinel-2 imagery. Either by using orthophotos or VHR satellite imagery as secondary data – or directly on Sentinel-2 for large-scale typologies such as land-use or habitat mapping.

Use case in Copenhagen

Using a vector dataset consisting of the positions

Figure 1: Tree detection analysis. Top part shows the area of interest and bottom of the image the result of the algorithm.

of individual trees on public areas, we have tried to locate / count individual trees other places in the image (for instance in private gardens). By using deep learning, we have experimented with so-called keypoint-estimation-networks that can mark the middle of each tree. During the training, we need to ensure we do not show data with trees that are not marked. Using this described search methodology, we can quickly use the ground truth dataset to generate training data containing trees in addition to using the mapping from figure 1 to generate training data that does not contain trees.

After testing the method, it becomes obvious, however, that the network overlooks too many trees to make it truly useful, and more time is needed to explore how this can be remedied.

Perspective for the future

The interactive method for refinement, described above, has been implemented in a very basic prototype. To use it properly, you need to be an expert user in the system, and currently it only runs on a single computer. Over time, the procedure will become web-based and thereby more user friendly.

Figure 2: Tree detection for the entire city of Copenhagen.

Sea Surface Temperature of the Baltic Sea, Kattegat and Skagerrak

The unusually hot summer of 2020 had severe consequences on the environment at high latitudes, and in particular in the Baltic Sea.

This images shows the Sea Surface Temperature (SST) as measured by one of the Copernicus Sentinel-3 satellites on 16 August in the southern part of the Baltic Sea and the Kattegat and Skagerrak straits. SST reached values above 24°C along the coasts of Poland, Russia, Lithuania and Sweden, and about 22°C in the Kattegat. These data, as reported by the Danish Meteorologic Institute, represent a SST thermal anomaly of approximately 3-4°C with respect to the 1985 - 2003 reference period.

The Copernicus Sentinel-3 mission is composed of two twin satellites (Sentinel-3A and Sentinel-3B) that are both equipped with the SLSTR Sea and Land Surface Temperature Radiometer from which SST data are retrieved. Sea surface temperature data is used as an input for weather and ocean forecasting, to observe and monitor ocean current systems and ocean fronts, eddies, upwelling areas, marine ecosystems and the development of large scale El Niño/La Niña events

Credit: European Union, Copernicus Sentinel-3 imagery.

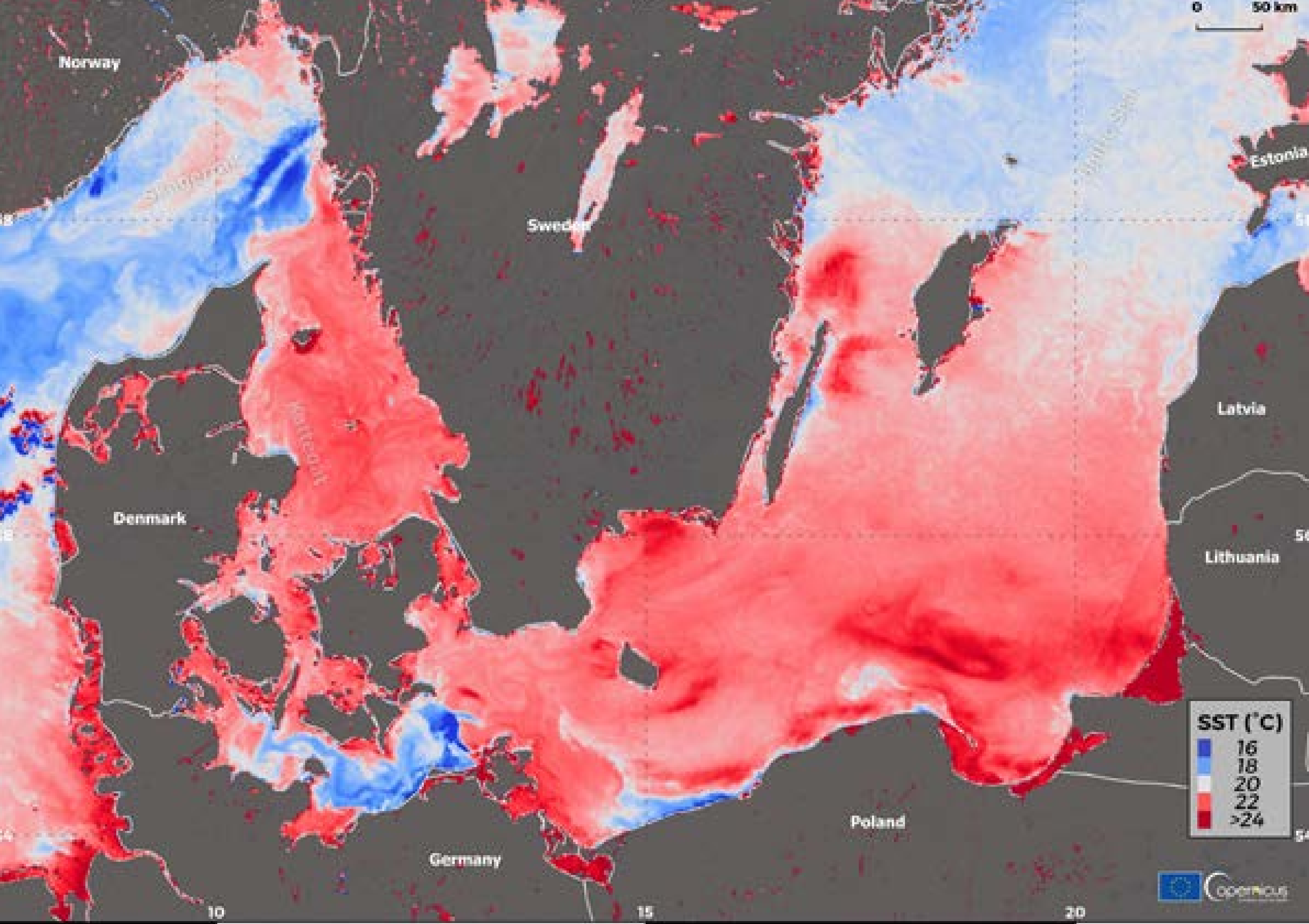
Ship Emissions from Space

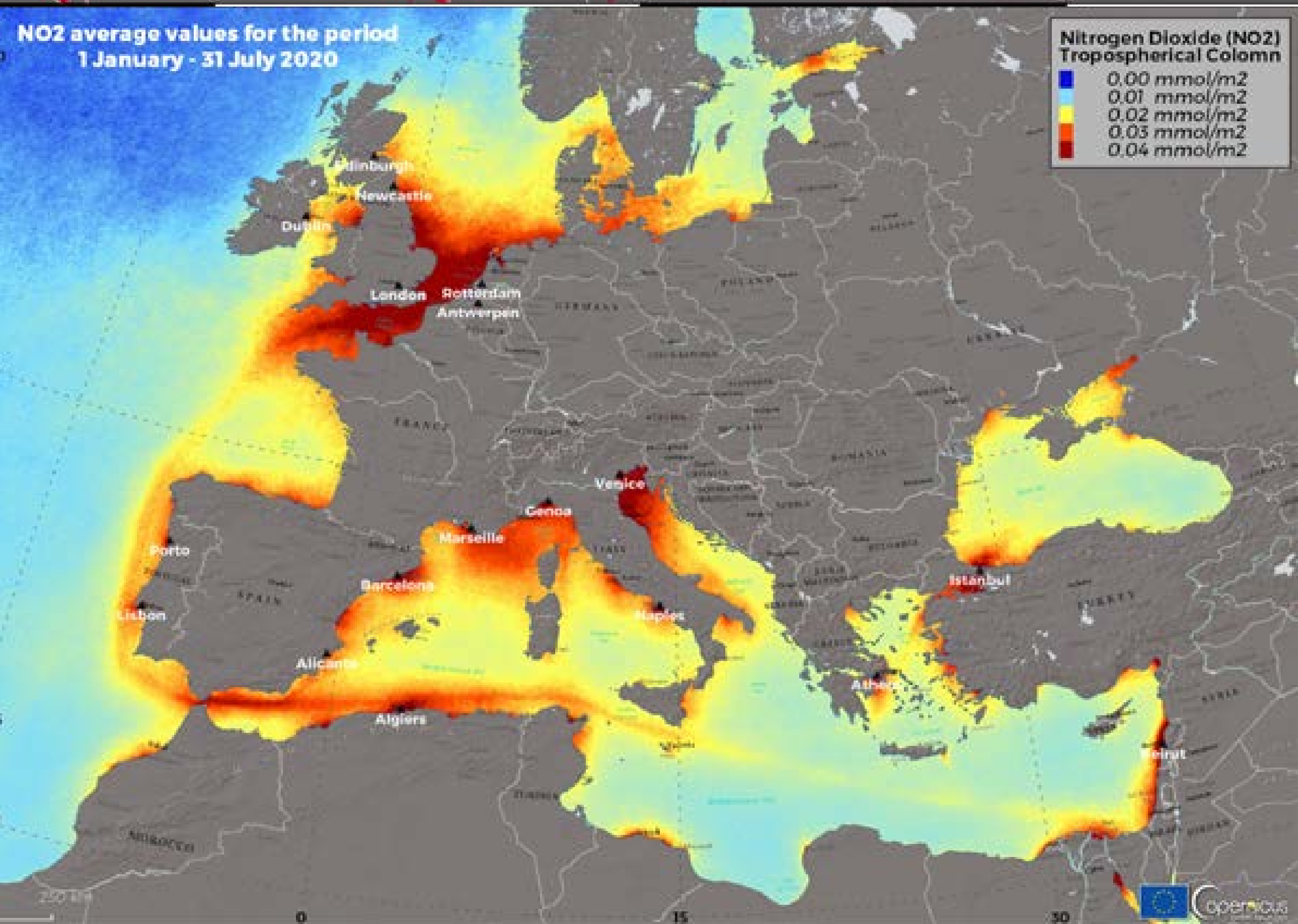
Maritime traffic has a significative impact on air quality: ships generate emissions of sulphur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM) and carbon dioxide (CO2) as a consequence of the composition of the fuel used to power them. In recent years, emissions have increased in a significative way, and as reported in a study commissioned by the International Maritime Organization (IMO), greenhouse gas emissions from shipping increased by 9.6% from 2012 to 2018, as rising demand outweighed efficiency improvements.

This image shows the average value of Tropospheric Nitrogen Dioxide (NO2) detected between January and July 2020 by the Copernicus Sentinel-5P Satellite for the open water areas of the European Region (Mediterranean Sea, Atlantic Ocean, etc). In this visualisation, the "highway" that the vessels use to navigate the Strait of Gibraltar is easily visible because all the ships follow approximately the same route and reject a significative amount of NO_2 in the atmosphere. For the same reason (long stays at destination areas before unloading their cargo), the areas around port areas like Rotterdam, Marseille, Venice, Barcelona, etc. appear red in this visualisation.

Nitrogen dioxide is a product of the combustion of fuels, in this instance from the burning of marine diesel and heavy fuel oil. Thanks to the TROPOMI instrument, that is onboard of the Copernicus Sentinel-5P Satellite, it is possible to see these shipping lanes with a spatial resolution of 7.5Km by 3.5 Km, a significant improvement when compared with the resolution of previous missions. The detection of NO2 concentrations in the atmosphere helps to monitor anthropogenic activities (notably fossil fuel combustion and biomass burning) and study natural processes (such as microbiological processes in soils, wildfires or lightning).

Credit: European Union, Copernicus Sentinel-5P imagery .


0 50 km
Norway
Sweden
Estonia
Latvia
Lithuania
Denmark
Poland
Germany
SST (°C)
16
18
20
22
>24
10
15
20


NO2 average values for the period
1 January - 31 July 2020
Nitrogen Dioxide (NO2)
Tropospherical Colomn
0.00 mmol/m2
0.01 mmol/m2
0.02 mmol/m2
0.03 mmol/m2
0.04 mmol/m2
Edinburgh
Newcastle
Dublin
London
Rotterdam
Antwerpen
Venice
Genoa
Marseille
Porto
Barcelona
Lisbon
Naples
Alicante
Algiers
Istanbul
Athens
Beirut
0
15
30

Enabling EO for Climate Mitigation and Adaptation in Urban Areas

Earth observation data is a cornerstone of monitoring systems in urban landscapes and can effectively be used to assess risk, resilience and long-term stresses caused by climate change.

Mads Christensen [A], Emil Møller Rasmussen [B]

A: DHI GRAS B: Copenhagen Municipality

The challenge

A changing climate is undeniably one of the greatest threats to our environment, ecosystems, and socio-economic structures and the struggle to combat climate change and mitigate climate impacts is never more pronounced than in urban landscapes.

With a future predicament of heavier rain, higher sea levels and warmer weather, urban landscapes are positioned on the frontline of climate impacts, and city planners and policy makers are faced with the daunting challenge of redesigning cities to enhance resilience against climate-induced impacts, while at the same time reducing greenhouse gas emissions.

However, while climate change is one of the top societal challenges, the ability to reshape cities in a changing climate inherently depends on good quality data and information.

The space-based solution

Earth Observation data is an indispensable and mature resource for monitoring and measuring key parameters relevant to climate change in cities. Satellites have the capacity to capture large quantities of timely and accurate environmental information on the physical, chemical and biological dynamics within urban landscapes.

Satellite data can be used to measure temperature differences in urban landscapes caused by urban heat islands, providing city planners with a critical tool to spatially allocate a more optimal composition of hard surfaces and green space vegetation in order to reduce overall temperature variability.

> **“The Municipality of Copenhagen has applied data from satellites to monitor so-called Urban Heat Islands in the city. This has provided planners with actionable information about which areas of the city need heat mitigation, for instance in the form of new green areas.**
>
> *Emil Møller Rasmussen, Copenhagen Municipality*

Impervious surfaces and vegetation cover can also be consistently monitored and mapped using earth observation data, providing an essential resource for modelling surface runoff and predicting urban flood exposure in order to manage flood risk and inform climate adaptation plans.

Extract from satellite-based temperature map of Copenhagen, Denmark, indicating the impact of green areas on urban surface temperature.

Monitoring surface water dynamics and frequency of flooding in southern Copenhagen.

Benefits to citizens

Earth observation data is more accurate and accessible than ever before, and the advent of the Copernicus programme providing freely available data in high spatial, spectral and temporal resolution is a game changer for operational monitoring of urban landscapes.

Satellite data is consistent and unbiased, thus providing a cost-effective way to assess the spatial and temporal evolution of urban processes at a fraction of the cost of traditional in-situ sampling and measurements.

The ability to track and monitor urban greenness, temperature and other relevant climate parameters provides an objective metrics for city planners and decision-makers to make our cities greener, more sustainable and more livable for its citizens.

As temperatures are expected to increase in the future, the ability to map urban heat islands and monitor fluctuations in vegetation cover will provide urban planners with a tool to make use of strategic planning of green infrastructure to mitigate the impacts of rising temperatures and the effects from climate change.

Outlook to the future

The ability to monitor urban landscapes in high spatial resolution, with frequent updates, is critical in order to inform city planning and climate adaptation measures in the future. Free data from the Sentinel satellites will continue to contribute to an expanded avenue of opportunities, providing a means to test and develop new tools to provide enhanced means for decision-makers to target urban spatial planning strategies in the context of a changing climate and sustainability performance requirements.

Future missions such as the Copernicus candidate Land Surface Temperature Mission (LSTM) are highly relevant as a potential future tool to monitor temperature variation and water use efficiency parameters in even higher spatial-temporal resolution.

Acknowledgements

We thank the municipality of Copenhagen for providing the opportunity and financial support to map and account for the urban heat island phenomenon in Copenhagen. We further thank the Department of Geoscience and Natural Resource Management at Copenhagen University for support and collaboration.

Municipal Applications of NDVI Analysis

How can analyses based on satellite imagery be used in a municipal context?

Emil Møller Rasmussen, Copenhagen Municipality

The challenge

More and more cities across the globe have seen an increasing interest from their citizens in accessing green areas – thus there is an increased focus on preserving and expanding the vegetated areas within cities.

The citizens of Copenhagen do not set themselves apart on this parameter, and the citizens are therefore very interested in the state of green in Copenhagen. This manifests itself as an important subject for the local politicians and the political administration. As such, the cities planners have increased their focus on mapping and analyzing the green aspects of the city.

The space-based solution

The improved access to satellite imagery of Copenhagen from the Copernicus programme has made it possible to use this data source as a basis of analysis on equal footing with more traditional data sources.

One of the advantages of satellite imagery is a guaranteed consistency and uniformity, whereas these qualities are harder to ensure when combining a wide variety of different datasets for a similar purpose.

Satellite imagery can be used as the basis for a broad range of analyses – such as analyzing the amount of vegetation in a given area within the image. This is done through a normalized difference vegetation index (NDVI).

Copenhagen as seen with the Sentinel-2 satellite. The picture has been cut to the city limits.

NDVI is a well-known and broadly used method, whereby inputting a few parameters provides an overview of vegetation in an area. Overall, the analysis works by utilizing the red and near-infrared bands in the satellite image. When a normalized index of the difference between the bands is cre-

The result of a NDVI analysis. Areas with vegetation stand out and have been colorized with a green tint.

ated, vegetation stands out. This information can then be used as is or as the basis of further analysis – providing an even more in-depth overview.

For citizens in Copenhagen

The results from the NDVI analysis can be used in a variety of contexts. First and foremost the data can be used to give an overview of the actual state and presence of vegetation in Copenhagen. The analysis has presently been used to provide an overview of how vegetation in Copenhagen is actually distributed in the city. These data can then be converted into statistical data, which can then be used for further analysis about the specificities of the vegetation – such as the distribution of vegetation in boroughs and neighborhoods of the city. Further insight is created by combining the NDVI data with new and other data sources providing insight into how the vegetation and green structures of the city have developed over time.

Outlook to the future

Satellite data are still not broadly used, in spite of the steps taken towards accessibility in the last decade. These analyses of vegetation show that this data source can be used alongside more ”traditional” data in a local government context.

It is therefore essential that municipal stakeholders increase their sharing of experiences and get better at networking, as this will make it easier to incorporate satellite data into the regular workflows of local government.

A Satellite View on Urban Dynamics

Coupled, earth observation and deep learning approaches provide an effective and efficient means of monitoring urban flows and detecting changes in urban areas near real time.

Mads Christensen [A], Emil Møller Rasmussen [B]

A: DHI GRAS B: Copenhagen Municipality

The challenge

As city populations continue to grow and urban sprawl increases, local authorities are faced with the challenge of managing the dynamics and activities in a constantly changing environment. Data and information on urban areas are often inadequate, generalized, outdated or simply not available.

In order to measure, analyze and understand the dynamic interrelationships and permanent changes in urban landscapes, spatial information is vital. However, while existing IOT solutions, video camera surveillance and interpretation of aerial photos and satellite images provide a means to assess urban dynamics, they are resource intensive, costly and unable to provide a synoptic overview of the dynamics in entire urban landscapes. There is a fundamental need for more automatic and consistent monitoring of the dynamic flows in cities in order to inform authorities, and support their efforts to redesign smarter, greener, more sustainable and more efficient urban environments.

The space-based solution

Deep learning technology has increased the potential of satellite imagery and reshaped the way we are able to monitor activities and dynamics in urban environments.

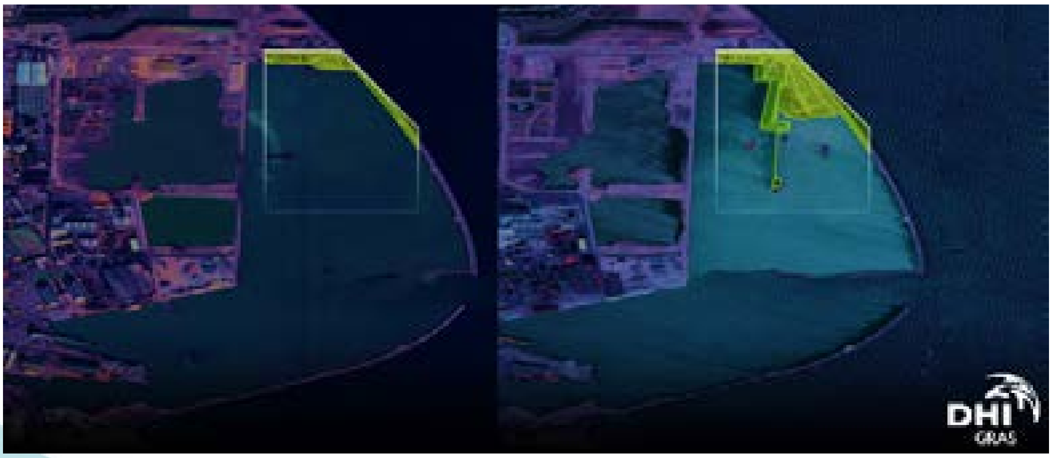
Deep learning algorithms can recognize patterns, shapes and context in imagery and use this to better map different objects of interest and thereby significantly accelerate the ability to systematically and operationally label objects and detect changes in urban landscapes.

In short, deep learning algorithms have allowed us to detect objects such as cars, tree crowns, solar panels, swimming pools, etc. with high accuracy and short turnaround for delivery, while only requiring a small amount of training data even for larger areas.

Using deep learning approaches to systematically process and label high frequent/high resolution satellite imagery (including Sentinel and Very High Resolution missions), city planners and authorities are able to tap into an indispensable resource tracking urban dynamic in near real time, allowing them to make informed management actions.

Benefits to citizens

Detailed and updated geographic information is an essential component for effective urban planning and monitoring. The use of the very high-resolution satellite imagery and deep learning algorithms offers objectivity, efficiency, and automation with regard to wide scale urban monitoring, providing



Monitoring progress of construction activities using automatic change detection on very high resolution satellite images in Køge harbor.

an efficient platform to consistently track urban dynamics and ensure up-to-date and accurate information about urban changes and movements. The added insight on urban flows and understanding about how people use urban landscapes will allow decision-makers and authorities to react faster and smarter and enable them to make informed decisions about urban policy frameworks and instruments based on actionable data and information about the structural changes and dynamics in city environments. This could support sustainable spatial development and make cities more livable, productive and inclusive.

> **“We have used satellite imagery from DHI GRAS for the routine surveys as well as follow-up and quality assurance of the construction work in the municipality. Data was easy to use and cost-effective, as well as providing good documentation for the development of the municipality’s projects.**
>
> *Steen Muchitsch, Køge Municipality*

Outlook to the future

Deep learning algorithms have only recently been adopted as an efficient approach to extract valuable data from satellite images. The technology is still in its infancy and the future will see significant advancement of deep learning approaches to leverage actionable data from earth observation data.

Furthermore, technological development within spaceborne sensor systems, such as access to video from space and rapidly increasing amounts of high-resolution sensors, will further facilitate improved options for surveying city flows in near real time, potentially reducing the need for in-situ observations of traffic patterns and other relevant urban dynamics.

Tracking and monitoring cars in urban areas with very high-resolution satellite imagery and deep learning.

Acknowledgements

We would like to thank AirBus and DigitalGlobe for providing very high-resolution imagery data. Furthermore, we thank Køge and Copenhagen municipalities for their long-term engagement, collaboration and support.

Agricultural Control Using Sentinel

The Danish Agricultural Agency uses time series of Sentinel satellite images to detect agricultural activities in all fields in Denmark. In this way, agricultural checks can be carried out without a physical inspection on the farm. This provides increased flexibility for both parties.

Sanne Eskesen [A], Lotte Nyborg [B]

A: Danish Agricultural Agency B: DHI GRAS

The challenge

Every year, the Danish Agricultural Agency carries out checks on whether Danish farmers comply with conditions for receiving agricultural subsidies. This has traditionally been done by physical inspections in the field for a percentage of applicants – a process that is costly and time-consuming for both the Agricultural Agency and the applicant. Often, a single visit will not suffice, as different farming activities can take place throughout the year. In order to reduce the number of inspection visits, the Agricultural Agency has established periods when different agricultural activities must take place.

Since many of the subsidy conditions can be confirmed based on advanced satellite image analysis, more work is being done on using this data as part of the check. This is expected to lead to fewer inspection visits and more flexible deadlines for farmers.

The space-based solution

By means of nationwide time series of Sentinel-1 and Sentinel-2, all fields in Denmark can be monitored. Particular activities that result in a marked change in the surface of the field, such as plowing or mowing, will be registered as a change in the time series of satellite-based observations. In this way, it is not a single picture, but a time series of satellite images of a field that most often brings value.

Time series of Sentinel-1 and Sentinel-2 data are processed and analyzed based on advanced 'machine learning' techniques and time series analyses to identify the specific times of events, such as plowing, mowing and harvesting, and mapping of crops.

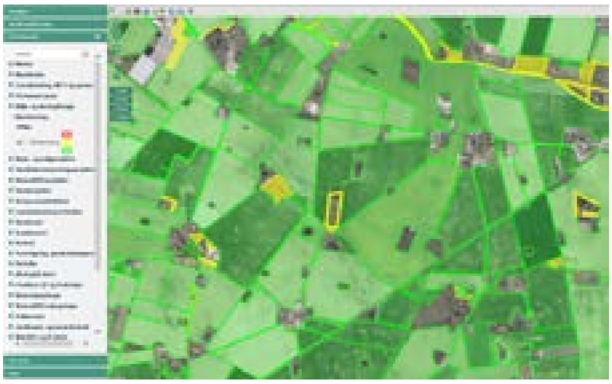
> **"I think it is a good help that you can follow your fields possibly go from yellow to green, as I have done.**
>
> *Anders Gade, Part-time farmer*

The processing is based on an advanced preprocessing system developed by DHI GRAS where all time series of Sentinel-1 and Sentinel-2 data are downloaded and processed for national coverage of Denmark. For all agricultural fields in Denmark, all satellite data and results are stored in a huge database. Finally, the results of the specific analysis and applications are visualized in a user-friendly web viewer where the Agricultural Agency can view time series of data for specific fields, view satellite images and evaluate results for specific fields.

Crop type mapping, example from Horsens. Source: Sentinel-2

Benefits to citizens

Up to now, these satellite observations have been used to guide the Agricultural Agency´s inspectors to potential holdings where subsidy conditions have not been met. An initiative by the European Commission has now made it possible to use Sentinel observations more as a basis for inspection. This will allow the Agricultural Agency to carry out future inspections using Sentinel observations.



Traffic light map for monitored fields from the Danish Agricultural Agency's web GIS "IMK".

For farmers to keep track of whether their fields have registered an activity, results are displayed for all fields on the Agricultural Agency's website. These appear as a map layer, with approved fields colored green and fields where the requirement has not been fulfilled colored red. Yellow indicates that there is no clear result for the field. If the satellite-based determination is incorrect, the farmer will have the opportunity to take a georeferenced picture of the field and send it to the Agricultural Agency via an app.

Outlook to the future

Under the current legislation, there are still subsidy preconditions that cannot be monitored using satellite images. With the new Common Agricultural Policy, it will be possible to further develop satellite-based monitoring by allowing future inspections to be targeted on large-scale systematic violations, as opposed to using resources on measuring small ineligible areas that may not have great financial impact. A further expected benefit is that use of the traffic light map will have a "nudging effect", by allowing farmers to choose to withdraw applications for fields once they can see that they do not meet requirements.

Acknowledgements

DHI GRAS and NEO B.V. are specialized in processing and analysis of satellite data and have for a couple of years worked together with the Danish Agricultural Agency to develop dedicated analysis tools for agricultural control.

Classification of Invasive Plant Species

Invasive plant species have a negative impact on natural vegetation. Consequently, the authorities seek to limit their expansion, and satellite data can be used for mapping these plants.

Casper Samsø Fibæk, NIRAS

The challenge

Invasive plants are species of plants that are non-native to their habitat and have a negative impact on the native flora and fauna. Due to the harmful effect of invasive plants, national and international measures are taken to prevent the expansion of invasive species.

Identifying the habitats of invasive species is an indispensable prerequisite for controlling expansion. Preferably, the plants should be identified soon after establishment in a new territory, thus preventing further expansion at an early stage. Traditionally, this has been a manual process through in situ observations. However, manual surveying is time demanding and challenging in hard-to-reach areas.

A satellite-based method holds potential for conducting nationwide mapping of selected invasive species. In this project, the potential for mapping two invasive species, Rosa rugosa and Solidago (aka. goldenrods), was tested for five smaller regions in Denmark.

The space-based solutiont

Sentinel-2 data has been used to identify Rosa rugosa and Solidago based on their specific spectral signatures and phenology. Rosa rugosa has a unique spectral signature all year, and Solidago has a characteristic yellow colour during the flowering stage in late summer. Both species grow in large patches, thus allowing for detection through Sentinel data with a spatial resolution of 10x10 m.

A machine learning algorithm was trained based on a spectral analysis of Sentinel-2 data, combined with observed occurrences of the two invasive plant species as well as relevant ancillary parameters, including soil types, ground water level, vegetation height, terrain slope and proximity to coast and forest. Additionally, a plant profile was created in collaboration with biologists and combined with Sentinel-2 data. This resulted in a classification of areas inhabited by the two plant species. Subsequently, these areas were segmented in confidence intervals based on the likelihood of correct detection by the algorithm.

The method proved particularly applicable for detecting larger occurrences of Rosa rugosa.

Invasive plant species. Above: Rosa rugosa. Below: Solidago (goldenrods).

Classification of Rosa rugosa. The classification "certainty" is specified by a scale from yellow to blue, with blue being the highest level of certainty.

> **Satellite based mapping can be a valuable tool for getting an overview of a species national coverage and, thereby, it helps facilitate the management of the invasive species.**
> *Josefine Møller,*
> *The Danish Environmental Protection Agency*

Benefits to Citizens

Mapping of invasive species can help the authorities limit their expansion. The maps provide an overview of existing occurrences, but through repeated analyses, these maps can also reveal areas that are vulnerable to invasive species. Additionally, the analysis can provide a good starting point for detecting areas that would be relevant to investigate further. Currently, the method is not completely accurate at the pixel level but yields promising results for larger and denser populations.

The application can yield both socio-economic and ecological benefits. In general, the increased knowledge on plant species' location and expansion can enable more focused preventive efforts, thus saving time and money in the public sector. Additionally, the improved control of invasive plant species that may result from this application can improve the conditions for native plant species and the animals that depend on them.

Outlook to the future

This application of Sentinel data is considered to be at stage 4 – "Early adopters". At this stage, the pilot project indicates the potential for nationwide mapping of Rosa rugosa and Solidago and points to a number of future improvements and applications.

Rosa rugosa and Solidago were selected for this pilot project due to their easily identifiable characteristics. However, it might also be possible to apply the method to other plant species as well.

Moreover, as data becomes accessible it will be possible to feed machine learning algorithms with this data and thereby improve the accuracy of the classification.

Additionally, it would be possible to augment the classification with a temporal dimension so that the analysis is executed several times throughout the season. Combined with knowledge on the seasonal changes, this may improve the accuracy of the classification and enable the classification of other plant species.

Acknowledgements

This pilot project was conducted on behalf of the Ministry of Environment and Food of Denmark. We wish to thank the Copernicus programme for the collection and provision of Sentinel data.

Using EO to Develop Intelligent Agricultural Technology Solutions

With a particular specialization in agriculture, we develop solutions and applications for processing and analyzing satellite and weather data with machine learning and computer vision.

Jakob Kragelund Larsen, FieldSense

The challenge

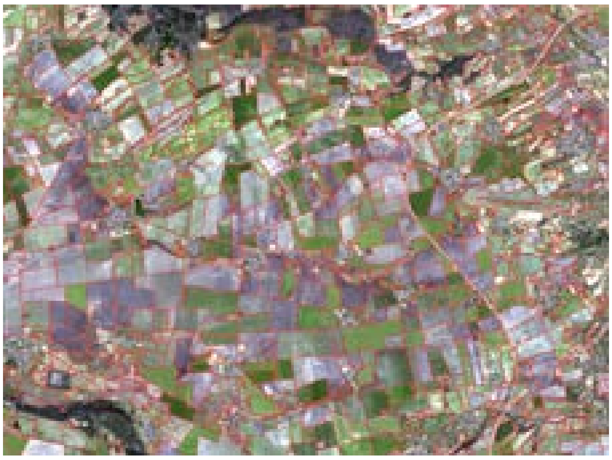
A continual rise in global population and food demand entails a need for significant agricultural optimization. Following the Fourth Industrial Revolution, artificial intelligence and big data are entering into the sphere of agriculture and revolutionizing an otherwise traditional sector. Capitalizing on its expertise in big data management, AI, machine learning and computer vision, FieldSense develops various solutions that integrate these technologies with the agricultural sector.

> **Precision Agriculture is here to stay, and I see great value in using FieldSense.**
>
> *Poul Jakob Bønløkke, farmer and FieldSense user*

In order to do so, FieldSense uses weather data gathered from its growing network of in-house developed weather stations as well as satellite imagery from the Copernicus Programme.

The space-based solution

FieldSense's core products are machine learning solutions based on satellite imagery from the Sentinel-2 and Landsat8 satellites. The raw imagery is processed through an internal pipeline which, among other things, enhances the quality of the imagery and filters clouds and cloud shadows. Based on this imagery, various AI solutions have been developed, e.g. automatic object detection (such as fields and field borders, silos and ponds), anomaly detection (such as irregular crop growth over time), and crop type detection.



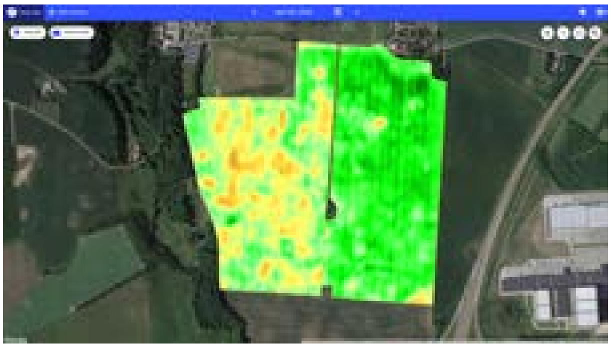
FieldSense's neural network detecting field borders in Central Germany.

Many of these features are integrated in the FieldSense-developed FieldSense-platform for farmers and agricultural consultants. In FieldSense, farmers can monitor their fields with biomass maps based on satellite imagery, where the NDVI vegetation index is calculated. As such, FieldSense functions as a year-round decision support platform with various tools, such as variable-rate fertilizer and plant protection application maps, and crop performance benchmarking. Due to the unprecedented availability of Sentinel-2 and Landsat-8 imagery, FieldSense offers its services worldwide and has analysed more than 500 million hectares of arable land.

Benefits to citizens

The automated processes and solutions that FieldSense offers benefit various stakeholders in various ways. Farmers can use FieldSense to efficiently monitor their fields using satellite imagery and in-field weather stations in order to check for problem areas and prioritize their work. They can also make their own variable-rate application maps, not only saving them money but benefiting the environment as well.

Many of the features integrated in FieldSense are offered as solutions of their own, such as field border detection. FieldSense has developed a neural network that automatically detects field borders on a global scale. More and more companies are offering Precision Agriculture software for farmers but have a hard time adopting users, partly because the onboarding process is time-consuming (such as the farmer having to manually draw his or her field borders in the programme). By integrating FieldSense features into their own platform, such companies will have an easier time landing clients. FieldSense is also involved in many different international projects that aim to develop innovative agricultural solutions. An example is snail attack prediction in crops; biomass maps from satellite imagery, hyper-local weather data and soil samples allow a machine learning algorithm to learn the factors that influence snail attacks and can thus begin to predict actual snail attacks when it recognizes conditions in fields.



Biomass map of two fields as shown in FieldSense. Eastern Jutland, Denmark.

Outlook to the future

Although FieldSense's products are primarily addressed to the Agro-Tech business, many other sectors are starting to take interest in them. The applications of satellite-based AI solutions are nearly endless, e.g. insurance companies monitoring changes in infrastructure, and environmental agencies monitoring illegal deforestation.

Acknowledgements

FieldSense has received funding from:

- The InnoBooster Programme and Industrial Ph.D. Programme under the Innovation Fund Denmark.
- The Green Development and Demonstration Programme under the Ministry of Environment and Food of Denmark.
- EU's H2020-Programme.

Satellite-based Mapping of Water in Fields

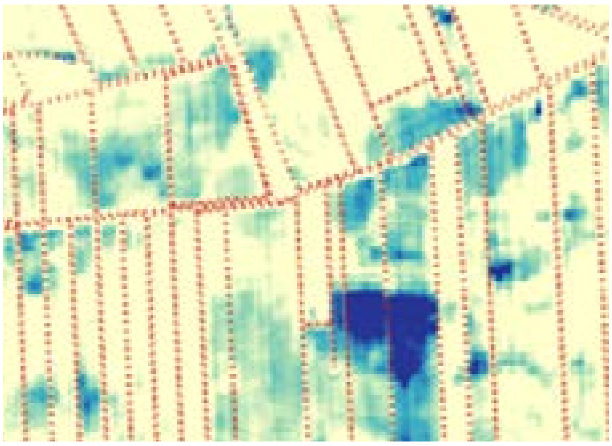
Satellite data is a time-efficient and inexpensive source for identifying and mapping waterlogged fields. With a particular specialization in agriculture, we develop solutions and applications for processing and analyzing satellite and weather data with machine learning and computer vision.

Stinna Susgaard Filsø [A], Lotte Nyborg [B]

A: SEGES B: DHI GRAS

The challenge

Since the systematic monitoring of climate observations in Denmark started in the late 1800s, the mean precipitation at the national level has increased annually by more than 100 mm, with an accelerated trend in precipitation increase since 1940. At the same time, the rainfall events have increased in intensity, leading to challenges with flooded and waterlogged fields. Flooded or wet fields challenge the optimal timing of crop sowing because the soil is too wet and cold to support germination and growth. This reduces the crop root development, which results in a loss of yield as well as a loss of unused nitrogen. Thus, it is essential for the farmer to have well-drained soil to maintain an optimal production and to reduce the environmental impact from the agricultural soil. In order to allow the farmer to accommodate floods, it is necessary to know the extent of affected areas with drainage problems. Such an overview is normally difficult and time-consuming to obtain. Here, high-resolution satellite data provides a unique opportunity to cost-effectively map wet areas in the field.

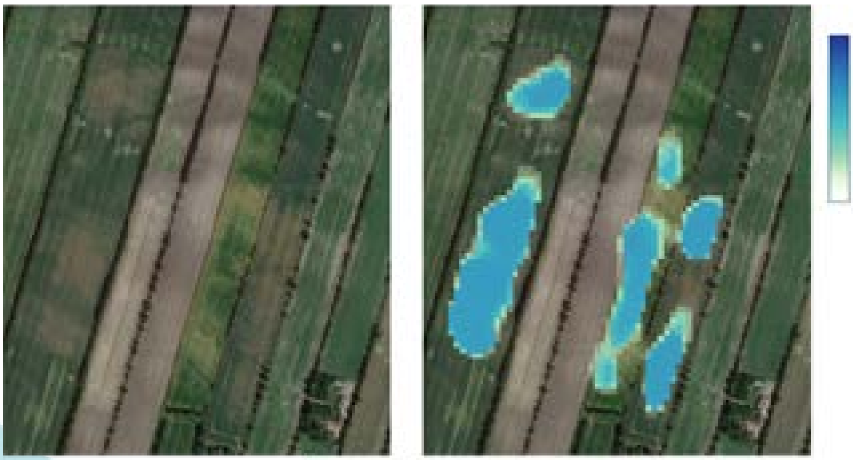


The darker the blue, the more wet the area was during the season from September to April. Copyright: DHI GRAS, contains modified Copernicus Sentinel data [2019].

The space-based solution

Large quantities of Sentinel-1 and Sentinel-2 data have been processed and analyzed to investigate and present different methods for mapping waterlogged soils in selected fields in Denmark. The optical time series from Sentinel-2 provide a good overview of the spatial distribution of water in fields, but the quality of the products is dependent on the cloud cover. The SAR-based data from Sentinel-1 has the obvious advantage of being independent of cloudless conditions and thus providing a more homogeneously distributed annual time series.

Time series of Sentinel-2 data can be analyzed and visualized in frequency maps, showing which areas are waterlogged during a growing season. Time series of Sentinel-1 data can be used to map larger areas with water issues and floods by using an automated method developed by DHI GRAS. Furthermore, the soil surface moisture at field level can be derived from Sentinel-1 observations, thereby mapping the annual relative development for independent fields. This can provide important in-



Flood-frequency map based on Sentinel-1 radar data. Copyright: DHI GRAS, contains modified Copernicus Sentinel data [2019].

formation for the farmers concerning the need for irrigation and the presence of waterlogged areas.

Further validation in relation to the observations made by the farmers is needed, but satellite-based methods provide a good opportunity to help understand which areas are prone to waterlogging and when the problems occur.

> **Mapping of waterlogged areas in fields provides important knowledge on where to improve drainage conditions – and where to minimize fertilizer and crop protection application.**
> *Jens Elbæk, farmer*

Benefits to Citizens

Mapping areas with drainage problems provides a way to focus and improve the efficiency of tools to secure a better drainage of cultivated areas.

Sufficient drainage of cultivated areas is key to an economically sustainable production of crops meanwhile securing a better utilization of nitrogen. This limits the risk of losing nitrogen from cultivated areas to the groundwater and surface water. Furthermore, the climate benefits because the risk of emission of the potent greenhouse gas nitrogen oxide (NO2) is reduced. The application benefits of developing satellite-based tools for mapping waterlogged farmland extend beyond agricultural interests.

The mapping will also be useful for governments, municipalities, and other stakeholders involved in climate adaptation, river management, and management of wetland areas.

Outlook to the future

Using satellite-based technology for mapping soils will only become more relevant in the future because of climate change invoking increased precipitation with more frequent incidences of intense rainfall. Additionally, artificial intelligence has the potential to contribute to the automatization of workflows even further in the future, hereby securing continuous monitoring of waterlogged fields.

Acknowledgements
This project was funded by Promilleafgiftsfonden for Agriculture.

Flood Mapping with Satellite Data

Using radar data from Sentinel-1, it is possible to map flooded terrain. This is an example of regional flood mapping after a period of heavy rain.

Mikkel Skovgaard Andersen, NIRAS

The challenge

Floods can have serious consequences, and the socio-economic repercussions can be enormous. To handle these floods optimally, it is essential to know which areas are at risk.

With land-based surveying techniques, it is possible to map floods at specific locations. However, for large-scale terrestrial floods, traditional methods fall short. Imagery from the Sentinel satellites, on the other hand, can cover a large area, and with a frequency of 2-5 times per week for Denmark, there is a high probability of obtaining data shortly after heavy rain.

Therefore, the challenge is to use Sentinel data for mapping the distribution of water on the terrain following heavy rain events.

The space-based solution

It is mostly cloudy during and immediately after a major rain event, so optical satellite imagery is not ideal for mapping flooded areas. However, radar data from Sentinel-1 can penetrate clouds, thus providing an obvious opportunity for mapping.

The RADAR signal from Sentinel-1 is reflected off the surface, and the intensity of the reflected signal is affected by the surface type.

Water and wet surfaces generally return lower intensity values than do dry land surfaces. This difference in reflectance makes it possible to map flooded areas.

Example of flooded terrain.

In the first half of March 2019, Denmark experienced unusual precipitation levels. This provided a case to test the method. Therefore, two Sentinel-1 images from mid-March were used in the analysis.

The Sentinel-1 images were pre-processed through calibration, noise filtering and georeferencing in SNAP - European Space Agency's free processing software. Next, low intensity values were classified as surface water. Roads and built-up areas can also have low intensity values, thus resulting in misclassifications. These errors were corrected by delimiting the study area based on Danish topographical data – such as vectorised roads and buildings.

Example of a flood map from the analysis. The blue areas are covered in water and the background is a Danish orthophoto.

Benefits to Citizens

Sentinel-1 data enables monitoring of much larger areas than most other technologies. Additionally, it is often possible to obtain data immediately after the floods have occurred due to a high over-flight frequency. These advantages make it a viable option for flood mapping.

> **This method for mapping the extent of flooding can be a valuable tool for the authorities in the management and preparation for future flood events.**
>
> *Morten Westergaard, Head of the surface- and groundwater department, NIRAS*

From a socio-economic perspective, flood mapping is of great value. Planners can use the maps in their urban and landscape management to reduce the damages induced by floods. Additionally, information on the prevalence and frequency of floods is invaluable knowledge for emergency responders and locals, who can prepare for future flooding events.

The financial consequences of flooding can be enormous, and anything that prepares us better for future floods has a great potential value.

Outlook to the future

This application of Sentinel data is considered to be at stage 4 - ”Early adopters” - since the method is operational but can benefit from further development.

The next step is to improve the accuracy of the method. This may be achieved through the following implementations:

1. Integrating Sentinel-1 data from multiple flooding events and using it to generate a risk assessment (how often does an area get flooded?).
2. Investigating other classification methods, including object-based classification and automatic classification using machine learning.

Acknowledgements

We wish to thank the Copernicus programme for collecting Sentinel data and for making it publicly available. We also wish to thank the European Space Agency for providing training courses and webinars on data processing.

Mapping of Wet Areas in Denmark using Sentinel-1 and Sentinel-2

Time series analysis of Sentinel-1 and Sentinel-2 images is useful for mapping wet areas in Denmark. This includes the mapping of permanent and temporary lakes as well as flooded areas caused by extreme weather events.

Eva Bøgh [A], John Kamper [A], Lotte Nyborg [B], Mads Christensen [B], Georg Bergeton Larsen [A]

A: Agency for Data Supply and Efficiency B: DHI GRAS

The Challenge

Denmark is a lowland being frequently exposed to storm surges and floods from heavy rain and increasing groundwater levels. National scale temporal mapping of wet areas is important to support climate adaptation, agricultural and land use planning, environmental management, infrastructure planning and financial investments.

At the same time, a concrete challenge of Agency for Data Supply and Efficiency (SDFE) is to decide whether the many small lakes of the country include new lakes or not. SDFE monitors and maps lakes at very high spatial resolution using aerial orthoimagery acquired each year in spring. However, it is uncertain whether the identified lakes are in fact lakes, or whether the water will disappear after a few days.

The space-based solution

Remote sensing based temporal maps of wet areas using Sentinel-1 and Sentinel-2 time series are valuable for mapping both permanent and temporal lakes as well as the flood frequency of open areas.

There is also a large potential for validating and improving hydrological models and prognostic flood forecasts using Sentinel-1 based real time flood maps in combination with the national elevation model.

How are satellite data applied?

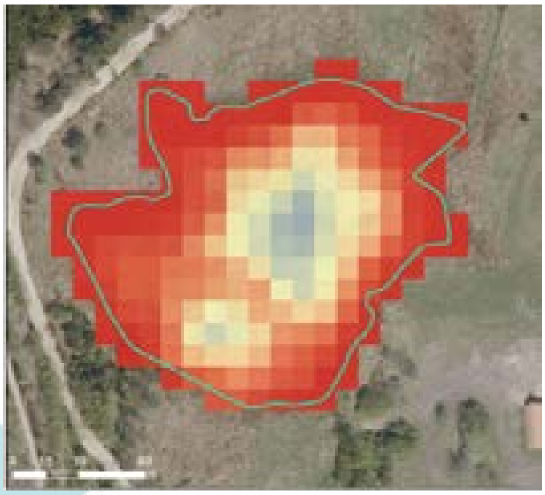
Copernicus provides data for both lake and flood mapping.

Flood mapping and modelling / Sentinel1 (S1): The application of S1-data is not limited by cloud cover. This makes these data very valuable as event data for floods during overcast weather which is typical for ”extreme-wet-events”.

S1-data can be acquired in 10 m resolution before, during and after the flood event. Flood maps can be used as snapshot views of exposed areas and compared with hydrological model simulations. The combination of Sentinel flood maps and hydrological modelling is particularly useful if the satellite acquisition time does not correspond to the time of peak flooding.

Temporary lakes / Sentinel2 (S2): S2-data are optical data and therefore applicable during cloud-free weather conditions. Cloud-free S2 data can be composited over a period (weeks, months, etc.) to give cloud-free national scale dataset.

Using composite data, different indices can be cal-



Mapping seasonally varying lake using Sentinel 2. © DHI GRAS.

culated. This includes the NDWI which is related to the wetness of land surfaces and highly sensitive to open water. Using time series analysis of NDWI, the fractional water cover of each pixel is mapped. The water fractions give information about the wetness of pixels during a certain period, e.g. a year. The results are classified in terms of "wetness classes", e.g. open land, meadow or moist grass. Using "ground-truth-data", the wetness classes are related to land cover types and upscaled to national level to identify permanent and temporary lakes.

NDWI is calculated using the near-infrared and green spectral band of S2-data in 10 m resolution.

SDFE has completed two projects in collaboration with DHI-GRAS to assess the potential of Sentinel-1 and Sentinel-2 for mapping floods and seasonal lakes in Denmark.

Benefits to Citizens

SDFE can use these results to assess whether a lake is completely dry in periods and therefore should be deleted from the lake database, or whether the wetness class suggests that the lake should be reclassified as meadow or other wet land surface types. Changes in the spatial extent of wet areas can also be mapped.

SDFE can use the same wetness classes to map areas that are flooded over shorter periods due to storm surges, cloudburst or high groundwater levels. For this purpose, it is also possible to use S1-data, as described above.

Perspectives and possibilities

SDFE expects that the methods also can be applied to map the dynamics of coastlines in tidal areas. This is particularly relevant in areas where tidal water fluctuates by more than 10 meters. Another perspective is to use Sentinel-1 and Sentinel-2 data in combination with SDFE's elevation model to map flooded areas.

Mapping of floods from Sentinel 1 data. Odense Å december 2015 © DHI GRAS.

Monitoring and Mapping Flooding Events from Space

Testing satellite-based approaches to map and monitor flood extent as a tool to verify the accuracy of flood models.

N.G. Hansted [A], N. Balbarini [A], H. G. Muller [A], L. Færch [B], P. Landsfeldt [C], M. B. Butts [D]

A: DHI A/S B: DHI GRAS C: Vejle Municipality D: Danish Meteorological Institute

The challenge

Flooding is a challenge in many parts of Denmark, and it is a challenge that is expected to grow in a changing future climate. A quick way to assess flood extent is therefore essential for emergency services, insurance cases, etc.

Together with the Danish Environmental Protection Agency, DHI GRAS has developed a simple, data-driven flood mapping method. The method is based on water level data, cross-sections, and an elevation model and does not require complex modelling. The objective is to use the method with forecasted water levels, thus being able to predict future flood extents. The method was applied and tested in the Vejle Å basin. In order to verify the accuracy of the model, data about the extent of historical flooding events was needed.

It is a general challenge in flood mapping that traditionally modelled extents are compared with photographs. Aerial photos from planes or drones provide the most detailed, correct, and easily interpretable information but are rarely available at the time of the flooding. Photos taken from the ground are more readily available but normally lack a large, 2-D extent and thus only provide information about parts of the flooded area.

The space-based solution

Satellite images can contribute to fill this gap in the data as there is an image available almost every day, and they can provide a 2-D image with a large footprint and an adequate spatial resolution.

In this project, Sentinel-1 data was used to map the extent of previous flooding events around the Vejle Å basin to verify the flood mapping method. The extent of historic flooding events was mapped through a machine learning algorithm that determined the threshold between water and non-water on the basis of known land and water pixels. The results were subsequently postprocessed with a Height Above Nearest Drainage (HAND) model to remove water from hill tops, etc.

> **Flood models provide critical tools to inform flood management and flood mitigation processes, and satellite data provides a good opportunity to improve the accuracy and performance of flood models.**
>
> *Peter Kaarup, Danish Environmental Protection Agency*

Benefits to citizens

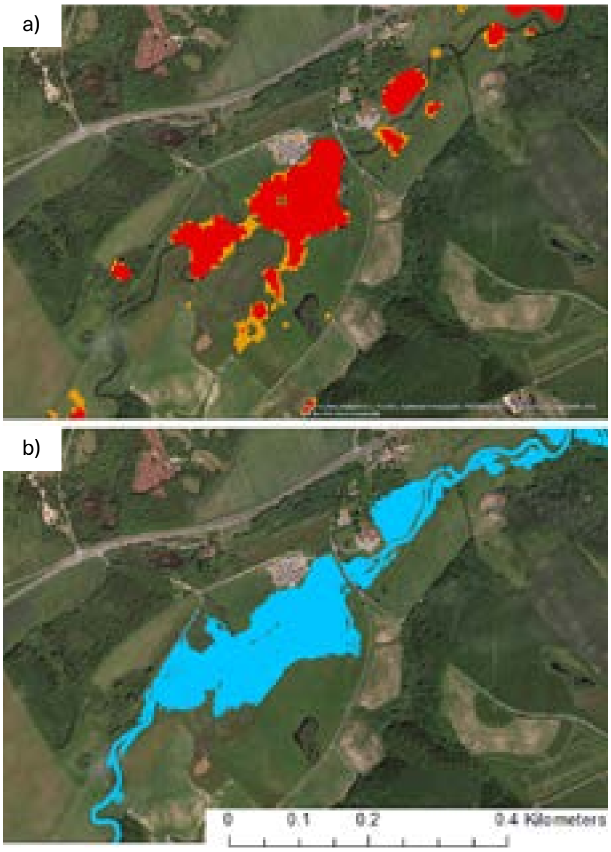
There is generally a lack of data to verify flood mapping models, especially for Danish floods where the response time is short and the flood extent changes quickly. Therefore, it is necessary to use methods that are not affected by meteorological conditions, such as cloud cover. This is where satellite-based SAR images have an advantage, as

Photo of flooding at Haraldskær which is also apparent in the satellite image and modelled flood extent. © Paul Landsfeldt, Vejle Municipality.

they are not affected by clouds. This makes it possible to map the flood extent immediately, without having to wait for clear skies. Satellite-based flood mapping thus provides critical input that can be used to improve flood models, thus improving the ability of authorities to reach to flooding events and mitigate impacts.

Outlook to the future

The high frequency and high-resolution data provided by the Sentinel satellites is a game changer for satellite-based flood mapping, and future development of deep learning approaches to automate workflows will provide potential for near-real time operational flood mapping. This will be useful for verifying modelled flood extents, not only from the simple method developed here but also from more complex hydrological methods.



a) Flood extent from satellite and
b) modelled flood extent on 17-03-2019

Utilizing Sentinel-2 data for the Evaluation of Coastal Development

The seasonal fluctuations in coastal morphology are often challenging to document from traditional data. Satellite imagery can be utilized for description and quantification of these fluctuations while increasing the temporal resolution of data.

Henrik Vinge Karlsson [A], Carlo Sørensen [A]

A: Danish Coastal Authority

The challenge

The coasts are dynamic, and changes occur within days, months, seasons and years. A storm can change the outline of yesterday's coastline overnight.

The quantification of changes is often based on yearly measurements, orthophotos, inspections, etc. A challenge remains in the lack of data in high temporal resolution.

Modern measurement methods from airplane, UAVs, total stations, etc. allow for monitoring of coastal stretches in both high temporal and spatial resolution, but data is rarely available or only budgeted a few times a year.

Sentinel-2 data provides alongshore information. Despite a coarse resolution, the satellite imagery can fill voids where no other data exists, or supplement existing data for validation.

The space-based solution

In the analysis of beach nourishment at Nørlev beach in northern Denmark, a primary goal was to gain a holistic understanding of the coastal variations. The alongshore migration of the bar system was of special interest, and since profile measurements are only conducted every 4th year with a 1000 m spacing, satellite imagery proved valuable.

The alongshore migration of bars was quantified as shown in Figure 1. These changes could not have been detected in the yearly orthophotos, but the sentinel data increased the temporal resolution of data, and large variations could be documented over shorter periods. Short-term changes in the beach width were also determined. Thereby it became clear that the width of the beach on multiple occasions corresponded well with undulations in the bar system.

> **"The many spectral bands from Sentinel-2 allow for a wide range of utilizations in evaluations of the coastal variation.**
>
> *Per Sørensen, Head of Coastal Research, Danish Coastal Authority*

This simple approach was utilized in documenting changes before, during and after a storm in December 2016 – see Figure 2. Satellite imagery, in combination with UAV imagery, water level and wave data, profile measurements and yearly orthophotos, was used to document the coastal variations and the diffusion of beach nourishment. Sentinel-2 data was also used as supplement to local profile measurements from 17th of January 2017, which is the day after the last satellite image in Figure 2.

Figure 1. Bar migration documented on the basis of Sentinel-2 RGB imagery at Skallerup and Nørlev beach in Northern Jutland.

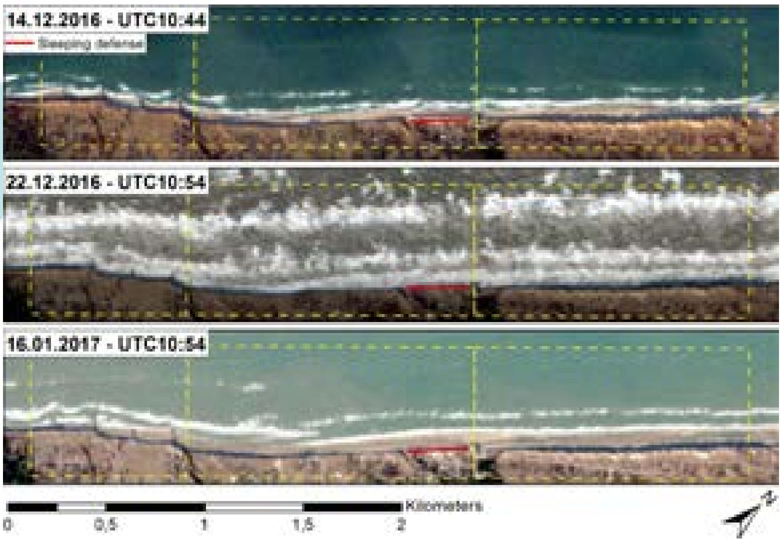


Figure 2. Coastal variations before, during and after the December storm of 2016.

Benefits to citizens

The data is freely available from the Copernicus Open Access Hub and can be imported into a GIS. The composition of imagery from the many band-widths can be managed from a pre-scripted tool in ArcMap or from an integrated tool in ArcGIS Pro. A more simplistic approach is to only download the True Colour Image (TCI) which is a ready-to-use RBG-composite available for sentinel-2 data. Geo-referencing is not necessary as satellite imagery is pre-set to the datum which it represents. By simple means it is possible to utilize the available data in e.g. coastal analyses, weather and acquisition time permitting. The methods are very simplistic and easy to handle on multiple professional and institutional levels.

Outlook to the future

The utilization of Sentinel-2 data in coastal studies is not limited to the description of morphological changes but may also be utilized for quantification in other respects. The many spectral bands of Sentinel-2 make for a wide range of usages.

The near infrared band can be used in NDVI analysis for determination of density and spread of vegetation in dunes (Bruijns, A.J., 2018). The shoreline position could also be analysed with relative certainty (Hagenaars et al, 2017). Automating import and composition of sensing data can contribute when analysing the fluctuations of the coast in time.

Mapping of bathymetries with sentinel data could further improve analysis in the coastal zone. Despite the coarse spatial resolution, the temporal resolution allows for visualization of morphological variations in time, which could be utilized in the analysis of e.g. the bar systems on the North Sea coast of Denmark or, potentially, morphological features at tide dominated coasts.

References and partners

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The work is supported by EU Interreg-project Building with Nature.

Satellite-based Monitoring of Coastal Dynamics

The Sentinel missions offer unprecedented potential for monitoring coastal dynamics and geomorphological changes in the coastal zone.

Mikkel Lydholm Rasmussen [A], Lisbeth Tangaa Nielsen [A], Carlo Sass Sørensen [B]

A: DHI GRAS B: Danish Coastal Authority

The challenge

Rapid changes in the coastal zone, such as storm erosion and accretion rates in the tens of meters per year, cause major challenges for governmental authorities, municipalities, and land owners alike. The lack of up-to-date data means that forecasting and prediction of future coastal changes are based on historical information. While surveys are fundamental for understanding and predicting changes in coastal environments, traditional methods are costly and slow, causing inadequately updated information capable of dealing with the variability and trends on e.g. seasonal scales needed to fully understand these dynamic environments.

The space-based solution

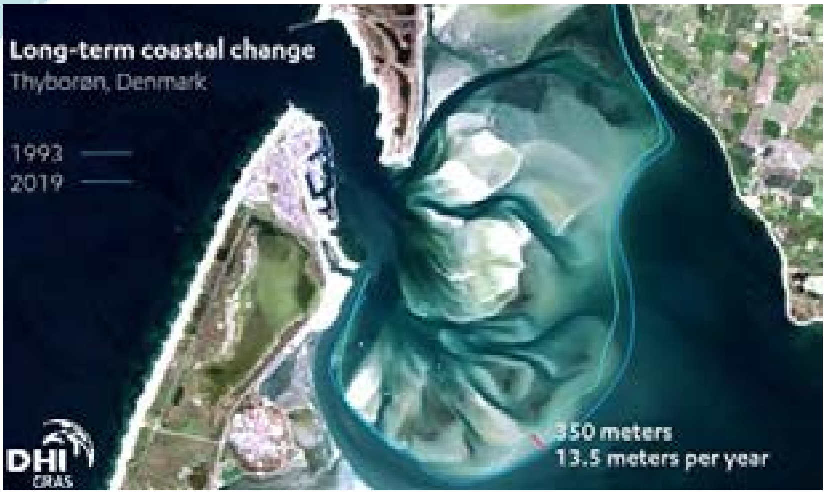
By leveraging the high revisit frequency of Copernicus earth observation data, particularly those of the Sentinel-1 and Sentinel-2 missions, frequent assessments of the status of the coastal environment can be performed, providing up-to-date information on topics such as erosion of exposed coastlines and changes to marine habitats. Through automatic processing of all newly acquired Sentinel-2 imagery, the effect of erosion mitigation strategies such as beach nourishments or newly constructed breakwaters can be monitored and evaluated. Additionally, by processing the historical archives of satellite imagery a solid baseline can be established to serve as a consistent and reliable basis for long-term forecasting, evaluation, and planning of mitigations and impact monitoring of coastal management choices. The coastline and beach width are accurately mapped in each acquired image by combining observations from the optical and near-infrared bands with indices and windowed statistical calculations employing machine-learning methods. The mapped coastline is then compared to harmonics-based tidal data to account for the variability in instantaneous water levels caused by the tidal cycle.

> **Accurate and continuously updated earth observation satellite data provided by the Copernicus missions serve to advance and to detail our understanding of coastal changes e.g. in relation to storm erosion, and provide for optimized coastal protection measures and enhanced environmental monitoring.**
>
> *Carlo Sørensen, Senior Advisor, Danish Coastal Authority*

Benefits to citizens

Accurate and up-to-date information on coastal dynamics provides the governmental authority and municipalities with the data they need to accurately plan and assess the impacts of previous erosion mitigation and climate adaptation initiatives. This leads to more efficient and effective erosion coun-

Coastline development at Port Fourchon, Louisiana, between February and October 2019.



Satellite based monitoring of long-term coastal change around Thyborøn, Denmark.

termeasures, where such are applied, and more accurate modelling and forecasting in areas where the environmental protection frameworks entail that the coast develops naturally. By using satellite imagery to provide a map along the entirety of the exposed coastline, instead of only isolated transects based on in-situ measurements, no area is left unassessed. This greatly increases certainty and a holistic understanding of which areas are experiencing erosion or accretion. This can also facilitate the identification of potential new sites for sourcing sand for beach nourishments or even as sources of raw materials for concrete production.

Outlook to the future

DHI GRAS will continue to improve on the accuracy of the automated assessment of erosion and accretion rates, while also looking into enhancing the user-interface to facilitate a wider adoption of the developed tool chain. By making it as user friendly as possible, it becomes possible for individual coastal modellers and interested citizens to access up-to-date and state-of-the-art data on coastal dynamics anywhere in the world. This widespread access to information will make it possible to effectively utilize the global nature of the Copernicus data and open up for an increased understanding of the coastal environments in data sparse regions.

Acknowledgements

The authors would like to thank the Danish Coastal Authority for providing transect data and the Danish government for providing financial support for development of tools for data-based marine and coastal management.

Measuring Water Depths in Shallow Water Areas using Satellite Imagery

Using state-of-the-art physical based modelling and advanced satellite image analysis to derive high quality bathymetry data at low cost.

Mikkel Lydholm Rasmussen [A], Lisbeth Tangaa Nielsen [A]

A: DHI GRAS

The challenge

High-resolution bathymetric data is a key requirement for managing coastal environments, planning and constructing of marine structures and is also used in modelling efforts aimed at quantifying the effects of extreme weather and climate change. While traditional survey methods provide water depths in detail, these observations are confined in space and rarely repeated due to the high cost of such measuring campaigns. Additionally, the very near coastal zones remain a challenge to survey by boat, leaving many such areas unsurveyed.

The space-based solution

Satellite-derived bathymetry techniques are able to retrieve water depths in shallow water areas using multispectral satellite imagery through the use of physically based models of the optical properties of the water column and seafloor. This allows for cost efficient mapping of water depths over large areas.

By matching the measured reflectances of incoming sunlight from the seafloor obtained from satellites with simulated reflectance, the water depth can be estimated along with water quality parameters and sea floor albedo. Utilizing the high revisit frequency of the Sentinel-2 constellation, imagery with the best environmental and metocean conditions at the time of image acquisition, critical for the satellite-derived bathymetry estimates, can be identified and applied for the analysis. With the continuously growing archive of satellite imagery, satellite-derived bathymetry can be used to analyse the current state, and the dynamics, of the near coastal zone on seasonal time scales.

Uncalibrated satellite-derived bathymetry for shallow water areas near Tauranga, New Zealand.

Benefit to the citizens

While lacking the precision of the physical observation campaigns, satellite-derived bathymetry can provide bathymetric depths covering large

Satellite-derived bathymetry for the area surrounding Anholt produced to supplement a multibeam survey.

areas, bridging the gap between the coastline and traditional surveys in shallow waters and providing a spatial context in areas surveyed by boat. This makes satellite-derived bathymetry an ideal complement for traditional survey campaigns, both in the planning stage by identifying the most critical areas needing observation and by providing a spatial coverage in a much larger area than what can be covered by a physical campaign.

> **Satellite based bathymetry (Sentinel-2) has improved the bathymetric description of 60 Danish water bodies and the quality of mechanistic ecosystem models used for environmental management.**
>
> *Danish Environmental Protection Agency, Ministry of Environment and Food of Denmark*

Additionally, satellite-derived bathymetry allows for identifying and mapping shallow water features in remote areas where the cost and hazards of traditional survey methods are prohibitive, such as in the Arctic. This region, which is currently experiencing increased marine traffic, has many areas which are unsurveyed or very data sparse. Satellite-derived bathymetry is a cost-efficient method for providing bathymetric information in this region that is needed in order to efficiently manage and protect the Arctic coastal zone.

Outlook to the future

DHI GRAS will continue to improve the satellite-derived bathymetry products and expand the database of high-resolution bathymetry in the coastal zone by including different satellite observations and improving the processing methodology. Combining the new generation of satellite laser altimetry with the satellite derived bathymetry has the potential to decrease the need for calibration data obtained from physical campaigns, especially in large remote areas with little or outdated information, thereby increasing its accuracy.

Acknowledgements

We thank the European Commission and the European Space Agency for providing free access to Sentinel-2 data through the Copernicus Open Access Hub.

Mapping Submerged Aquatic Vegetation from Space

Artificial intelligence and high-resolution satellite imagery are game changers for maritime surveying, providing synoptic insight on submerged aquatic vegetation.

Mads Christensen [A], Lotte Nyborg [A]

A: DHI GRAS

The challenge

Traditionally, monitoring of submerged aquatic vegetation is based on highly detailed diver transects in a limited number of locations repeated every year. While providing a detailed breakdown of species distribution along those transects, the approach is expensive, and it misses large-scale spatial patterns. Furthermore, it is subject to large uncertainty due to the mobility of vegetation between years.

While interpretation of aerial and drone photos provides one means to map and monitor submerged vegetation over larger areas, the photos till do not provide large-scale synoptic overviews covering larger areas.

Access to maps of underwater vegetation covering larger regions and even entire countries provides unique and valuable insights into the marine environment and the dynamics affecting it.

The space-based solution

The Sentinel missions under ESA's Copernicus programme provide a continuous monitoring framework offering high temporal data coverage in high resolution, covering countries and continents on a weekly basis. The Sentinel satellites deliver impactful data that can be used to map and monitor submerged aquatic vegetation covering large areas, and long-term time-series of Sentinel-2 data is an ideal vantage point for assessing spatio-temporal dynamics of underwater vegetation over large areas.

By combining Sentinel-2 satellite data, novel machine-learning techniques and advanced data processing, DHI GRAS has created the first-ever national overview of the spatial distribution of shallow-water submerged aquatic vegetation in Denmark.

> **Seabed vegetation is one of the most important marine habitats in coastal water ecosystems. However, the spatial distribution has until now been relatively limited. I expect Sentinel data to be a game changer in the assessment of spatial coverage for future marine management and as input to environmental impact assessments.**
>
> *Anders Eriksen, DHI*

Using hand selected training data points derived from orthophotos and atmospherically corrected Sentinel-2 mosaics covering all Danish territorial

Satellite-derived mapping of submerged aquatic vegetation around the Danish island of Laesoe.

waters, a gradient boosting algorithm was applied to classify underwater vegetation density at national level.

The national mapping provides key insight on the distribution of aquatic vegetation (eelgrass and macroalgae) observed in 2018 and forms an important baseline for evaluation of changes at large to regional scale in the coming years.

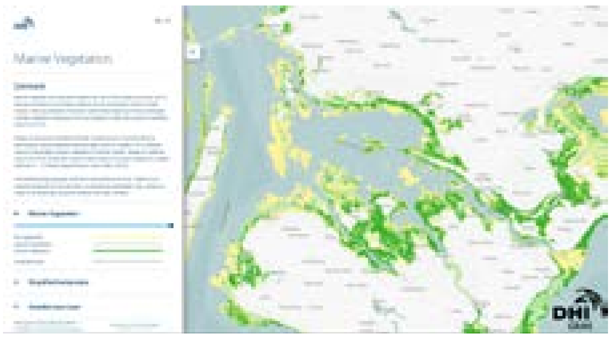
Benefits to citizens

Aquatic vegetation is an overall indicator of ocean and estuary health and a critical component of marine ecosystems, providing important ecosystem services, including habitat for invertebrates and fish.

However, effective environmental impact assessments and marine management policies have been hampered by lacking data and information on the extent and dynamics of aquatic vegetation. Satellite- based solutions to map and monitor the distribution of underwater vegetation dynamics in shallow water areas provide a cost-effective and efficient tool for consistent synoptic monitoring of large areas. By delivering key insight on vegetation status and trends. The mapping provides a critical tool, enabling management authorities and decision-makers to make more effective decisions towards protecting and managing marine environments and resources.

Outlook to the future

The national map of submerged aquatic vegetation in Denmark provides an important baseline on the current status of vegetation density in Danish territorial waters. With an established methodology in place, future efforts will aim to further advance the baseline by making continuous assessments on year-to-year and intra annual variations in vegetation cover at national level. This will provide further insight on vegetation growth rates, seasonality patterns and impact of extreme events and climate change on vegetation health and coverage.



The satellite-derived national level dataset on submerged aquatic vegetation in Denmark *http://satlas.dk/marine-vegetation/dk/.*

Acknowledgements

This activity was made possible by a generous grant from the VELUX Foundation as part of their Environment and Sustainability activities.

Copernicus Maritime Surveillance Helps Denmark Battle Illegal Activities

Denmark uses several tools from the Copernicus toolbox. Among other things, the satellite images make it easier to catch those who illegally release oil into the oceans.

Lise Høiriis, Royal Danish Navy

Denmark finds the Copernicus Maritime Surveillance Service to be of great use when surveilling the Danish waters, especially focusing on the protection of nature, search and rescue missions and enforcement of Danish sovereignty and Danish law in relation to, for example, cross-border illegal activities. The Danish Navy Command – a part of the Danish Defence – is the point of contact when it comes to Copernicus Maritime Surveillance. In other words, they are responsible for providing information to other national authorities about the options offered to Denmark as well as assisting in gaining access to the information that these options present.

Maritime surveillance is multifaceted and uses both coastal radars and lookouts as well as Automatic Identification System, AIS. AIS is a system which makes it possible to identify ships that exceed a certain size. It is based on the VHF band and enables ships to exchange information in order to make navigation easier and to avoid collisions. For instance, the AIS transmits the positions of the ships, and the EU member states are obliged to collect this data. AIS can be used in cases of emergency, enabling the emergency services to gain a rapid overview of the situation. The AIS system shows the positions of nearby ships in case they need to be redirected from their current course to the distressed vessel in order to assist.

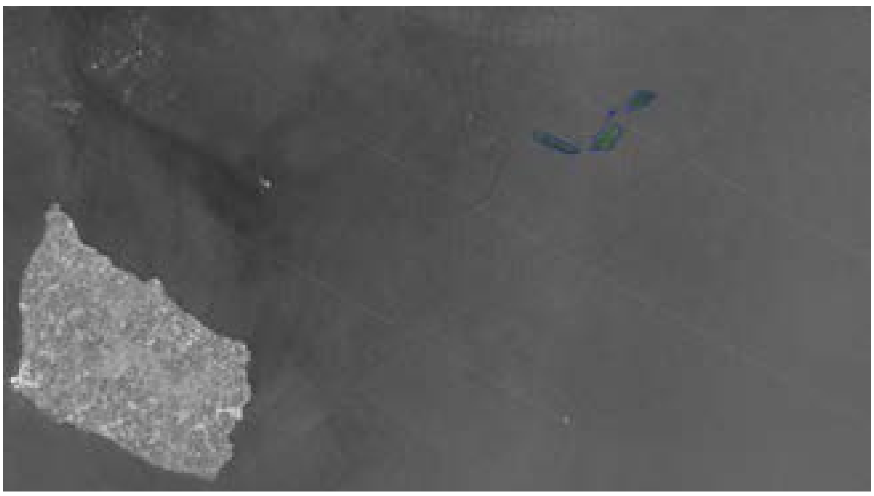


Image of an oil spill east of the Danish island of Bornholm

An optical image of a yacht and its wake west of the Danish island of Fanø

The satellite AIS data from Copernicus is also used to track ship routes if necessary. For instance, to localize a ship which is out of range of the land-based AIS, in case of oil spills or in man-over-board situations.

Can detect oil spills

The satellites used in the Copernicus Maritime Surveillance can also produce two types of images. The first type is an optic satellite image. It looks very much like a real photograph in a relatively high resolution. It is rarely of use in Denmark, however, since it only works when there are no clouds – and only during daytime.

The other type is called SAR – Synthetic Aperture Radar (not to be confused with "Search And Rescue", also abbreviated SAR). Using this, the satellites use a radar to build images that reflect the surface of the sea. Unlike the optic satellite image, the SAR is not dependent of daylight or clear visibility to work.

Since the satellite images usually cover the waters of both Denmark and neighboring countries, the EU countries have access to each other's data. Member states can also share this data actively.

This type of maritime surveillance is a part of the EU co-operative service called CleanSeaNet. These SAR-satellite images may indicate oil spills. However, the images also show changes in the sea surface which are not necessarily oil slicks. For example, large quantities of pollen from plants on the sea surface will also show on the image and may have the same visual characteristic as an oil spill. Therefore, it is always necessary to have suspected oil spills confirmed by a second source.

If there has been an actual, illegal oil spill performed by a ship or an oilrig, the relevant authorities will intervene to collect evidence and identify and charge those responsible.

Wind Farm Construction on Land

Satellite-based data layers can ease estimations of the annual energy production for potential wind farms on land. A reduction of uncertainties would reduce the financing cost of wind farms.

Merete Badger [A], Ebba Dellwik [A], Rogier Floors [A], Charlotte Hasager [A], Henning Skriver [A], Jan E. Balling [A], Morten Thøgersen [B], Torsten Bondo [C], Kenneth Grogan [C]

A: Technical University of Denmark B: EMD International C: DHI GRAS

The challenge

Hundreds of site assessment analyses are carried out daily by wind energy and consultancy companies in Denmark alone. The purpose of such analyses is to estimate the wind resource at a given location and investigate the feasibility of wind farm construction.

Site assessment today is a rather manual process that involves digitalization or thorough quality control of background maps. Alternatively, all-purpose global data sets are used even though their temporal and spatial resolution is coarse. This shortcoming makes it difficult to characterize the land surface precisely.

> **"The wind energy industry - turbine manufacturers, developers, investors - strives for every half-a-percent reduction in the uncertainty in annual energy production estimation, as it could lead to M. of euro financing cost reduction, depending on the size of the project.**
>
> *Yavor V. Hristov, Vestas*

Land cover classification followed by assignment of aerodynamic roughness lengths, which flow models for wind energy can utilize, represents a highly qualitative approach. It can lead to uncertainties and inconsistencies depending on the site and the specialist undertaking the analysis.

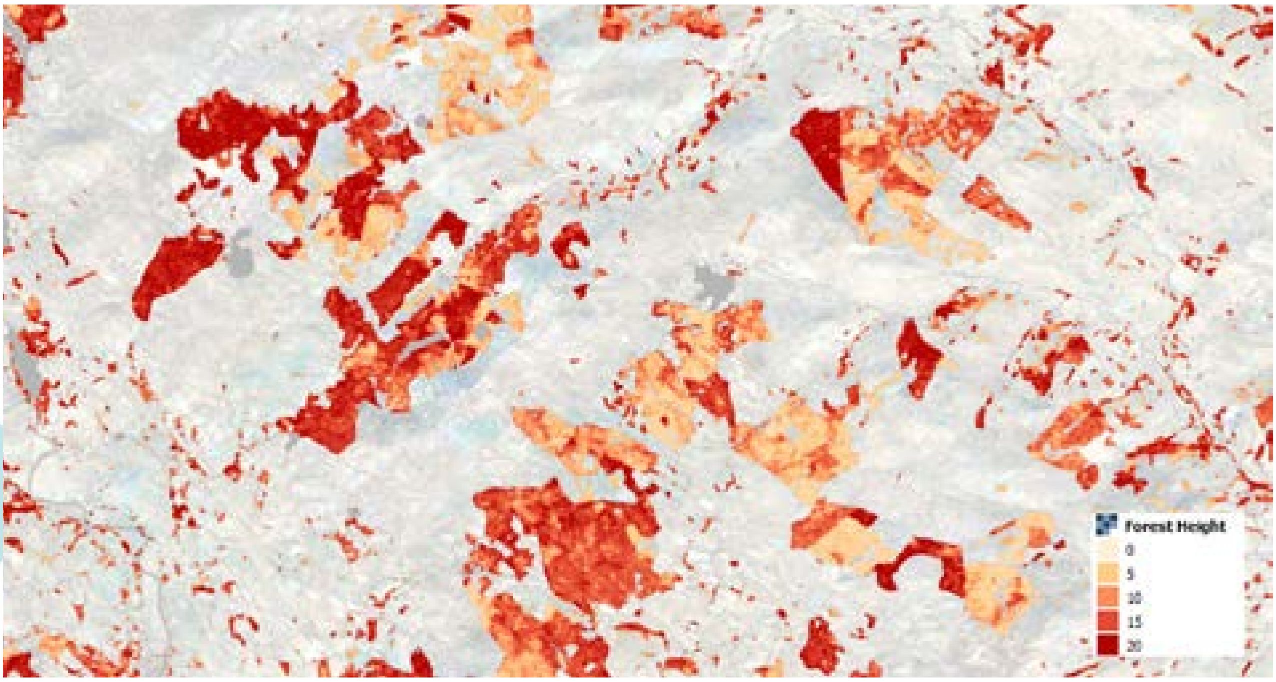
Researchers and specialists from the wind energy industry work together in the InnoWind project to automate procedures for site assessment by offering more and better data layers based on new generations of Earth Observation data from Copernicus.

The space-based solution

Raw satellite data from Sentinel-1 and Sentinel-2 forms the basis of a completely new product: a data package containing leaf area indices, land cover, and forest heights. Together, these parameters enable a new approach for modelling of wind resources over forests where the vegetation is characterized in physical terms as an alternative to the indirect roughness classification approach.

The development of novel tree height maps is a new and innovative achievement. Coherence of Synthetic Aperture Radar observations over time turns out to be correlated with the forest height. The forest height, in turn, plays an important role for the wind resource and thus for estimation of the annual energy production of a given wind turbine.

Analyses of 10 sites around the world indicate that there is a large potential for improving the accuracy of wind resource modelling through physical parameterization of the land surface. This would be extremely valuable for the wind energy industry.



Forest height map over a site in Scotland retrieved from Sentinel-1 and -2 observations delivered by Copernicus.

Benefits to citizens

The development of satellite-based products tailored to the wind energy industry has already created value. More than 40 new data layers from Copernicus and other data providers are now integrated in the portfolio of online data available to users of the wind prospecting tool WindPRO. These new products are used by more than 1500 software users.

Outlook to the future

The novel data layers, which InnoWind has delivered, indicate a grand potential for exploitation of Earth Observation data for more precise mapping of wind resources all around the globe.

Initiatives like The Global Wind Atlas and the New European Wind Atlas can benefit from such data layers as soon as their coverage is expanded to the global scale. At the national and regional scale, or for individual sites, there is a business potential in delivering tailor-made maps as 'Premium products' to users of flow modelling tools for wind energy applications.

High-resolution satellite data from Copernicus is used to estimate the annual energy production. Here for a site in Sweden.

Acknowledgements

InnoWind has received funding from Innovation Fund Denmark and the following partners participate:

- Technical University of Denmark
- EMD International
- DHI GRAS
- Vestas
- Vattenfall

Offshore Wind Farm Planning from Space

Satellite ocean wind products are used to assess the wind resource and estimate the potential electricity production worldwide for sustainable energy transition.

Charlotte Hasager [A], Merete Badger [A], Ioanna Karagali [A]

A: Department of Wind Energy

The challenge

Offshore wind energy gives consumers green electricity. The challenge is to plan in an optimal way wind farms offshore in Europe, Asia and North America.

Offshore wind data is very limited. Satellites have global coverage. Radars on board satellites view the Earth in all weather conditions, day and night, and can provide maps of wind speed and wind direction.

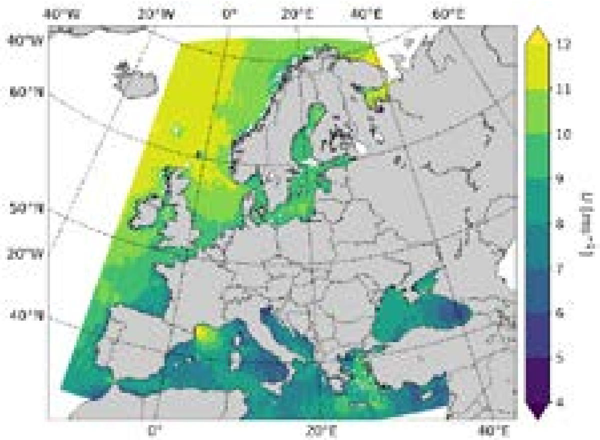
Satellite wind maps are treated in software to produce wind resource statistics. Wind resource data is key input in the planning phase of offshore wind farms to identify windy places suitable for wind turbines.

The expected energy production depends on the wind speed to the third power. In other words, it is necessary to know the wind as accurately as possible.

The space-based solution

The Copernicus Sentinel-1 satellites with Synthetic Aperture Radars on board are uniquely suited for very detailed wind speed mapping. It is possible to map the ocean winds at 1 km by 1 km resolution.

Offshore wind farms typically cover from 30 km² to more than 100 km². The land influences the winds offshore, and therefore the wind resource varies across each wind farm area. It is important to include such detail in the planning to estimate the production of each wind turbine.



European offshore wind atlas from Envisat ASAR and Sentinel-1 entire archives from 2002 to 2018. Mean wind speed at 100 m height. Source: DTU Wind Energy.

> **Satellite wind maps are giving us important insights into how much the wind speed varies over large areas and how the wind farms influence each other through wakes.**
>
> *Nicolai Gayle Nygaard, Ørsted*

Wind farm wake at Horns Rev 1 offshore wind farm in the Danish North Sea. Source: Vattenfall.

Radar images for Europe and selected other sites globally are received daily at DTU Wind Energy. The radar images are calibrated, and a wind retrieval algorithm is applied. The near-real-time wind maps are produced and offered free of charge. More than 200,000 scenes are available at the database https://satwinds.windenergy.dtu.dk/.

Benefits to citizens

The benefits to citizens of clean energy include:

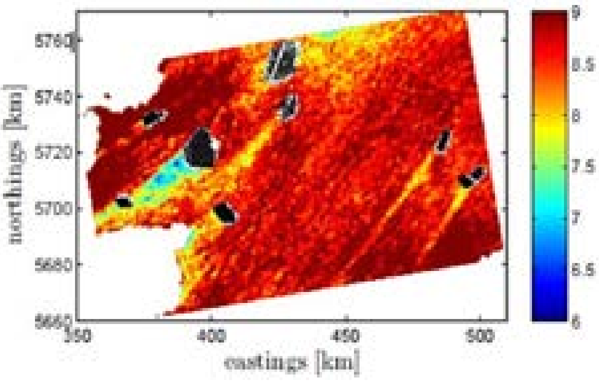
1. Firstly, offshore wind is an abundant resource.
2. Secondly, wind energy is sustainable energy with great potential to support United Nations Development Goal on Energy.
3. Thirdly, offshore wind energy is cost competitive.
4. Fourthly, high- and low-tech jobs are available within the offshore wind industry in coming years, often in less favorable regions giving better life conditions.

The benefit of clean energy from offshore wind turbines is a key driver for modern societies with need for electricity. Electricity at cost-competitive price and its secure delivery, from local to regional areas, are part of the green solution.

European world-leading knowledge is expected to introduce cost-competitive solutions worldwide based on Copernicus data within offshore wind energy.

Outlook to the future

Offshore wind energy is expected to deliver clean energy in the future energy system across the world. Satellite remote sensing will be used for planning and operations to optimize siting, production, operation and maintenance. Sentinel-1 of the Copernicus programme will be essential in coming years.



Wind farm wakes observed by satellite radar in Belgium and UK North Sea. The black colour indicates wind farms. Lower winds southwest of each wind farm are the wake (lee effect). The wind is blowing from the northeast. Wind speed in m/s. Source: DTU Wind Energy.

Acknowledgements

Copernicus Sentinel-1 scenes. Funding for the New European Wind Atlas ERANET+ project and the EU H2020 e-shape project. Wind retrieval SAROPS software from JHU APL and NOAA.

Greenland Uses

Landslide Screening in Greenland

Detailed measurements of land deformation from Sentinel-1 SAR data are an essential tool for assessing the risk of landslides in Greenland.

Anne Munck Solgaard [A], Sara Salehi [A], Marie Keiding [A], Kristian Svennevig [A], John Merryman Boncori [B]

A: Geological Survey of Denmark and Greenland B: DTU Space, Technical University of Denmark

The challenge

On June 17th, 2017 the village of Nuugaatsiaq in West Greenland was hit by a tsunami generated by a landslide in Karratfjord. A large part of the village was destroyed, and four people lost their lives. The disaster made it clear that there is a need to know where there is a risk of future landslides in Greenland of a size that could cause new tsunami accidents.

Due to the size of Greenland and the fact that it is difficult and expensive to get around, it is not possible to visit all mountainsides to determine whether they pose a risk. Instead, satellite data combined with knowledge of the geology can be used to investigate which locations are at risk.

The space-based solution

ESA's two Sentinel-1 satellites are used to measure surface deformation – such as slow-moving rock masses down a mountainside. New satellite radar data covering Greenland's coastal areas is continuously recorded and is freely available, making it ideal for monitoring large and deserted areas. Deformation can be measured either by comparing data from two different times or by comparing whole time series of satellite data.

In addition, Sentinel-1 data has the advantage that clouds or the polar night does not limit its use, as is the case for optical images.

Optical images from the Sentinel-2 satellites are recorded several times a week over Greenland. The resolution of the images makes them unsuitable for detailed mapping, but landslide activity, such as deformation of larger slopes or rockfalls on snow, is clearly visible.

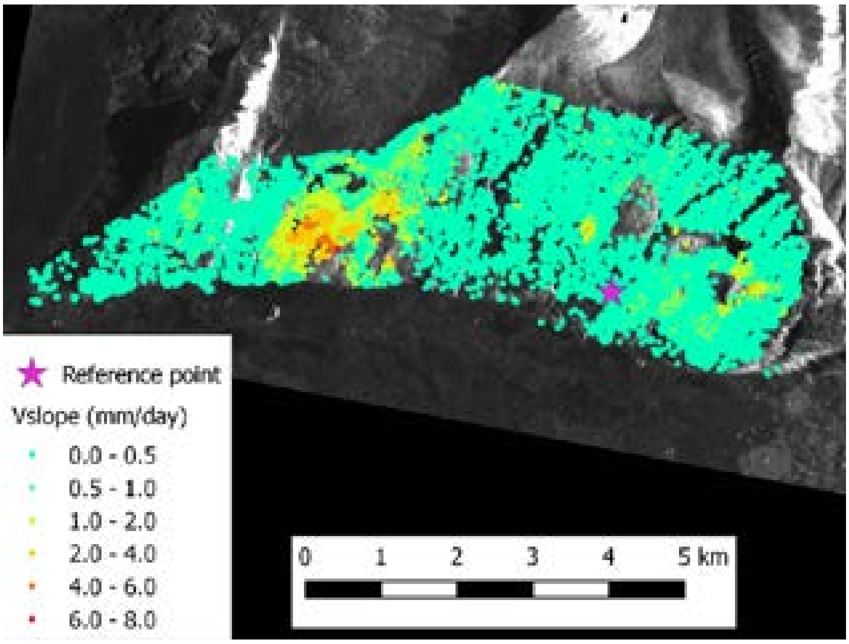
Benefits to citizens

The combination of deformation from Sentinel-1 and optical images provides important and rapid information to evaluate the stability of a mountainside. This knowledge can be used to refine and define which areas to visit and study further. This saves time and money.

In the case of a landslide, satellite data can help provide an initial overview of the event. In addition, time series of data make it possible to investigate the development of the area prior to a landslide.

Larger landslides are also detected by seismographs measuring ground motion. Here, you can take advantage of the fact that different types of data offer different benefits. Seismic measurements can determine the time of an incident accurately but not the exact location, while the opposite is the case for the satellite observations.

The figures show examples of the applied data: a map of displacement rates based on Sentinel 1 data and an optical image from Sentinel 2. The



An example of average deformational speeds of a slope in Karratfjord between June and October 2018.

color of the dots on the velocity map indicates how fast the slope is deforming. The figure with the optical image shows how an area with a previous landslide (marked in red) is still active (falling rocks color the snow brown).

Optical images can provide overview of larger areas and proved basis for mapping of geological structures.

Outlook to the future

When dealing with areas as large and sparsely populated as Greenland, we need satellite data as an important source of overview. In addition, it provides the possibility to a certain extent to remotely monitor potentially dangerous mountain slopes. In combination with field observations, it is possible to study the geological processes and circumstances that cause slope instability. They are typically different from location to location and very dependent on local geological conditions.

Acknowledgements

This work is carried out in collaboration between the Geological Survey of Denmark and Greenland (GEUS) and the Technical University of Denmark (DTU Space).

Satellite Data for Mapping Remote Regions of the Arctic

Sentinel-2 imagery is used as the base level orthophoto when mapping Greenland. Sentinel-2 data ensures up-to-date and homogenous data, perfectly suited to provide a foundation in the mapping efforts.

Andrew Flatman [A], Mark Falkenberg [A], Niels Johnsen Vinther [A]

A: Agency for Data Supply and Efficiency

The challenge

Having accurate and reliable maps is important; however, in the Arctic, it can mean the difference between life and death. The Agency for Data Supply and Efficiency, being the authority for mapping Greenland, is currently updating and remapping Greenland in its entirety. However, mapping the Arctic is not a trivial task. Mapping more densely populated areas is usually done using aerial imagery, but in remote regions of the Arctic, with many hours flight to even remote settlements, airplanes are not a cost-effective or safe solution. For this purpose, the Agency for Data Supply and Efficiency is using Sentinel-2 satellite imagery that is readily available.

But how does the agency ensure that data is accurate and reliable in this remote and sparsely populated region of Greenland?

The space-based solution

For the new generation of maps of Greenland, satellite data is used. For this, Sentinel-2 data plays a key role in establishing a continuous and homogenous base layer covering Greenland. Using this and supplemental higher resolution satellite data, orthophotos are produced, elevation models are created and vector themes such as lakes, coastlines, and settlements are mapped.

To ensure that data is accurate, Ground Control Points (GCPs) are needed. However, when collecting GCPs some of the same challenges arise as when collecting the satellite imagery i.e. remote areas with little or no infrastructure.

Therefore, to counter this, scientists visiting Greenland were equipped with precision GPS equipment and asked to measure natural GCPs such as large rocks and huts. This, unfortunately, turned out to be problematic. Often rocks and other natural objects are nearly impossible to see even in high-resolution satellite imagery.

> **"The access to freely available Copernicus data is of great benefit to our mapping efforts in Greenland. In addition, having a continuous flow of data ensures that our maps will stay up to date. For future work, we are looking forward to utilising even more bands for new and interesting products.**
>
> *Lola Bahl, Mapping project leader, Agency for Data Supply and Efficiency*

For SDFE it became increasingly clear that a different approach was needed to solve this challenge.

Remapping Greenland with topographic maps, ortho photos and elevation models from satellite imagery

Images taken from a helicopter are image matched to become a 3D model

The solution was to reinvent the classic Ground Control Point as the Ground Control Area – GCA.

Benefits to citizens

For GCAs, new photogrammetric possibilities were utilized. As a supplement to measuring an object on the ground, scientists visiting the area via helicopter photograph the entire area with a GPS- equipped camera. In practice, the helicopter makes two rounds at two different altitudes. With state-of-the-art photogrammetric software, the images are stitched together producing an elevation model and an orthophoto. Combined with the accurately GPS-measured GCP, the elevation model and orthophoto now become a Ground Control Area. The big benefit with this approach is that the GCA can now both visually and mathematically be located in both high- and low-resolution satellite imagery. As an added bonus, since the GCA now also consists of an elevation model, this can also be used directly as a control for elevation models made from e.g. satellite radar or imagery data.

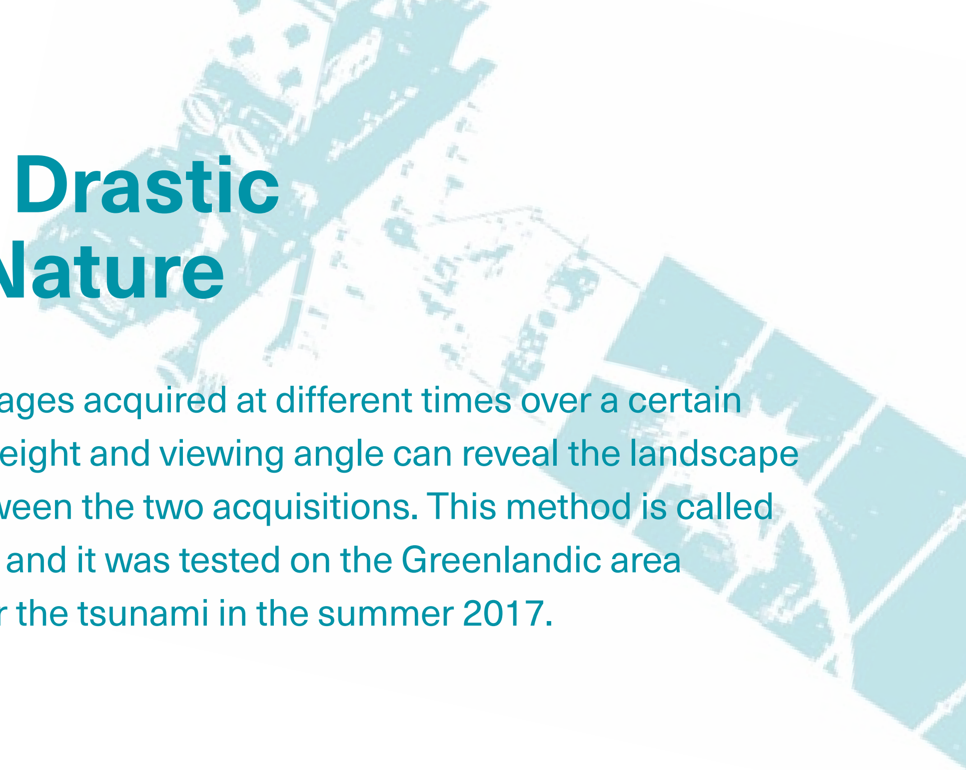
With this new technique, the accuracy of the maps can be controlled in a common way across all the different map products.

Outlook to the future

In the coming years, as Greenland is remapped, more and more GCAs will be measured and become available, making maps of Greenland more accurate and reliable. Measured GCAs will also be made available for the public, making other users of Sentinel satellite data able to check and enhance new datasets.

Acknowledgements

The development of the base layer orthophoto of Greenland is made possible by the Copernicus programme. Work on mutual information co-registration courtesy of Allan Aasbjerg Nielsen, DTU Compute. Close-range photogrammetry acquisition courtesy of Finn Bo Madsen, DTU SPACE.



Detection of Drastic Changes in Nature

A comparison of two SAR images acquired at different times over a certain area from exactly the same height and viewing angle can reveal the landscape changes that took place between the two acquisitions. This method is called Coherent Change Detection, and it was tested on the Greenlandic area Nuugaatsiaq before and after the tsunami in the summer 2017.

Claus Sølvsteen, GeoMETOC (DALO)

The challenge

In many situations, you might want to examine if a change has occurred during a certain time span, and/or where a change has happened and/or how big a given change is. For this purpose, a comparison of satellite images acquired before and after a possible change may be useful, and both satellite images in the optical as well as in the radar frequency spectrum can be used for this type of analysis. Optical images look very much like the world as we see it, but nothing can be seen during night time or by cloud cover. Radar images take some time to adjust to, but can be applied also during night time and during cloud cover. This analysis examines the tsunami in Nuugaatsiaq (Greenland) on June 17, 2017, using three Sentinel-1 radar images, two acquisitions before and one acquisition after the tsunami.

The space-based solution

Three Single Look Complex (SLC) Sentinel-1 images in interferometric mode (IW) have been used. A pairwise ‘coherent change detection’ (CCD) analysis has been applied to the images, and the resulting CCD images show areas with changes in black/dark colours, whereas areas without changes are shown in white/bright colours.

The changes do not necessarily originate from the examined changes (in this case the tsunami). They may also have been caused either by landscape phenomena like newly fallen or melted snow, plants that have grown, etc., or by natural phenomena between the earth and the satellite like atmospheric disturbances, or by differences caused by slightly changed viewing angles from the satellites.

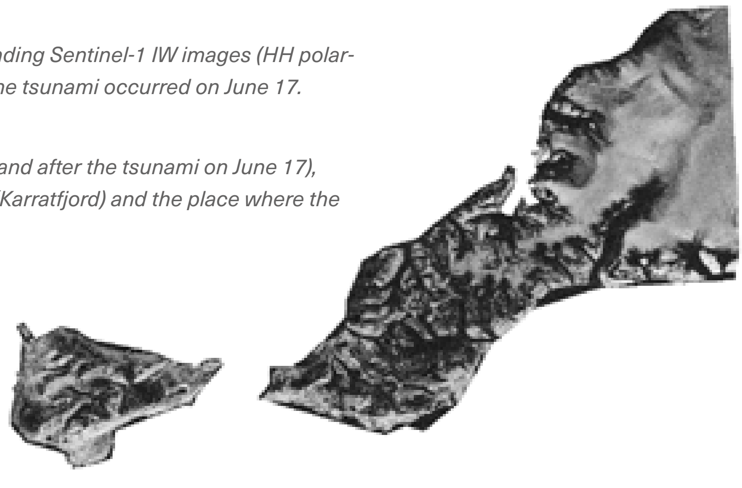


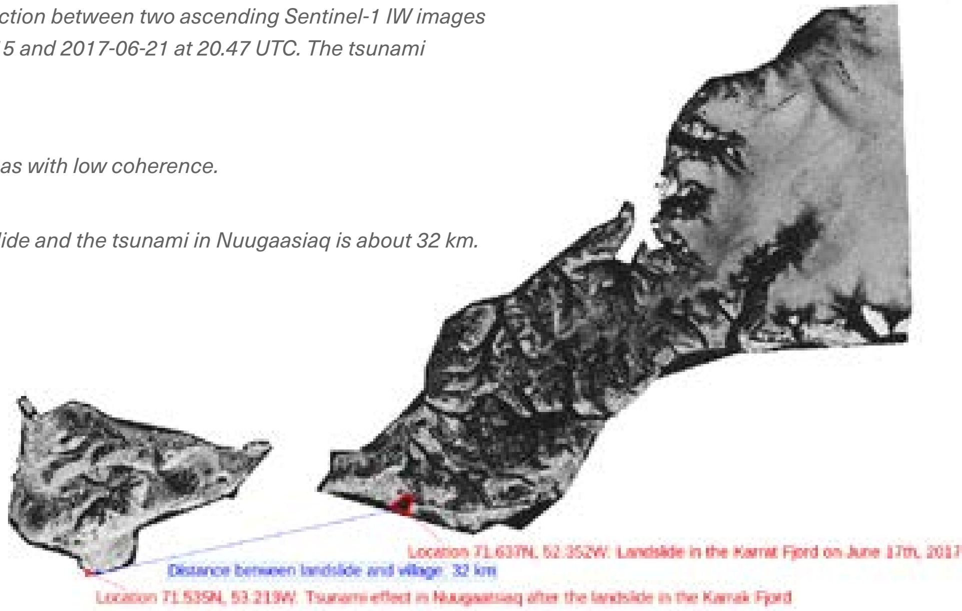
Figure 1: Coherent Change Detection between two ascending Sentinel-1 IW images (HH polarization) from 2017-06-15 and 2017-06-21 at 20.47 UTC. The tsunami occurred on June 17.

Comparing the images from June 15 and June 21 (before and after the tsunami on June 17), one may identify the place where the landslide occurred (Karratfjord) and the place where the tsunami hit (Nuugaatsiaq).

Figure 2: Coherent Change Detection between two ascending Sentinel-1 IW images (HH polarization) from 2017-06-15 and 2017-06-21 at 20.47 UTC. The tsunami occurred on June 17.

Note the locations of the two areas with low coherence.

The distance between the landslide and the tsunami in Nuugaasiaq is about 32 km.



As can be seen from the CCD comparison of two images before the tsunami (from June 9 and June 15, 2017, respectively), there are many dark areas (indicating changes), even though none of these changes are related to the tsunami. You definitely have to know what you are looking for and where to look in order to benefit from this type of analysis.

Benefits to citizens

This type of analysis is not only able to show locations of landslides and tsunamis, but it can also show the extents of floods, volcano eruptions, earthquakes, fires, rainforest devastations, etc. As mentioned, the CCD analysis shows all the changes that have taken place between the acquisitions and not only the changes that you want to detect. It may therefore be rather challenging to identify the relevant changes.

The more images you have before the relevant change has occurred, the better, since you can then get a better understanding of the variability of 'normal' changes between scenes. Furthermore, it is optimal with a short time distance between the two images acquired before and after the relevant change, so that you can better identify the relevant changes from the non-relevant changes.

Outlook to the future

A CCD analysis based on Sentinel-1 images only works if IW scenes are acquired over the area of interest. Furthermore, as mentioned above, the more IW scenes that have been acquired over the area, the better for the analysis. IW scenes with their relatively high resolution are generally applicable for detecting landscape changes and displacements, for calculation of digital terrain models, etc., and therefore IW scenes are generally very suited for land analyses. Consequently, the more IW scenes that are acquired over land, the better for a long time series of land-based analyses.

References and partners

John Peter Merryman Boncori, DTU Space, Technical University of Denmark for valuable contributions to this work.

Ice cap melting in southern Greenland

The effects of climate change are becoming increasingly visible at high latitudes. According to a study published in Nature, Greenland lost 586 billion tons of ice in 2019, adding 1.5 millimetres to global sea-level rise.

The summer of 2020 did not reach the exceptional levels of 2019 in Greenland, but, according to the US National Snow and Ice Data Centre (NSIDC), it was once again a season during which the melting of the ice sheet was higher than the reference value for the period 1981 - 2010.

This image, acquired by one of the Copernicus Sentinel-2 satellites on 20 August 2020, shows the effects of the thaw in the area south of Nuuk, in southern Greenland: the grey-blue waters are coloured by the sediments carried in the surface runoff that pours into the Arctic Ocean.

Data acquired by the Copernicus Sentinel satellites are used to detect changes in land surfaces in high detail even at northern latitudes and help monitor the glaciers melting.

Credit: European Union, Copernicus Sentinel-2 imagery.

Ice cap thawing season in Greenland

On 22 June 2020, the season during which the ice sheet loses more mass from melting than it gains from snow, started in Greenland.

The Danish Arctic research institutions group published, on its Polar Portal, a map of the areas affected by melting. This map shows that approximately 40 % of the total Greenland ice sheet is thawing, one of the highest values ever recorded in June when comparing to the 1981-2010 average.

This image, acquired by one of the Copernicus Sentinel-2 satellites on 28 June 2020, clearly shows small melt ponds, which are the result of thawing, scattered across the Avangnardleq and Kujatdleq glaciers.

The Copernicus Sentinel satellites are particularly useful for monitoring the impact of climate change in the Arctic region.

Credit: European Union, Copernicus Sentinel-2 imagery.


Arctic Ocean


Mapping Greenland's Ice Marginal lakes

Greenland has over 3300 ice marginal lakes. The documentation of these in the first inventory was made possible by combining Copernicus datasets with other base datasets.

Alexandra Messerli [A], Penelope How [A], Eva Mätzler [A], Maurizio Santoro [B], Andreas Wiesmann [B], Rafael Caduff [B], Kirsty Langley [A], Mikkel Høegh Bojesen [A], Frank Paul [C], Andreas Kääb [D]

A: Asiaq Greenland Survey B: Gamma Remote Sensing C: University of Zürich D: University of Oslo

The Challenge

Greenland has approximately 3347 ice marginal lakes, which occur at the ice margin and are often dammed at one or more locations. An ice marginal lake can drain rapidly when it reaches a critical volume large enough to cause the ice dam to fail. As the ice margin thins and retreats in response to climate change, the behaviour of these lakes can change unpredictably. The frequency of lake outburst floods can change as ice thickness fluctuates, causing changes in the threshold volume for ice dam floatation/failure. It is only possible to monitor changes in the extent and drainage frequency of ice marginal lakes by the use of satellite imagery.

The space-based solution

Greenland is vast, covering more than 2 million square kilometres. Nearly 80% of this area is covered by glacial ice that forms the Greenland Ice Sheet. Monitoring environmental change at a high level of detail is impossible to achieve using traditional approaches alone, due in part to the lack of roads between the settlements dotted along the coastline. Satellite imagery is therefore a valuable tool for monitoring Greenland at a high spatio-temporal resolution, with approximately 147 Sentinel-2 satellite scenes covering the non-glaciated region at a 10 m-resolution every 6 days. Such frequent, detailed data is valuable for monitoring such an immense and extreme expanse. Much of the country lies above the Arctic Circle, and the availability of Sentinel-1 data allows us to monitor these regions even in cloudy conditions or during the polar night when there is no solar illumination. This increases the frequency of images over the same point, allowing us to detect lake changes and drainage events at an unprecedented temporal resolution.

Benefits to Citizens

Hydrological resources in Greenland, including ice marginal lakes, are of great importance. Whilst Greenland is unlikely to run out of water in the immediate future, climate change is altering where and when water resources are available. We have in-situ, highly detailed measurements from select hydrological catchments in Greenland. In combination with satellite imagery, we are able to monitor catchment changes at a broader scale as well, such as changes in reservoir size for hydropower.

Ice marginal lakes are a potential natural hazard in Greenland. Whilst the country is sparsely populated, many people use areas that lie directly in a flood path, for example for hunting and fishing. Additionally, ice marginal lakes pose a risk to infrastructure downstream, such as settlements, roads and bridges. Outburst floods often occur suddenly and without warning, unleashing a large volume of water containing debris and icebergs. By combin-

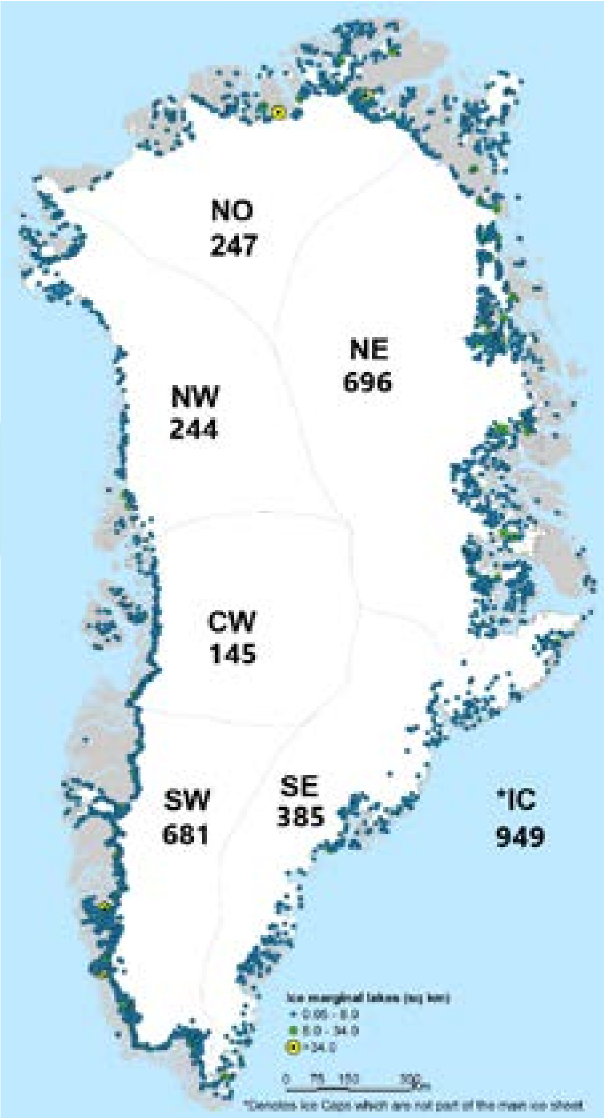


Figure 1: Greenland's ice marginal lakes. Annotated values are the number of lakes identified in each sector.

Figure 2: Example of lakes detected by each method, in South-west Greenland.

ing satellite detection with in-situ measurements, we can inform user groups and municipalities of changes in lake conditions and advise on potential risks of flooding.

Outlook to the future

The inventory forms a valuable baseline dataset that documents the frequency of ice-marginal lakes in Greenland that can be built upon with additional data sets from other satellites and old aerial images. The continued acquisition of data from the Sentinel-1 and Sentinel-2 satellites will ensure the future monitoring of ice-marginal lakes in Greenland. With further observations, we can observe changes in the number of these lakes compared to the baseline lake inventory and examine their drainage dynamics under a changing climate.

Acknowledgements

The inventory was funded by the ESA CCI Glacier programme.

How Fast Does the Greenland Ice Sheet flow?

Mapping the flow of the Greenland Ice Sheet using data from Sentinel-1 gives the possibility to observe ice dynamics in near real time.

Anne Solgaard [A], Kenneth Mankoff [A], Robert Fausto [A], Anders Kusk [B]

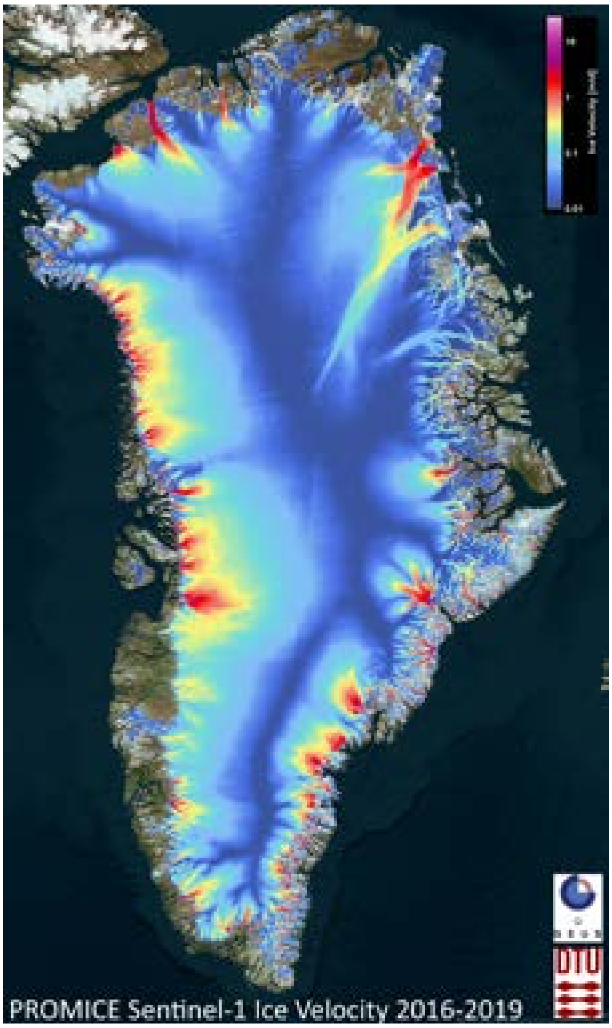
A: Geological Survey of Denmark and Greenland   B: DTU Space, Technical University of Denmark

The challenge

Global sea level is rising as the Greenland Ice Sheet and other land-based ice masses melt and become smaller year by year. Water that used to be bound as ice on land is melted or has ended up as one of the many icebergs produced from the outlet glaciers of the ice sheet.

This has consequences not only locally but for all low-lying areas of the world. Therefore, it is important to gain knowledge about how much mass the ice sheet loses each year and to understand its dynamics.

This is the goal of PROMICE (Programme for Monitoring the Greenland Ice Sheet), which is tasked with monitoring Greenland's ice sheet. The Greenland Ice Sheet covers a huge area of 1.8 million square kilometers, making monitoring impossible from the surface alone.

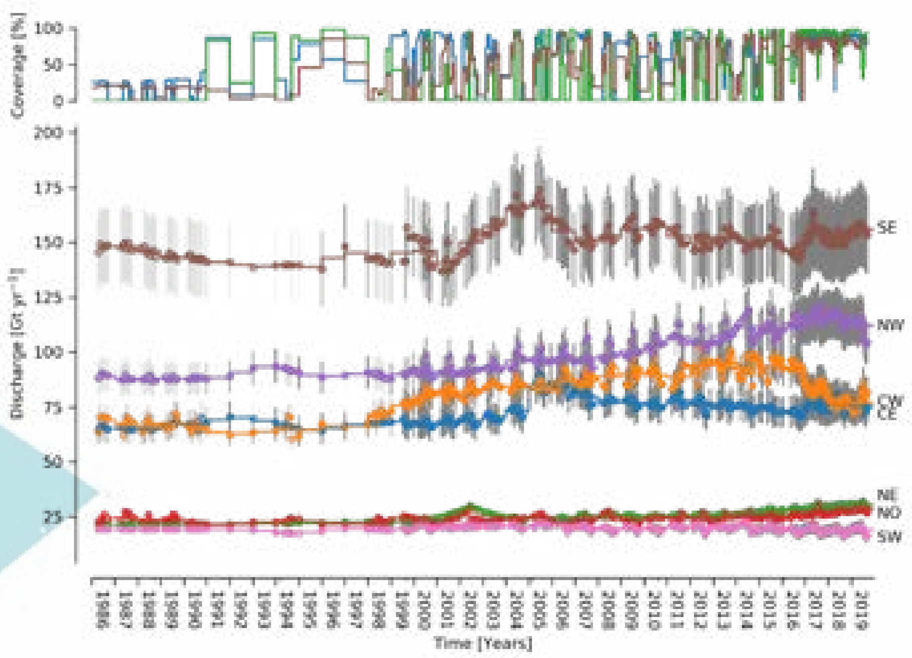


An example of an ice velocity map. The fast outlet glaciers show up in red.

The space-based solution

In PROMICE, Synthetic Aperture Radar (SAR) data from Sentinel-1 is used to calculate how fast the ice is flowing and produce ice velocity maps covering the entire Greenland Ice Sheet margin every 12 days.

This is done by applying a technique called 'offset tracking' to pairs of radar images covering the same area. The method can track displacements of both distinct features (such as crevasses) as well as speckle patterns (i.e. patterns in the noise distribution). The measured displacements between the two images are then converted into ice velocities. By using many image pairs that cover different areas, the analyst can join them into a mosaic covering all of Greenland as shown in the figure above.



Calving rates for different areas of the Greenland Ice Sheet.

Benefits to citizens

Surface ice velocities are used in several contexts:

The inland ice loses mass by melting and by outlet glaciers calving into the ocean. The amount of ice that calves off can be calculated using the ice velocity maps combined with knowledge of the thickness of the ice where the glaciers reach the sea. Due to the high temporal resolution of satellite data, it is possible to keep track of how much ice is transported into the sea virtually 'live' (see the figure above).

The total mass budget of the inland ice can thus be estimated as the sum of the mass gain (precipitation) and the mass loss (melting and calving rates).

The flow of ice is affected on both a shorter and longer time scale by many different factors, e.g. melting on the surface or seawater temperature. Here, the ice velocity maps can help to understand the interaction between the various elements and how ice dynamics are affected.

Outlook to the future

The ice velocity maps based on Sentinel-1 data and solid ice discharge rates for all marine terminating glaciers in Greenland are routinely produced as part of PROMICE. They are freely available to everyone and can be downloaded from www.promice.dk. Both aspects are important: That the time series grows as new data is recorded provides a unique opportunity to gain insight into dynamic processes and how they play together right here and now. The fact that data is free to everyone means that the user base is increased and that anyone can use the time series for precisely their idea.

Acknowledgements

PROMICE is funded by the Geological Survey of Denmark and Greenland (GEUS) and the Danish Ministry of Climate, Energy and Utilities under the Danish Cooperation for Environment in the Arctic (DANCEA) and is conducted in collaboration with DTU Space and Asiaq.

Present-day Greenland Ice Sheet Volume Change

Data from the ESA Cryosat-2 and the Copernicus Sentinel-3 satellite missions can be utilized operationally to provide ice sheet-wide elevation change estimates for the general public at polarportal.dk.

Sebastian B. Simonsen [A], Louise S. Sørensen [A]

A: DTU Space, Technical University of Denmark

The challenge

The High Arctic is experiencing enhanced global warming compared to elsewhere on Earth. A global warming of 2 degrees is expected to be doubled in the Arctic region (a phenomenon called Arctic amplification). Hence, the Greenland ice sheet is a key region to monitor the impact of global warming.

The Global Climate Observing System (GCOS) has defined 54 Essential Climate Variables (ECVs). An ECV is a physical, chemical or biological variable (or set of variables) that contributes to the characterization of Earth' s climate. The surface elevation change of ice sheets has been defined as an ECV.

Strong winds moving snow on the Greenland ice sheet, only one of many phenomena altering the surface elevation. The most important contributions are the summer melt and the winter snowfalls. Photo by S. Simonsen.

The space-based solution

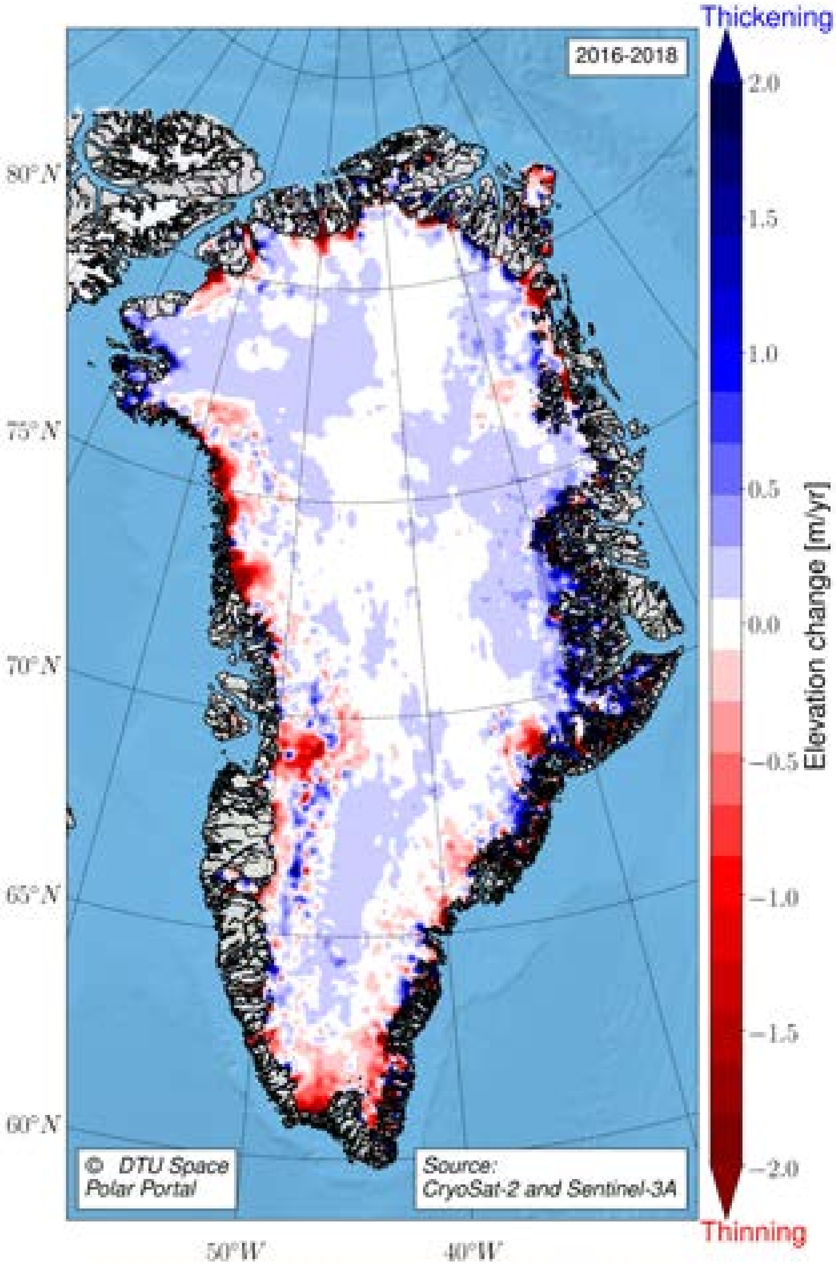
The vast extent of the Greenland ice sheet makes it impossible to monitor completely by in-situ measurements. Hence, for Greenland-wide monitoring programmes of ice-volume change, the only applicable source of data is in the form of remote sensing from satellites.

The European Space Agency has a long tradition of launching satellite radar altimeters with an orbit and frequency suitable for monitoring the snow-covered regions of the High Arctic. This time series was started in 1991 with the launch of ERS-1 and was continued by ERS-1, ERS-2, ENVISAT and CryoSat-2; all providing estimates of ice sheet elevation. With the commissioning of the Copernicus Sentinel-3 series of satellites, this long-time series of elevation change is ensured to be continued into the future and we can start to build operational services deriving the surface elevation change ECV.

The long time series of ice sheet elevation measurements is analysed to give a climatological estimate of surface elevation change over 3-5 years of data. As the Sentinel-3A mission has now been operational for three years, data from this mission is now being used alongside data from ESA's CryoSat-2 data to give annual updates on the present state of the Greenland Ice sheet on polarportal.dk.

Benefits to citizens

Polarportal.dk is an Arctic monitoring website, at which the Danish Arctic research institutions present the newest knowledge and state of the two major components of the Arctic climate system:



The surface elevation changes from January 2016 to December 2018, as derived operational from combining data from Cryosat-2 and Sentinel-3A.

The Greenland Ice Sheet and the Arctic sea ice.

Annual estimates of ice sheet-wide surface elevation rates are presented at the site and provide, alongside with the other climate parameters present, a go-to site for both the public and decision-makers when they wish to see the present state of the ice sheet and its direct contribution to global sea-level rise.

Outlook to the future

Sentinel-3 is planned as a tandem mission with two satellites in orbit at all times. Sentinel-3A has been in orbit since February 16, 2016, and Sentinel-3B was launched on April 25, 2018. Hence, we are now waiting for the time series of Sentinel-3B to mature before adding it to the operational product available through the polarportal.dk. As the CryoSat-2 mission is already way beyond life expectancy, we expect soon to rely solely on the data stream from the Copernicus Sentinel programme. However, with the Sentinel-3C and Sentinel-3D being ready for filling the shoes of A and B, the annual SEC ECV update is secured for a long time to come.

Acknowledgements

Polarportal.dk is financed by the DANCEA (Danish Cooperation for Environment in the Arctic) under the Danish Ministry for Energy, Utilities and Climate.

Ice Reports to Ships Operating Near Shore

High-resolution Sentinel-1 SAR data in constellation with TerraSAR-X has successfully replaced helicopter operations for provision of localized ice information in South Greenland.

Keld Qvistgaard, Greenland Ice Service, Danish Meteorological Institute

The challenge

Navigation in certain ice-covered areas poses extraordinary challenges for shipping. One of these areas is the South Greenland inshore waters that are characterized by many small and medium-sized ships and narrow straits mixed with sea ice and icebergs. This is a major hazard and obstacle for local shipping year round.

The Greenland Ice Service has through several decades used dedicated helicopter services and special trained staff on-site to monitor, map and report local ice conditions to shipping.

This setup is costly, labour intensive, and vulnerable to weather, and the achievable update frequency not satisfactory for the increasing number of users at sea.

The space-based solution

The launch of the Sentinel-1 constellation was a game changer. In November 2017, Danish Meteorological Institute (DMI) closed its local Greenland office and helicopter-based services after 4 years of preparation and implementation of high-resolution SAR data in the production line in the headquarters in Copenhagen.

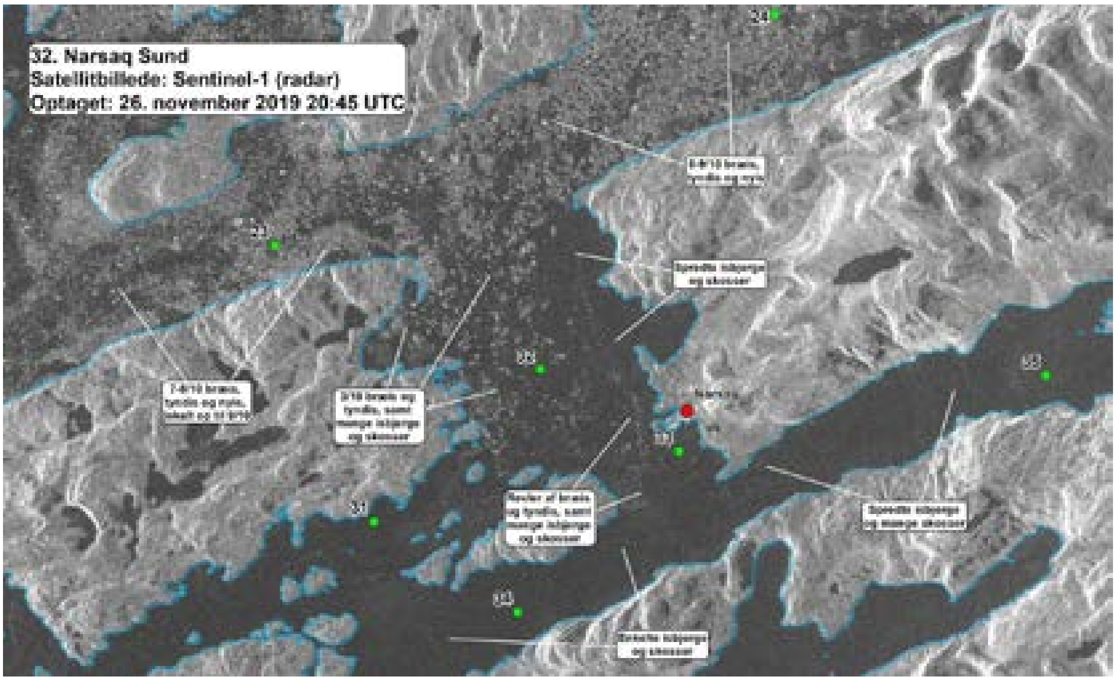
Sufficient data resolution is essential, and only SAR data in HH-polarization and with pixel size better than 10m works for this type of routine mapping of ice for shipping.

Even at this resolution, some small-scale ice features are missed. The only practical way to compensate for this is through a significantly increased update frequency, compared with the helicopter era, which allows the ice analyst to better track any hazardous ice in satellite imagery.

> **We've finished our sailing in Greenland and for the time being we do not require this service anymore.**
>
> *Bridge Team, World Explorer*

Icebergs and/or sea ice blocking South Greenland shipping routes pose a risk to all types of navigation.

The new space-based solution is partially based on Near Real Time access to Sentinel-1 (IW) provided by Copernicus. The stable Sentinel-1 acquisition scenario is repeated every 12 days. The update frequency is, however, not satisfactory, so DMI has also implemented its own contractual



Graphical Annotated Sentinel-1 IW Quicklook showing the local ice report to ships operating in Narsaq Sund, South Greenland.

arrangements with a data provider for provision of TerraSAR-X ScanSAR imagery, which is available in 8 m pixels.

The Sentinel 1/TerraSAR-X constellation has for a couple of years been the primary data source for local ice mapping in South Greenland. The two satellite systems are back-up for each other.

Despite the contract with a commercial data provider, the overall costs of running the ice services to the mariners were reduced by about 50 pct. In addition, the number of ice reports to mariners has more than doubled, reducing ice information gaps to a low level.

Benefits to citizens

The setup reduces costs for the taxpayers, but even more importantly the satellite-based setup improves the local situational awareness related to ice for the entire region. This improves safety and provides a solid basis for marine planning and operational decisions onboard the ships.

The ice at sea is retreating due to climate change, but it is still extremely variable through the seasons. The number of ships of all sizes is increasing, and demands for ice information are increasing and becoming more diverse. Due to the success of the satellite-based setup for localized ice monitoring in South Greenland, the setup is now being considered for implementation in other regions but awaits high-level decisions.

Outlook to the future

The satellite-based high-resolution setup will continue, and as long as Sentinel-1 IW is available NRT, it will be one of the pillars for the provision of nearshore ice services. Obviously, the next generation of Sentinel-1 Satellites and availability of high-resolution mode will be carefully analysed.

Efforts will be put into investigations of automated processing, analysis and product dissemination to mariners.

Sentinel-2 data could also provide important supplementing data in cloud free conditions, if the access times to these satellite images were reduced.

Acknowledgements

Copernicus Marine and Environmental Monitoring Services and European Space Agency for provision of Sentinel-1 and Sentinel-2 data.

Mapping Coastal Areas is Important for Safe Navigation in the Arctic

As critical buffer zones between land and ocean, coastlines are highly dynamic and susceptible to change. However, earth observations provide a possible means to monitor and map coastal zones.

Torben W. Rasmussen [A], Lotte Nyborg [B]

A: Danish Geodata Agency   B: DHI GRAS

The challenge

Detailed and up-to-date knowledge about the extent of coastlines, their dynamics and the location of submerged rocks and shallow water areas is critical for safe navigation.

Detecting coastlines and rocks has significant importance for navigation. It inherently depends on precise and up-to-date knowledge on coastline extent and dynamics and information on location of rocks.

The coastline in nautical charts has to be in a detailed quality, in which it is possible to overlay the real coastline detected by onboard radar, ensuring mariners' confidence in the electronic chart.

The space-based solution

The new generation of high-resolution and freely available satellite data offered by the Sentinel missions has propelled the potential for automated and consistent monitoring approaches for shoreline detection and mapping of marine hazards.

In a pilot project undertaken by DHI GRAS in South-East Greenland, a new automatic approach

Mapping intertidal zones, coastline extent, small islands and submerged hazards using Sentinel- derived data composites.

to mapping coastlines, submerged hazards (rocks) and intertidal areas was tested. More than 160,000 km of coastline was mapped, including 40,000 small islands and submerged hazards. Various indices and statistical parameters were extracted from time series of SAR data from Sentinel-1 and optical data from Sentinel-2 in order to reduce hundreds of raw images into a few optimized information rich data composites.

An automatic object-based algorithm was applied to the composite data in order to segment ele-

Sentinel time-series provides critical insight on waterline reach in intertidal areas.

ments into various objects of interest, including coastlines, small islands, intertidal areas and submerged hazards.

> **The Sentinel-2 images in time-series and the auto-detected coastline and rocks have been a new primary source in our coast-rock process for new charts in Greenland.**
>
> *Torben W. Rasmussen, Danish Geodata Agency*

The utilization of time-series composites and integration of both optical and SAR satellite images significantly minimized the effects from clouds, ice and terrain in order to reduce classification error and derive a seamless classification of coastal areas in the pilot study area. Furthermore, time series analysis of Sentinel imagery provided a detailed insight on tidal areas and dynamics within tidal zones.

Benefits to citizens

The Danish Geodata Agency used the Sentinel-2 images and the auto-detected coastline and rocks in new charts in 2018 and 2019. The biggest benefit is the time-series of images – where it is possible to see the variation in tides and sea ice cover. Images in RGB colors make it easy to distinguish objects such as ice, rocks, etc.

The auto-detected coastline has been a primary source in detection of coast and rock for new charts in Greenland. However, while the technology is a potent and scalable approach to map and monitor remote uncharted areas, special cases still require manual checking of the output data prior to usage. With adjustments of algorithms, over time, automatic detection of coast and rock can be brought closer to an operational level.

Outlook to the future

The Sentinel missions have paved the way for consistent satellite-based operational monitoring of coastal regions and the ability to deliver highly detailed and consistent monitoring of large uncharted areas. However, operational monitoring of large areas using satellite data ultimately depends on the ability to automate processes and data analysis. Deep learning has already been a game changer in remote sensing, and future application of satellite-based operational monitoring systems in coastal regions will ultimately depend on further advancing deep learning technology.

Acknowledgements

We appreciate the work done by DHI GRAS to test and trial how Copernicus data could be used to monitor and map large uncharted areas in remote regions.

Routine Mapping of Sea Ice to Shipping around Greenland

Safe navigation in ice-covered waters requires situational awareness of the ice situation. Similar to other national ice services, the Danish Meteorological Institute provides regional ice information for navigation using Copernicus satellites and contributing missions.

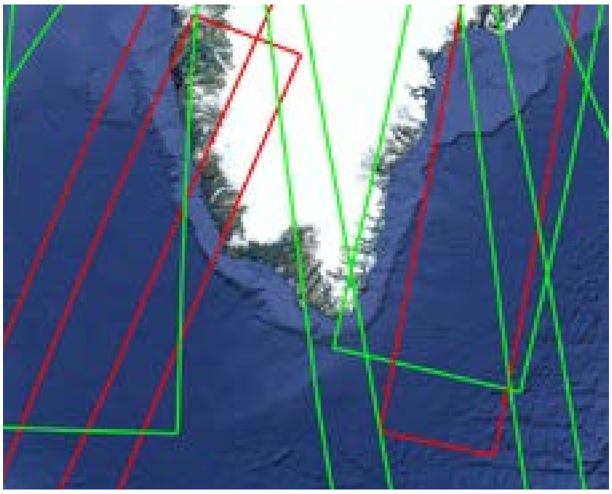
Keld Qvistgaard, Greenland Ice Service, Danish Meteorological Institute

The challenge

Safe and efficient shipping in polar waters is challenged by the presence and variability of sea ice and icebergs. Updated, reliable and standardized ice information is essential for navigation.

In the past the DMI Greenland Ice Service used fixed-wing aircraft and helicopters to acquire the necessary platform to produce ice information for navigation in Greenland waters.

This setup provides very detailed information about ice conditions, but is also vulnerable to weather, range dependent and costly, given the distances in Greenland, and only portions of the ice-covered ocean can be mapped for navigation. This is not sufficient to cover the navigable waters in Greenland.



Sentinel-1 images acquired 15-16 April 2019 illustrating the importance of gap-filling contributing missions to issue daily regional ice charts.

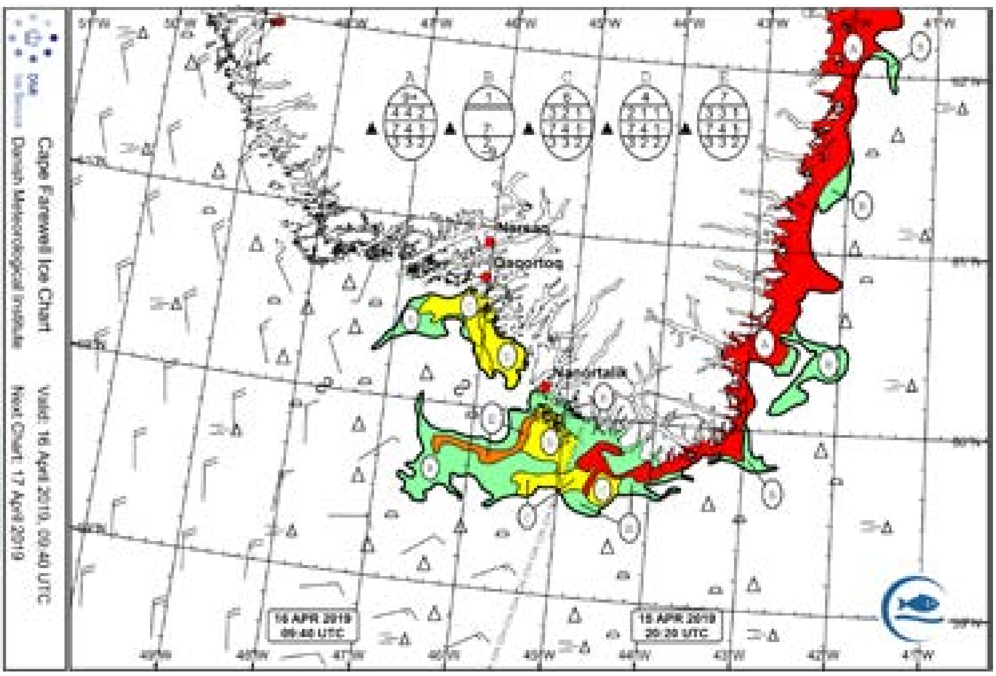
> **Satellite ice charts are good today, but we need more frequent ice information in areas with high currents.**
>
> *Anonymous Captain*
> *International Ice Charting Working Group Survey 2019*

In addition, shipping is increasing and due to climate change the operating windows get longer. The substantial variability of the ice remains, the waters are never ice free, and increasing shipping means more demands for ice products for navigation.

It became more and more clear that maintaining aircraft as the primary source for data collection was not the way forward. It would be very costly and ineffective, and it would only satisfy a very limited user group and still not take full advantage of technical advances.

The space-based solution

With the availability of SAR satellites, the aerial reconnaissance and on-ground infrastructure in Greenland were gradually phased out. In November 2017, all ice products serving navigation were based on cloud-independent and high-resolution satellite data.



Standard regional ice chart for navigation near South Greenland using Copernicus satellite data and contributing missions.

The production is primarily based on the Copernicus satellites, Sentinel-1 and Sentinel-2, and the Copernicus Contributing Missions, to fill Sentinel-1 gaps or provide crucial resolution in certain regions. The data is available in Near Real Time, which is important for the provision of updated ice information to ships in ice-covered waters.

All satellite data is processed automatically and analysed by a specially trained team of ice analysts, using specialized software. The outcome to ships is text bulletins, scalable/graphical ice charts describing sea ice edge, total ice concentrations, floe size and ice thickness categories and iceberg clusters.

In addition, all regional ice charts produced by DMI Ice Service are automatically exported to the Copernicus Marine and Environmental Monitoring Service portal in netcdf for integration into numerical forecast models.

Benefits to citizens

Ice at sea is an obstacle and a major hazard for navigation. Many ships are not designed for operations in ice, and almost all ships would always look for the most favorable ice conditions for any transit, it would be ice avoidance if possible.

The primary purpose of provision of regional ice charts is to provide information to the captain's strategic decisions along planned route or at scheduled destinations. The background for this is risk management as it is important to make the right decisions. Greenland is enormous, infrastructure and Search and Rescue facilities are extremely sparse, and any upgrade would be costly, so information services focused on incident elimination are obvious. This protects the environment and also supports supply operations and passenger transfers.

Outlook to the future

The sea ice retreat related to climate change increases demands for updated and relevant ice information to ships, especially at sub-Arctic latitudes (50°N-70°N). Daily Sentinel-1 coverage is not possible, and some users even need more frequent updates. The need is expected to be integrated into future Sentinel-1 constellations as well as the Copernicus Contributing Missions.

The future Copernicus ROSE-L mission is expected to be a game changer for high-resolution classification of sea ice as well as iceberg detection in sea ice.

Automated methodology for data handling, analysis and production is gradually implemented in the production line.

Sea Ice Charting from Multisensor Data Fusion

The Danish Meteorological Institute and the Danish Technical University use Copernicus Sentinel-1 data and novel deep learning techniques for sea ice information retrieval to develop an automatic sea ice product service for maritime safety in Greenland waters.

Matilde Brandt Kreiner, Danish Meteorological Institute

From manual ice charting ...

Manual ice charting from multi-sensor satellite data analysis has for many years been the method at National Ice Centers around the world for producing sea ice information for maritime safety. Also at the DMI Greenland Ice Service, ice charts are today made by ice analysts that use all relevant imagery available, primarily Copernicus Sentinel-1 radar imagery (SAR), due to its high resolution and capability to see through clouds and in polar darkness.

Royal Arctic Line cargo ship navigating in sea ice in Northeast Greenland. Photo: Jens Jakobsen, DMI.

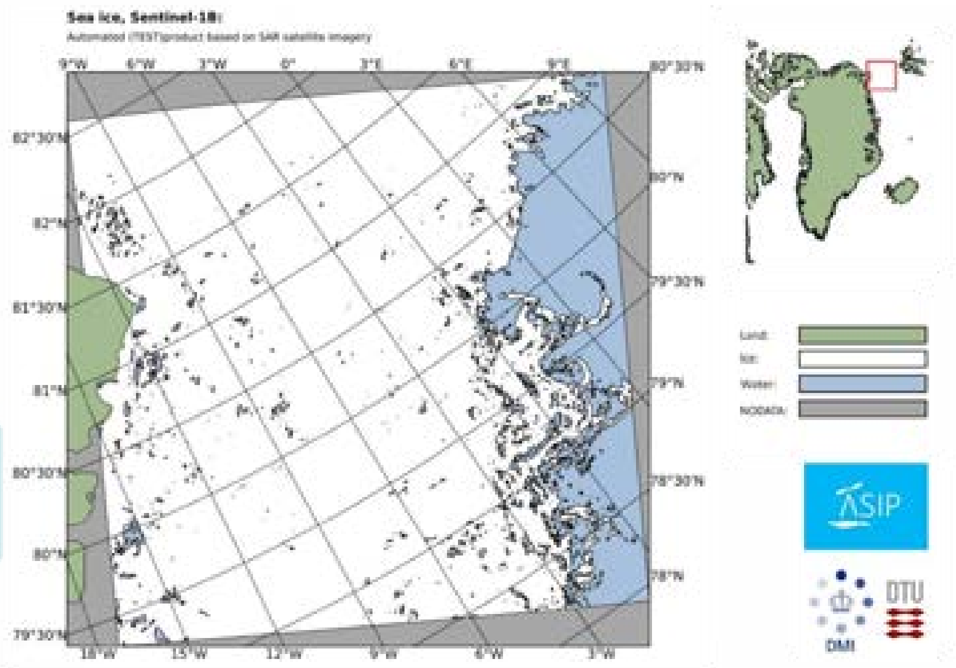
Manual ice charting is a time-consuming method that is increasingly challenged by the vast amount of free satellite imagery available these years. Along with a growing user group accessing wider parts of the Arctic due to the retreat and thinning of the Arctic sea ice, this calls for a more effective way of producing detailed and timely ice information to the users.

... to Artificial Intelligence

ASIP (Automated downstream Sea Ice Products) is a Danish R&D project that seeks to develop an automatic sea ice product service that can meet the increased demands for better and more timely sea ice information to improve efficiency and safety of marine operations in Greenland waters.

> **The ASIP automated sea ice products will improve the service we provide to our users, in terms of timeliness and updates .**
>
> *Jens Jakobsen, Ice Analyst at DMI Ice Service*

Using deep learning algorithms, researchers have found that combining Copernicus Sentinel-1 imagery with radiometer data from the Japanese AMSR2 (Advanced Microwave Scanning Radiometer 2) satellite sensor ensures the best outcome from both instruments. Sentinel-1 provides the high resolution needed to meet the demands of Arctic marine users, but ambiguities can occur e.g. between open water in windy weather conditions and homogeneous sea ice surfaces. Microwave radiometers, which measure brightness temperatures, have coarser resolution but complementary



ASIP sea ice test product covering Northeast Greenland.

capabilities for distinguishing between ocean and sea ice, independent of weather.

Making use of a large archive of manually drawn Ice Charts from the Danish Meteorological Institute's Ice Service, which on a daily basis provides ships with sea ice information around Greenland's coast, and combining them with Copernicus Sentinel-1 scenes, has provided a very good dataset for training the ASIP deep learning model. The ASIP model has been implemented and a Sentinel-1 image can be processed by the model in just a few minutes. The products have higher spatial resolution, better geographical and timely coverage than the current manual ice charts.

More ice charts for all of Greenland

The project is currently in a validation phase, where ice analysts make sure that the automated sea ice charts are of high quality in all geographical regions and weather conditions. Hereafter, the products will be sent to ships for an end-user evaluation and ultimately made freely available through the Ice Service.

A wide range of public and commercial stakeholders in Greenland will benefit from the new products. Sea ice retreat due to climate change has led to increased marine access to all parts of Greenland. Thinner and more dynamic sea ice will continue to be a hazard. Social, cultural and commercial possibilities, as well as sovereignty, security and safety issues and environmental concerns, arise as marine access increases. These activities and associated stakeholders require detailed ice monitoring for larger areas of the partly ice-covered waters, for marine traffic purposes, strategic planning and risk assessment.

Towards improved sea ice forecasts

Ultimately, maritime users want reliable ice forecasts for safe navigation and planning. To be able to provide these, there is a need for the ASIP automated, detailed and standardized ice observations from satellite data for integration in forecast models. It is a project goal for the near future to test an assimilation of the ASIP ice maps in the institute's sea ice model and to do demonstration services to end users.

Acknowledgements

The ASIP project is a collaboration between the Danish Meteorological Institute, the Technical University of Denmark and Harnvig Arctic & Maritime. It is funded by Innovation Fund Denmark and partners.

Satellite Images for Tactical Navigation in Ice-Covered Waters

Marine operations in ice-covered waters rely on a suite of standard ice-metocean products, recently supplemented with satellite images for onboard decision-making.

Keld Qvistgaard [A], Jørgen Buus-Hinkler [B]

A: Greenland Ice Service, Danish Meteorological Institute B: Danish Meteorological Institute

The challenge

Safe and efficient marine operations in ice-covered waters require ice-metocean information that is

- Relevant, Actual
- Simple
- Reliable
- Accessible

for the captain's planning and en-route decision-making. Certain areas, near harbors or glacial outlets, in straits or fjords require dedicated information for the tactical navigation close to hazardous ice. The vessel often requires frequent (typically daily) and near real time updates (less than a couple of hours). However, this is not really manageable for the Ice Service as the manual selection and interpretation of incoming images is labour consuming and associated with delays, which means the final product is less useful for the mariner. In addition, significant bandwidth limitations concerning communication exist to all ships.

The space-based solution

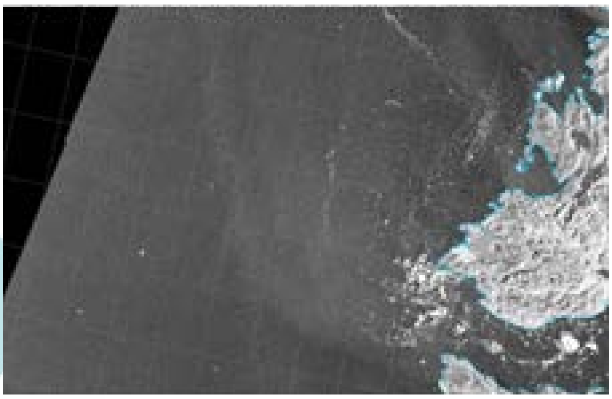
Since delivery time is critical for the mariner operating in ice-covered waters, it was decided in 2018 to develop an automated solution in collaboration with a primary professional user, using Copernicus satellite data of necessary resolution.

A file size of maximum 1-2 Mbytes can be provided to most ships. Secondly, the necessary resolution must be available, typically 10m or better to be useful for the mariner to reflect the true ice conditions. In other words, the near real time product should be balanced between the geographical coverage and resolution. In collaboration with the end user, sub-areas were defined of about 30x20 km in size, for ice-infested areas challenging navigation.

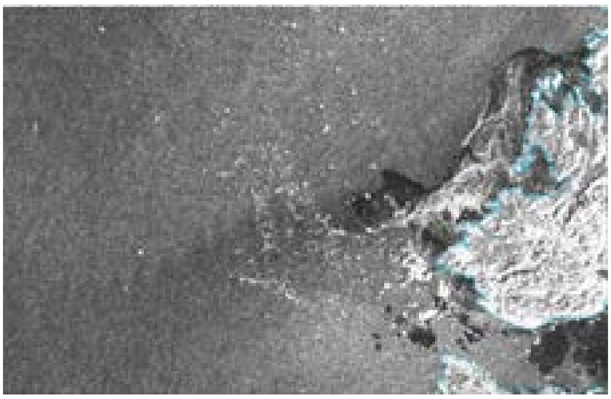
> **We have been very satisfied with the focused satellite quicklooks provided by DMI. We look forward to receiving them again in 2020.**
>
> *Eyðun Simonsen, Master, Royal Arctic Line*

The automated production setup processes incoming SAR data of relevant resolution for the defined sub-areas and produces a graphical image time stamp, sensor, shoreline and lat-lon grid overlay. This file is automatically distributed as an email attachment to the client.

It should be noted that this provision cannot stand alone but is an early warning that supplements standard ice products to the vessel. Secondly, the mariners are not fully trained in advanced SAR



Example on automated image product to shipping, here from Ilulissat, Disko Bay. The interpretation is easy for the mariner.



Example on automated image product to shipping, here Ilulissat, Disko Bay. The interpretation is difficult for the mariner.

image analysis so we have also developed tutorial tools to assist mariners.

In 2019, the automated satellite quicklook provisions were expanded to three professional users, to receive feedback from a broader user community.

Benefits to citizens

The automated setup is tested in Greenland waters at selected cargo, passenger and cruise ships with Danish captains or pilots. Despite some open ends in the production setup, the feedback from the mariners is positive. It is reported to improve the situational awareness and provide solid guidance for decisions and safety margins at a very early stage.

This means that decisions for navigation can be made faster, that vessel waiting times are reduced and that navigation can be based on updated information, which improves safety, or that access is established to ice-covered waters which could not navigated if actual satellite information was not available.

The initial feedback from the mariners using the automated setup indicates that combined with existing ice information products, it also helps activities related to cruising, like tour operators and resource management at harbors. Finally yet importantly, the setup provides a solid basis for safety decisions at sea as they are based on the most recent information available. This is important for the industry operating 24/7 in an environment where the ice is constantly changing.

Outlook to the future

The setup needs improvements at various levels, like training of mariners, improvement of programme user interface, compression of products, future web interface, inclusions of more SAR/Optical satellites of necessary resolution and, eventually, inclusion of new user groups.

Acknowledgements

Copernicus Marine and Environmental Monitoring Service for providing daily satellite data. Greenland Pilot Service, Royal Arctic Line and Arctic Umiaq Line for using the test setup and providing valuable feedback..

Iceberg Detection in Greenland Waters

Sentinel-1 imagery is used for automated detection of icebergs around Greenland. Iceberg detection makes navigation safer and can contribute to climate research, particularly in Arctic regions.

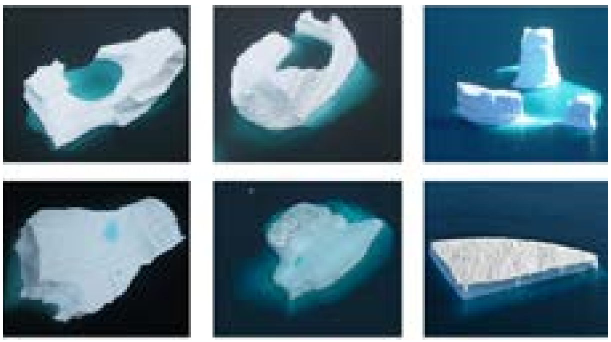
Jørgen Buus-Hinkler, Danish Meteorological Institute

The challenge

Icebergs pose a danger to navigation and offshore activities, and they are an important component of the mass balance of the Greenland ice sheet.

Most historical data on icebergs comes from ship-based and aerial surveys. These observation methods are, however, very time-consuming and costly.

With regard to time and geographical coverage, satellite-based iceberg detection is, however, much more efficient and extensive.



Icebergs of various types and shapes in Greenland waters. Photos: Martin Nissen, DMI 2010.

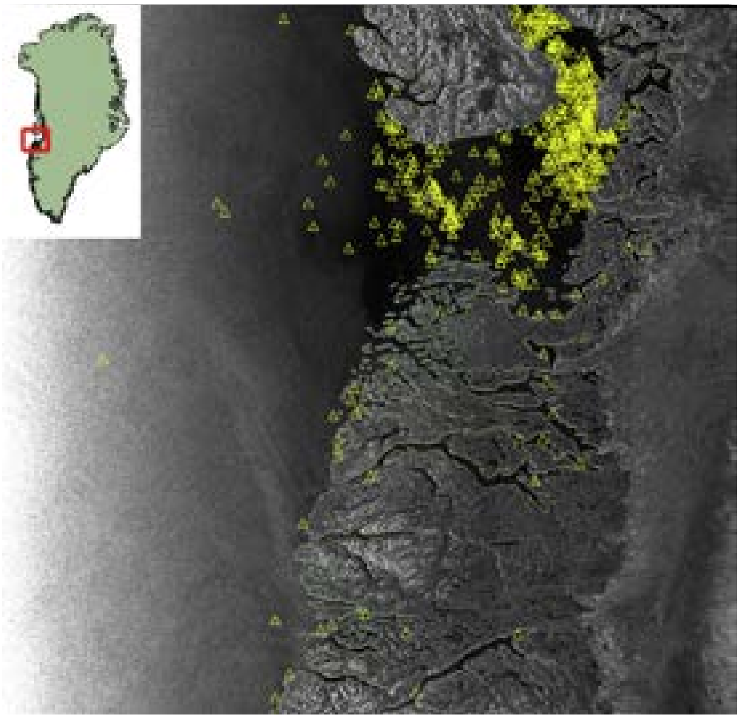
In Arctic areas, cloud cover is frequent and daylight is absent during a long period of the year. Because radar based technology is independent of these factors, it is ideal for observation in these regions.

The detection of icebergs using the vast amounts of radar imagery acquired by the Sentinel-1 satellites requires capability for handling "big data" and development of efficient and reliable detection algorithms.

The space-based solution

Every day, the Danish Meteorological Institute receives up to about 100 scenes of radar imagery from the Sentinel-1 A & B satellites. Together, these 100 images cover more than ten million square kilometers and contain more than 35 billion pixels – all input to dedicated iceberg detection algorithms deciding whether a pixel constitutes a part of an iceberg. Iceberg detection is run operationally by Danish Meteorological Institute and is part of the Copernicus Marine Environmental Monitoring Service (CMEMS).

An iceberg is by definition a chunk of ice – larger than 15 m horizontal length – that has formed on land and has entered into the sea by calving (breaking off) from a glacier. However, icebergs may take many forms with sizes ranging from a few tenths of meters to more than one kilometer. To cope with this, the DMI detection algorithms are able to automatically adapt to work at different scales and to analyse the shapes with which objects appear in the imagery. Refinement of these algorithms is an ongoing process.



Radar imagery, Sentinel-1B 2019-09-02 20:54:19 Disko Area West Greenland with indications of detected icebergs.

Access to iceberg data (i.e. detected icebergs per 10kmx10km) for Greenland Waters is a Copernicus Service and is available at http://marine.copernicus.eu.

Benefits to citizens

Because iceberg data products are a Service under Copernicus, they are freely available for anyone who subscribe as a Copernicus user. Particularly for mariners navigating in the Arctic waters around and just south of Greenland, iceberg information is valuable for risk assessment in route planning.

> **To the benefit for Arctic navigation satellite based iceberg detection makes it possible to provide iceberg information at much larger scales than hitherto possible.**
>
> *Jens Jakobsen, Ice Analyst, DMI Ice Service*

Iceberg calving is one of two basic components that make up glacial loss from the Greenland ice sheet, with the other component being melt-off. The balance between the two is currently not well described, and thus quantification of icebergs will give researchers a better understanding of the mechanisms (e.g. climatic changes) that govern the mass balance of the ice sheet.

Outlook to the future

There are still unsolved difficulties that complicate iceberg detection from space-based radars. Small icebergs less than about 50 meters in size may not necessarily be detected in all images. This is due to limitations in the spatial resolution of the radar images and to weather conditions (particularly high winds) that decrease signal to noise ratio. Such noise, and sometimes also ships, can be misjudged as false iceberg targets.

The next generation of Copernicus iceberg products will be improved with regard to these difficulties. Along with geographical position, each iceberg observation will hold information on the uncertainty with which the iceberg was detected. Furthermore, ship tracking (AIS) will be used to remove falsely detected icebergs from the observations.

Acknowledgements

The development of automated iceberg detection was made possible through the Copernicus Marine and Environmental Monitoring Service.

Dust storm in the peninsula of Nuussuaq, Greenland

Even though dust is commonly associated with deserts, significant dust events have also been reported at high latitudes at which winds are occasionally strong enough to send plumes of sediment along the coasts. This phenomenon has been observed often in Greenland: The dust there emanates mainly from glacial flour, a fine-grained silt formed by glaciers grinding and pulverizing rock. This image, acquired by one of the Copernicus Sentinel-2 satellites on 1 October 2020, shows a dust storm in the peninsula of Nuussuaq, Greenland.

Data acquired by the Copernicus Sentinel satellites are used to detect changes in land surfaces in high detail at Northern latitudes and to aid in monitoring melting glaciers.

Credit: European Union, Copernicus Sentinel-2 imagery processed by Pierre Markuse.

Sea ice along the East coast of Greenland

Sea ice is of capital importance in climate dynamics as it reflects most of the solar radiation that it receives, thus affecting the average albedo of the earth, and also because it interposes a solid layer between the ocean and the atmosphere which reduces the free transfer of heat and moisture between the two.

In 2020 Arctic sea ice has reached the second-lowest area in 42 years, according to the US National Snow and Ice Data Center, a trend that experts believe is showing how climate change is impacting this vulnerable ecosystem and those who rely on sea ice for their livelihood. As sea ice is less dense than water, it floats on the ocean's surface and can help trace the underlying ocean currents, which result in typical swirls or eddies visible from satellites.

This true colour image has been captured by the Copernicus Sentinel-3 on 25 September and shows numerous sea ice swirls along the eastern coast of Greenland.

The Copernicus Sentinel-3 mission, that consists of two twin satellites (Sentinel-3A and Sentinel-3B), allows to develop innovative applications for sea ice monitoring, thanks to the onboard instruments that are able to retrieve accurate information about sea ice extent, temperature and thickness.

Credit: European Union, Copernicus Sentinel-3 imagery.


Copernicus

Evolving Production of North Atlantic Iceberg Limit Based on Satellites

Climate change, sea ice retreat and increasing shipping require new products for safe navigation in bergy waters.

Keld Qvistgaard, Greenland Ice Service, Danish Meteorological Institute

The challenge

The loss of S/S Titanic and more than 1500 lives in 1912 was a wake-up call for the world about the ultimate risk related to icebergs. Monitoring and reporting of icebergs in the North Atlantic shipping lanes was included in the first SOLAS convention.

USCG International Ice Patrol monitors icebergs in the North Atlantic shipping lanes using dedicated C-130 aircraft.

Icebergs occur everywhere and year-round in Greenland waters, extending hundreds of nautical miles from shore, and pose a risk to all ships, including those in North Atlantic transit.

> **The satellite-derived limit was incorporated into the daily products, providing a relevant reconnaissance based limit to mariners in the North Atlantic.**
>
> *USCG International Ice Patrol,Annual Report 2019*

Through the last decade, shipping has increased in the North Atlantic, including Greenland. Ship tracks also move further north, close to bergy waters, increasing the demands for iceberg products and services to ships.

The area of interest is enormous, in exess of 1.000.000 km², and investments in aerial technology would need to be very big, and solid estimates of the operating cost for collecting iceberg information have not been possible.

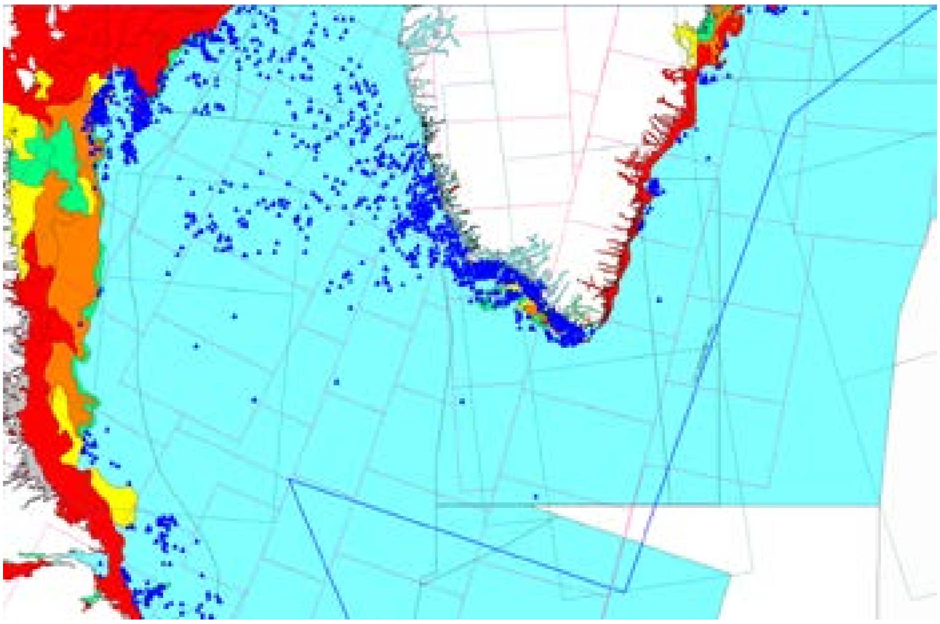
Small-scale ice is not detected by satellite due to resolution cut-off, which must be addressed in iceberg products to shipping.

The space-based solution

Target detection in open sea is not new, but with the Sentinel-1 constellation online, data access and substantial coverage became a reality for the ice services.

Danish Meteorological Institute provides routinely automated target densities in netcdf to Copernicus Marine and Environmental Monitoring Service for the Greenland waters not covered by sea ice, based on Sentinel 1 IW/EW mode.

The provisions to Copernicus Marine and Environmental Monitoring Service cannot be used by the ice services, so it was decided to go one step backwards and process the sentinel-1 data to individual targets and shapefiles that can be handled, analysed and filtered by the ice experts.



Iceberg limit near South Greenland derived from filtered target data from Sentinel-1.

Testing satellite analysis and methodology for filtering has been developed in close collaboration with International Ice Patrol and Canadian Ice Service.

Limitations of the technology were found in areas with small icebergs and high number of ships, like the Grand Banks or near Iceland.

These areas were excluded from 2019 full season test production of a satellite-based iceberg limit in the North Atlantic, from northwest of Iceland, via the southern tip of Greenland to the Labrador Sea.

Through 2019, from early February to late August, a total of 64 iceberg limits based on satellites were derived and used internally as well as exchanged with North American partners for review, recommendations and potential integration into ice products to ships.

Benefits to citizens

All navigation in bergy waters is associated with a risk for ship, cargo, crew, passengers, etc. Situational awareness and reduction of risk is always the first priority for any captain. Reliable and updated environmental information reduces risk and need for search-and-rescue infrastructure and provides solid ground for safety margins related to any particular journey in or near bergy waters.

Outlook to the future

The 2019 experience will be implemented for a new and more sophisticated test in the 2020 season. The obtained experience will also be included in next-generation iceberg products to Copernicus Marine and Environmental Monitoring Service.

The 2019 season also confirmed well known challenges in detecting small-scale ice, which is the primary hazard for ships. In dynamic situations and regions, the Sentinel 1 constellation update frequency is insufficient. This can be addressed via future contributing missions or maintaining the current sentinel 1 constellation after launch of next-generation Sentinel-1 satellites.

The future Copernicus ROSE-L is expected to be a milestone for detection of icebergs in sea ice, which is not possible with today's Copernicus satellites.

Acknowledgements

European Space Agency for Sentinel-1 provision. Copernicus Marine and Environmental Monitoring Services for funding, which lead to the derived test of services to ships in bergy waters.

The Danish Joint Arctic Command uses Copernicus daily

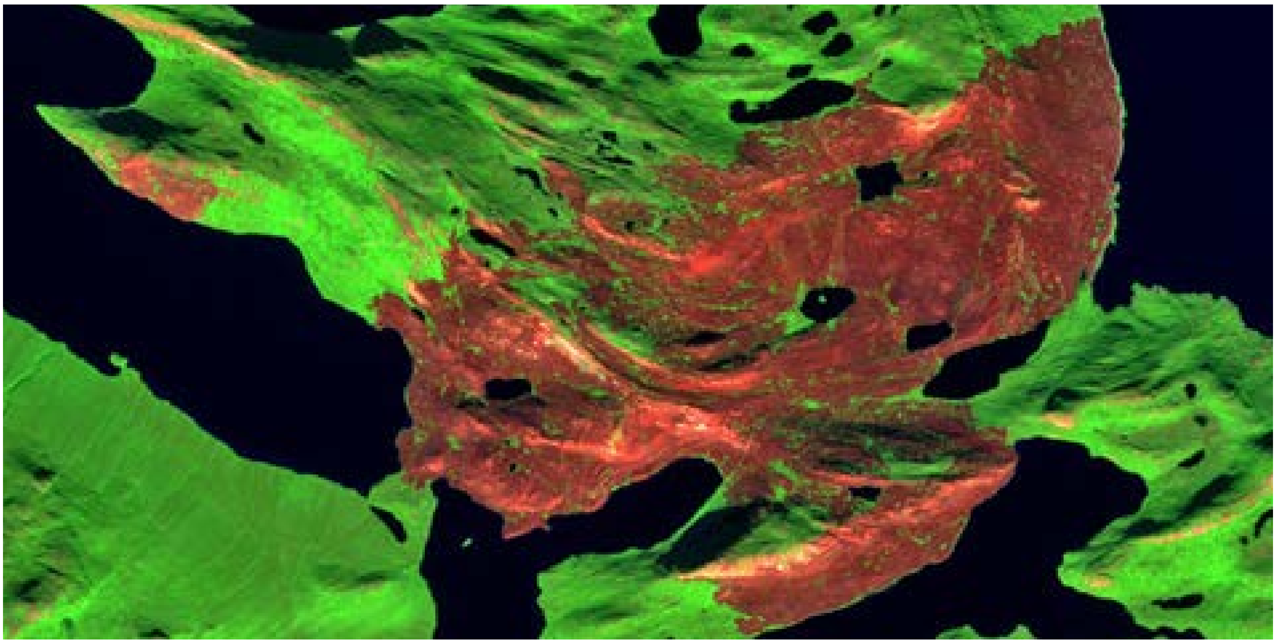
In the northernmost parts of the Kingdom of Denmark, the Joint Arctic Command considers Copernicus to be of considerable value. Recently, the system was used when battling a large wildfire.

Lise Høiriis, Royal Danish Navy

When a large wildfire ravaged the mountain slopes near the town of Sisimut in western Greenland in the summer of 2019, the Danish Joint Arctic Command played a leading role in the battle to contain it.

The mission involved around 40 firefighters from the Danish Emergency Management Agency who were flown into the area by a Royal Danish Air Force C-130 Hercules transport plane along with equipment for extinguishing the fire. In order to plan and coordinate the work as efficiently as possible, satellite images from Copernicus ware put into play.

The Copernicus system enabled Joint Arctic Command as well as Danish Emergency Management Agency to received updated satellite images of the area daily, giving an accurate account of how the wildfire spread. Simultaneously, satellite images from the Sentinel-2 satellite were used. These images were taken in the infrared frequency range, making it possible for the viewer to see which parts of the fire were most active. The firefighters managed to extinguish the wildfire by mid-August, after it had raged for about a month. Meanwhile, the Royal Danish Navy had also managed to evacuate three hikers in the area by helicopter.



Satellite image from Sentinel-2, taken in the infrared frequency range. It shows the difference between the less active and the most active parts of the fire.

Image of the wildfire by Sisimut, taken from Royal Danish Air Force Challenger plane.

Oil spills and fishing

The Danish Joint Arctic Command also uses the Copernicus system for less extraordinary events than large wildfires.

On a daily basis, satellite imagery is used for general surveillance of the waters surrounding Greenland in order to establish a situational awareness of the many activities going on around this vast country.

In this, aspects regarding environmental protection such as oil spills are of a high priority. In most cases, if an oil spill is detected and confirmed, the ship that is responsible for the spill will eventually be found. In another example of how the Joint Arctic Command uses Copernicus for environmental protection, satellite high resolution images were requested through Copernicus after a shipwreck in order to keep an eye out for possible oil spills.

The Joint Arctic Command also uses satellite images to identify areas with a high concentration of fishing vessels. This information can be used to direct resources to the specific area in order to perform inspections or show presence.

Wildfire in greenland

Sentinel-2 is used by the Copernicus Emergency Management Service to detect and monitor wildfire. This image show a larger wildfire in western Greenland, about 150 kilometers northeast of the city of Sisimiut, Greenland's second-largest city. For several weeks, the fire burned in an area covered with grass, shrubs, and peat.

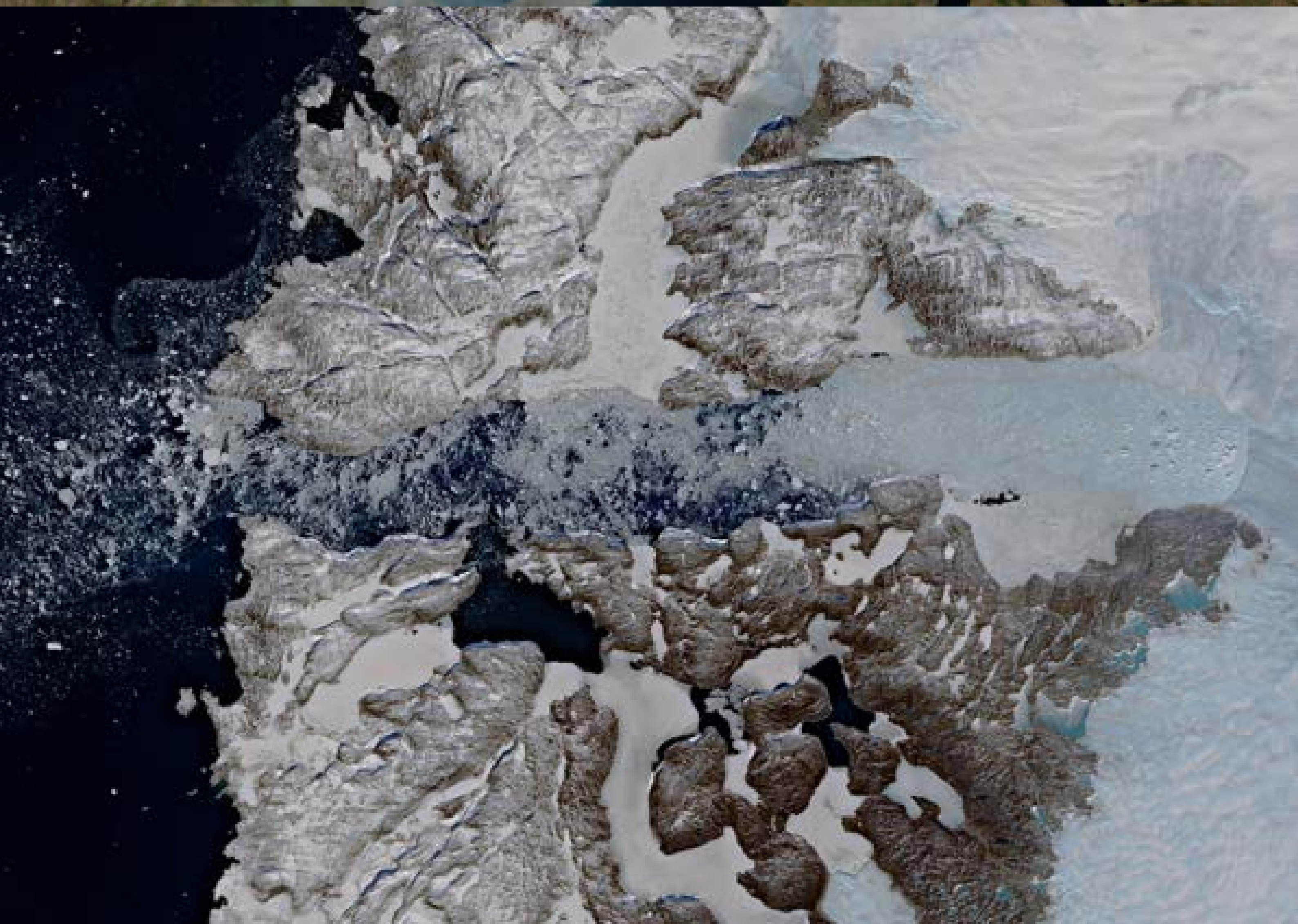
Credit: contains modified Copernicus Sentinel data, processed by ESA

The Ilulissat Icefjord in west Greenland

The Ilulissat Icefjord in west Greenland seen from Sentinel-2 on 29 April 2019. Massive icebergs calve from the Sermeq Kujalleq glacier at the bottom of the fjord. Various types of satellite data have been used to understand and monitor the glacier's flow over the last decades. The glacier and surrounding landscapes lie just south of the town of Ilulissat and is one of the most northern UNESCO's World Heritage Sites.

Credit: contains modified Copernicus Sentinel data (2019), processed by ESA


Greenland
Iceland



International Uses

Suporting Financial Inclusion

Sentinel-1 has been used as a key data source for the development of a decision supporting system for financial service providers.

Casper Samsø Fibæk, NIRAS

The challenge

Financial inclusion plays an important role in reaching several of the Sustainable Development Goals (SDGs). It is included in eight out of the seventeen goals but is particularly relevant for the first: ending poverty. Here, financial inclusion is described as the goal to secure equal rights and access to financial services.

To achieve these goals, it is necessary to assure that the services reach rural and poor districts. Research has shown that it is not merely physical distance to services that limits usage but also social distance. Poor and densely built urban areas are, in the context of financial inclusion, akin to countryside districts. Therefore, it is important to map different settlement structures.

> **This tool is making us more efficient at mobile agent deployment and will help promote trade between rural farming communities and peri-urban (food stuff selling) communities.**
>
> *Abednego Darko, DSS*

The mapping of financial inclusion is impeded in developing countries by the lack of high-quality geographical data and statistics. Therefore, satellite data is used for mapping residential urban structures. The analysis is part of a larger decision supporting system for which the purpose is to measure progress on the SDGs but also to enable financial service providers to find new business cases, which is necessary to ensure that all parties are invested in the progress towards the goals.

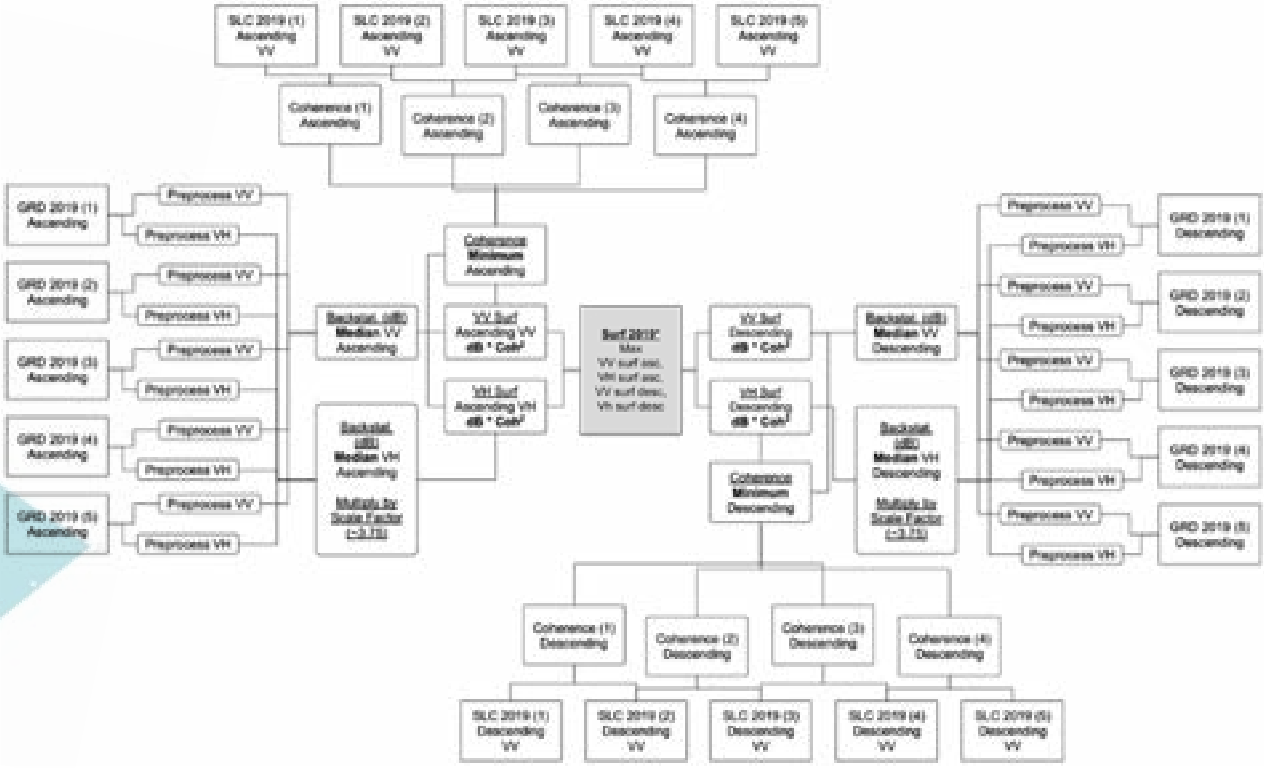
The space-based solution

Many satellite data sources have been used in the project. Sentinel-1 was used for an initial sorting of residential areas. This was achieved by making a mosaic of the dry and wet season for the area. Subsequently, coherence was calculated for both time-series and adjusted with backscatter. This resulted in a map of highly reflective surfaces which display a strong backscatter value and a stable signal across time. These surfaces are a good indicator for urban areas.

Sentinel-2 and texture analysis were used for segmenting the various areas. The local variance in the red and infrared bands is highly indicative of the type of area. A slum area has low variance in the green bands, while suburban and more prosperous areas have higher variance.

In addition to Copernicus data, night-time light from VIIRS (NASA) was also used. Night-time light is a good indicator for both density in residential areas and prosperity in developing countries.

Sentinel-1 image of the primary project area - Accra, the capital of Ghana.



Flow chart for processing Sentinel-1 involving several images and processing methods.

To combine the data, the satellite images were fused with OpenStreetMap data using the python machine learning toolboxes.

Processed map of surface structures in the capital region - 'Greater Accra Region'. The image is a combination of Sentinel-1 Coherence and Backscatter.

Benefits to citizens

Satellite imagery made it possible to create a decision supporting system for an area lacking basic geographical data. It has been important to assure usability, therefore, the finished analysis and supporting layers have been made available as a public API, which can be connected to various applications. To improve the usability for the financial sector, an add-in to Excel was made which enables querying in datasets. Through the add-in and the API, it is possible for financial service providers to make queries such as these: In which type of area are most of my banks situated? How many people can my mobile money agents potentially reach? Where is the most populated and least serviced area? What proportion of the population lives within half an hour's walk from an agent or bank?

Outlook to the future

The utility of satellite data in this project is at an early stage. A pilot product is completed, but there is room for improvement regarding the methodology and the accuracy of the estimates on demographic and socioeconomic indicators like, for example, prosperity and population density.

Acknowledgements

We wish to thank the Copernicus programme for making the data available. SNAP (European Space Agency and Orfeo Toolbox (CNES)) have been important tools in the project, which is a collaboration between NIRAS, Oxford Policy Management and The Mastercard Fund.

Satellite-based Warning System for Vector-borne Diseases

Satellite data, especially the operational data from Sentinel satellites, provides a unique tool in warning and monitoring systems for vector-borne diseases, including malaria and dengue fever.

Per Skougaard Kaspersen [A], Inge Sandholt [B], Martin Drews [A], Morten Larsen [A], Kenan Vilic [B]

A: DTU Management, Technical University of Denmark B: Sandholt ApS

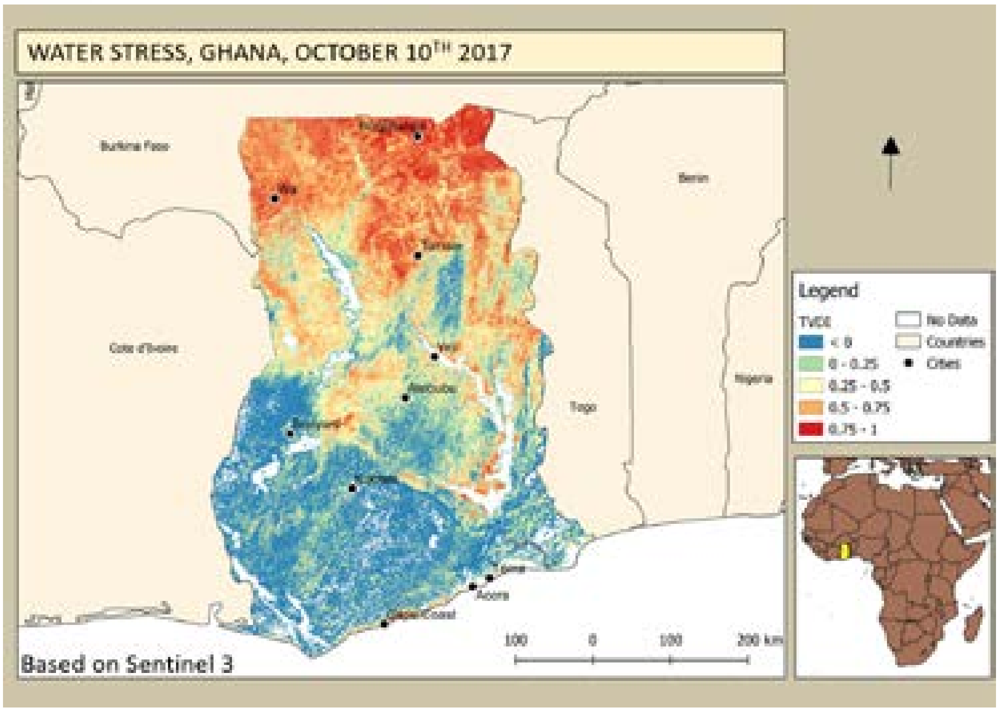
The challenge

Vector-borne diseases, including malaria and dengue fever, cause more than 700,000 deaths annually worldwide and account for approx. 20% of all infectious diseases. Furthermore, WHO estimates that more than 4 billion people in 128 countries live in areas at high risk of being infected with vector-borne diseases. Vectors are living organisms, such as mosquitoes, ticks and flies, that can transmit infectious diseases between humans or from animals to humans. Vector-borne diseases occur most frequently in subtropical and tropical areas and mainly among the poorest population groups in developing countries, including Africa. Outbreaks and spread of vector-borne diseases are influenced by a complex interplay between climatic, demographic, social and institutional factors. Climate change and changes in agricultural practices, e.g. increased irrigation, may affect the frequency of outbreaks and conditions favourable to the spread of vector-borne diseases. The extent of the diseases can be prevented and limited through various technical, institutional and behavioural measures. A key element for this is monitoring and identification of times and places where the climatic and societal conditions are ideal for disease outbreaks. Satellite-based warning and monitoring systems provide a unique tool for spatial and temporal observation of key climate parameters, such as temperature, rainfall, humidity (soil / air), and water availability in high spatial resolution. In combination with relevant socio-economic data, it will be possible to identify times and places where the risk of disease outbreaks is high.

Senegal River Valley, September 1999.

The space-based solution

The project will help to investigate the possibilities for developing new satellite-based methodologies and data products related to operational warning and monitoring systems for outbreaks and the spread of vector-borne diseases in developing countries. The products will include new improved



Water Stress, Ghana, 10 October 2017. Based on Sentinel-3 data.

estimates of critical climatic parameters, such as precipitation, temperature and soil moisture, based on state-of-the-art algorithms applied to Sentinel satellite data and other relevant Copernicus data.

In the innovation project, analysis and testing of existing data sets, including TVDI (Temperature-Vegetation-Dryness Index), and development of new data sets for temperature and precipitation for selected case areas in Africa will be performed. The overall purpose of the analyses is to investigate in what way and on what scale (with different spatial and temporal solutions) satellite-based estimates of climatic parameters, especially water and soil moisture and other indicators related thereto, can help to improve the mapping of the particular conditions which affect the outbreak and spread of vector-borne diseases. Thus to show how they can be a key element of operational warning systems for these diseases.

Benefits to citizens

The satellite-based data sets related to water will be linked to other data (in-situ measurements and reanalysis data), epidemiological data and relevant information on the social, institutional, economic and demographic conditions, which are also markers of vector-borne diseases. Against this background, a simple model for predicting the risk of an outbreak of disease will be established and used to benchmark and validate the satellite products. In addition, climate model projections for the relevant climatic parameters (precipitation, temperature) will be analysed in order to estimate the consequences of future climate change for outbreaks and spread of vector-borne diseases (and thus the market potential).

Acknowledgements

The study receives funding from the European Regional Development Fund (ERDF) and the Capital Region Growth Forum through a Water-Innovation-SME project hosted by Water DTU.

Large-Scale Wetland Mapping and Monitoring

Sentinel imagery is used to develop methodology for high-resolution mapping of vegetated wetlands.

Torsten Bondo [A], Christian Tøttrup [A]

A: DHI GRAS

The challenge

More than 1 billion people rely entirely on the provisional services provided by wetland ecosystems, and healthy and functional natural wetlands are intrinsically linked with human livelihoods, well-being and sustainable development. However, despite their value, wetlands are facing major threats due to several reasons: conversion for commercial development, overfishing, tourism, pollution and climate change, to name a few.

Thus, there is an urgent need to strengthen, and reinforce, national policies and legal frameworks to help countries protect and restore critical wetland ecosystems. Efforts to preserve and restore wetlands, however, have been hampered by lacking data on the locations, types and sizes of wetland resources.

This data and information are crucial to measure the effectiveness of policy, legal and regulatory mechanisms and essential for tracking progress against the Sustainable Development Goals.

The space-based solution

Accurate mapping of wetland extent is essential for monitoring habitat distribution, abundance, and connectivity, all of which are critical parameters for developing targets, plans and priorities for future restoration, protection and enhancement.

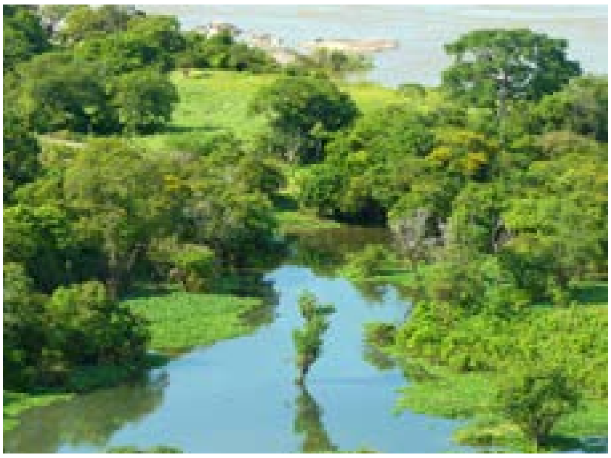
The dynamics and large diversity of wetlands are a challenge for global-scale mapping, and as of today, only coarse resolution data exists on a global level.

Traditional work on wetland mapping has relied on standard image processing techniques (map interpretation, digitizing, collation of ancillary data and image analysis) to compile spatial information about wetland extent. This process is both resource- and labor-intensive, inconsistent and difficult to scale.

> **The use of satellite-based Earth Observation data for monitoring water-related ecosystems is accepted as a viable source of information for decision-makers.**
>
> *Gareth James Lloyd, UNEP-DHI Center*

However, the Sentinel satellites now provide global imagery at the required temporal and spatial resolutions to accurately derive information on wetland extent in high resolution. Recent mapping efforts by GlobWetland Africa (http://globwetland-africa.org/) have demonstrated the multipurpose capacity of the Sentinel missions to support wetland assessment, inventory and monitoring across wetland sites and regions in Africa.

Wetland monitoring in Chad. The wetland extents can be input to UN national reporting on SDG 6.6.1.


AI technology is perfectly positioned to automate the analysis and interpretation of satellite images to detect and delineate wetlands at global level and with minimal human input.

Together with United Nations Environment - DHI GRAS has developed an artificial intelligence – machine-learning algorithm as a globally applicable method for mapping of vegetated wetland extents in response to the Sustainable Development Goals monitoring requirements (https://www.sdg661.app/). In a nutshell, supervised machine-learning algorithms are trained by example to build a general model for wetland extent prediction beyond the learning examples.

Benefits to citizens

Wetland monitoring is crucial for conservation and restoration of wetland ecosystems and is explicitly mentioned in many national conservation plans. Hence, monitoring and reporting is not only important for reporting on the Sustainable Development Goal indicators but should be anchored within and used by the national agencies to avoid further degradation of wetlands.

Outlook to the future

It is expected that the methodology in development could pave the way for a state-of-the-art scalable wetland monitoring methodology that can improve the management and preservation of global wetlands.

The findings could have global-level impact as the data and the algorithms developed within the scope of this project will be freely available to all countries in the world as a critical resource for tracking the status and extent of national and regional wetland ecosystems.

This will effectively bridge the information gap in many countries, regions and cities, allowing them to act and react to water-related issues and stresses through informed decision-making.

Acknowledgements

Thanks to United Nations Environment Programme.

Irrigation Management

More efficient irrigation management will contribute to food security, poverty alleviation and economic growth by sustainable use of water. Satellites can help provide important decision material for irrigation.

Torsten Bondo, DHI GRAS

The challenge

Irrigation is one way to expand agricultural production and ensure increased crop productivity.

Due to the rapid growth of population as well as drought and rainfall pattern changes caused by climate changes, it is expected that irrigation will play a more and more essential role in future agriculture.

However, while irrigation schemes provide an operational platform for efficient water mobilization and distribution, farmers/managers need to know when to irrigate, and how much, in order to derive optimal water use.

The space-based solution

Satellites can assist irrigation management by exploring irrigation potential and providing reliable information on spatially distributed Crop Water Stress as decision material for the irrigation managers.

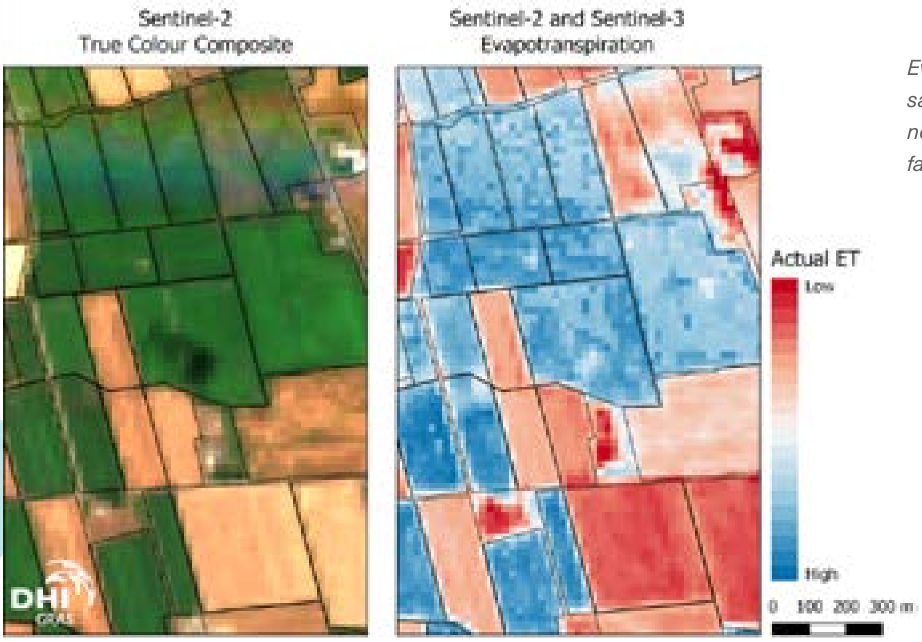
Easy access to reliable estimations of Evapotranspiration is considered a key requirement for this since Crop Water Stress is derived from evapotranspiration measurements. When evapotranspiration is successfully estimated at high resolution, it can be used to map crop water stress at field scale.

While extensive research has assessed evapotranspiration for water management using EO data at a regional scale, previous technology and satellite sensors have not allowed assessment of evapotranspiration at field level (farm level).

Evapotranspiration is a key parameter and part of the water cycle in agriculture. New technology for assessment of evapotranspiration based on Sentinel has been developed.

This has now changed, and Sentinel 2 (optical 10m) and Sentinel 3 (thermal 1km) European Space Agency satellites have the right combination of frequent revisit times, novel spectral capabilities and high-resolution images that makes the satellites ideally positioned to derive evapotranspiration at field scale.

Thermal data is essential for the estimation of evapotranspiration since land surface temperature (LST) forms the lower boundary in the land surface-atmosphere energy transfer system. The land surface temperature is produced from thermal observations of the Sentinel-3 satellite with a 1 km spatial resolution. This resolution is not sufficient for field-scale crop water stress monitoring, and



Evapotranspiration determined from satellites in high resolution. This technology will be used in the future by farmers to manage irrigation better.

therefore it is sharpened to 20 m resolution with the use of Sentinel-2 optical observations.

This sharpening is novel and will be applying machine-learning. Initial findings show that the sharpening technique performs the best when strong thermal contrast is present within the scene as is the case in an irrigated landscape.

> **"Farmer access to decision material based on reliable field scale evapotranspiration data could potentially change how farmers irrigate water intensive crops."**
>
> *Rita Hørfarter, SEGES*

This sharpening concept builds on already well-proven and previous engineering and scripting code based on combination and integration of open source software packages such as QGIS, BEAM and SNAP.

So far, results from this new method have been published and tested in the European Space Agency project Sentinels for evapotranspiration. New users are currently testing the product with promising results. See project website http://esa-sen4et.org/

Benefits to citizens

Beneficiaries are irrigation schemes in drought-prone countries eager to implement the source code and work with similar methods.

Outlook to the future

It is expected that the technology can lead to significant water savings for the same yield, which would greatly benefit farming community and irrigation managers.

Acknowledgements

Thanks to European Space Agency for funding the initial research going into the development of the evapotranspiration code in the sentinels for evapotranspiration project (http://esa-sen4et.org/).

Mapping of Grass Fallow Systems from Sentinel-2 Data

Accurate and spatially explicit mapping of fallow land in developing countries is an essential, yet neglected, part of food security monitoring.

Xiaoye Tong [A], Martin Brandt [B], Rasmus Fensholt [B]

A: DHI GRAS B: Department of Geosciences and Natural Resource Management, University of Copenhagen

The challenge

Remote sensing-derived cropland products have depicted the location and extent of agricultural lands with an ever increasing accuracy. However, limited attention has been devoted to distinguishing between actively cropped fields and fallowed fields within agricultural lands, and in particular so in grass fallow systems of semi-arid areas. In the Sub-Saharan Sahel region, one of the largest dryland regions worldwide, crop-fallow rotation practices are widely used for soil fertility regeneration. Yet, little is known about the extent of fallow fields since fallow is not explicitly differentiated within the cropland class in any existing remote sensing-based land use/cover maps, regardless of the spatial scale.

The space-based solution

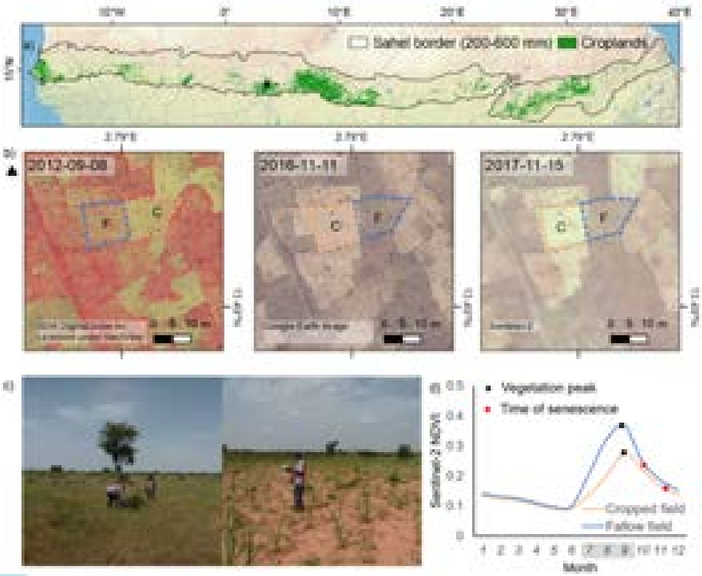
With a 10 m spatial resolution and a 5-day revisit frequency, Sentinel-2 satellite imagery has made it possible to disentangle agricultural land into cropped and fallow fields, facilitated by Google Earth Engine for big data handling. Here, we produce the first Sahelian fallow field map at a 10 m resolution for the baseline year 2017. Training data for the classifier was collected from VHR images provided by Google Earth, and Sentinel satellite data was processed in Google Earth Engine. The approach takes advantage of the differences in phenological behavior between fallow fields and actively cropped fields during the annual growing cycle. The full-year Sentinel-2 NDVI time series, representing one year of crop phenology, was used as predictor variables for the final crop/fallow land classification. A machine-learning classifier (random forest) was applied based on a two-step automated reference data generation workflow, which is spatially representative for the landscape studied and highly reproducible. For each Sentinel-2 tile, each decision tree grows on an independent bootstrap sample from the training data.

> **Sentinel-2 data has opened an exciting possibility for taking agricultural monitoring to a new level, which can improve agricultural statistics in developing countries.**
>
> *Rasmus Fensholt, University of Copenhagen*

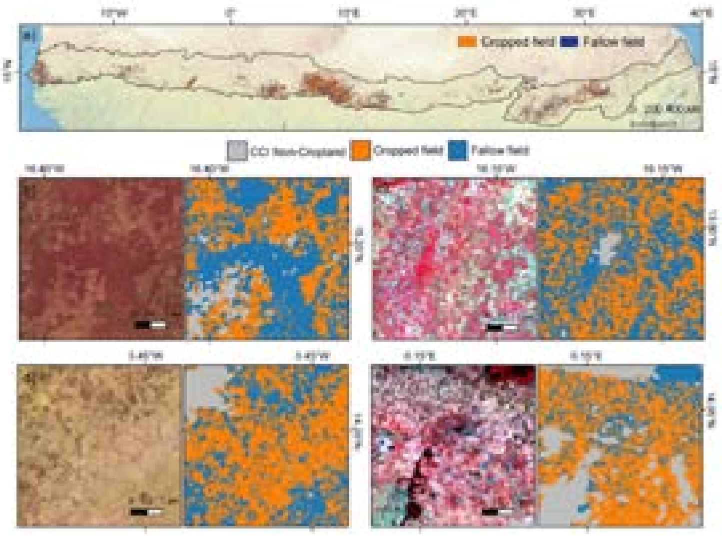
We found that fallow fields occupied 57-63% of Sahelian agricultural lands in 2017 (calculated among six different state-of-the-art remote sensing cropland products).

Benefits to citizens

Our application of Copernicus data advances current understandings of agricultural systems in the region as they demonstrate how fallow plays a greater role than previously assumed. Our approach provides a benchmark map of fallow fields across the Sahel, which can facilitate an improved understanding of how crop-fallow rotation cycles are linked to agricultural management practices, pressure on land, soil fertility and food security.



Seasonal Sentinel-2 NDVI signatures of cropped and fallow land across croplands of the Sahel. The difference in NDVI signatures between fallow land and actively cropped fields is evident.



Classification of cropped and fallow fields at 10 m for the Sub-Saharan Sahel using Sentinel-2 NDVI signatures. Examples are shown for subsets covering Senegal, Mali and Burkina Faso.

The results show that a considerable extent of what is mapped as cropland did actually not produce crop yields in 2017, which needs to be considered when food production is estimated based on cropland products.

The fact that fallow fields dominate over cropped fields contradicts common narratives that population pressure and increased demand for food have caused a Sahel-wide extinction of fallow practices leading to unsustainable land management systems. The method developed is reproducible for mapping the extent of fallow fields across global croplands.

Outlook to the future

Future applications based on multi-year time series are expected to improve our understanding of crop-fallow rotation dynamics in grass fallow systems. This is key in teasing apart how cropland intensification and expansion affect environmental variables, such as soil fertility, crop yields and local livelihoods in low-income regions across the world such as the Sahel.

Acknowledgements

This story is based on the work performed within the project: Greening of drylands (DFF-6111-00258): Towards understanding ecosystem functioning changes, drivers and impacts on livelihoods. The Danish Council for Independent Research.

Mapping of Individual Trees in Savannas from Copernicus Data

How Sentinel-1 and Sentinel-2 data advances mapping of savanna woody vegetation; from mapping of woody cover towards mapping of woody canopies.

Wenmin Zhang [A], Martin Brandt [A], Rasmus Fensholt [A]

A: Department of Geosciences and Natural Resource Management, University of Copenhagen

The challenge

Woody vegetation is a central component of savanna ecosystems, providing ecosystem services for local livelihoods. Accurate monitoring of woody vegetation in savannas is therefore desirable, yet large-scale remote sensing-based mapping approaches rely on coarse spatial resolution satellite data, which cannot directly capture the scattered nature of savanna trees. Present information at regional scale therefore resorts to mapping of the fractional cover of woody plants. The quality of existing products is low and it often remains unclear what kinds of woody plants are considered (e.g. shrubs, tall trees, closed canopy areas, forests).

The space-based solution

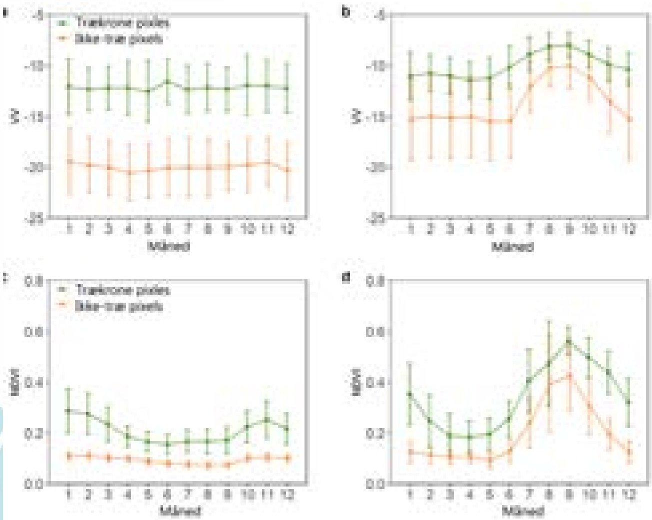
With the launch of the Sentinel satellites (Sentinel-1 and Sentinel-2), the spatial resolution of images approaches the size of medium/large tree crowns, providing the opportunity to map the presence or absence of tree canopies, rather than the fraction of woody cover or forested areas. Here, we used a machine-learning algorithm (support vector machine) to classify the presence/absence of woody canopies from Sentinel-1 and Sentinel-2 data at a 10-m spatial resolution for the entire African Sahel. Training samples for the image classifier were collected from VHR images provided by Google Earth, and Sentinel satellite data was processed in Google Earth Engine. The approach takes advantage of the differences in phenological behavior between woody and herbaceous vegetation (including crops and grasses) during the annual growing cycle. Monthly VV and NDVI signatures of woody canopy and non-woody pixels were derived from Sentinel time series (from July 2015–December 2018) overlaying the training samples.

> **The advent of Copernicus data has opened an avenue towards large-scale mapping of individual woody canopies for savanna ecosystems.**
>
> *Rasmus Fensholt, University of Copenhagen*

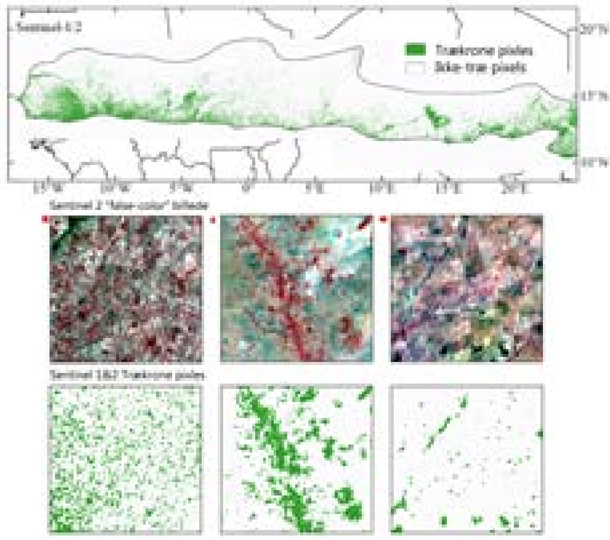
The mapping was compared with existing tree cover maps and showed noticeable differences, reflecting the need for new woody cover products adapted to the nature of savanna ecosystems. The woody canopy mapping from Sentinel performs very well and is able to reproduce the pattern of scattered woody canopies.

Benefits to citizens

This first mapping of savanna ecosystem woody vegetation at regional scale provides important information for the assessment of savanna ecosystems in relation to the causes and consequences of woody vegetation expansion or degradation.



Seasonal signatures of woody canopies and non-canopies for savannas of 5% (a+c) and 25% woody cover (b+d). The difference in NDVI and VV signatures is evident.



Classification of woody canopy pixels and non-woody pixels in Sub-Saharan Sahel using Sentinel-1 VV and Sentinel-2 NDVI signatures.

Timely remote sensing-based information at a 10-m spatial resolution about the distribution of woody vegetation in relation to the coexistence with herbaceous vegetation facilitates an improved understanding of the ecosystem services provided by savanna ecosystems. Sentinel-based mapping, in particular with a temporal component, could contribute to the management of woody vegetation in relation to e.g. the abundance of woody cover and resources in agroforestry systems knowing that woody vegetation can benefit crop growth and can provide ecological services, such as food, wood for fuel and building material. Moreover, analysis of woody vegetation changes in response to climate change, fire activities, and humans/herbivores can be explored to a greater depth to improve our knowledge on savanna ecosystems and how these can contribute to future ecosystem services.

Outlook to the future

The cloud-based Sentinel-1 and Sentinel-2 mapping is a step towards large-scale mapping of woody canopy in savannas. Ultimately, such direct assessment of woody canopy areas will allow monitoring of temporal dynamics of woody canopies in future studies as Sentinel time-series expands to multiple years.

Acknowledgements

This story synthesizes the work performed within the project: Greening of drylands (DFF-6111-00258): Towards understanding ecosystem functioning changes, drivers and impacts on livelihoods. The Danish Council for Independent Research.

Earth Observation for Sustainable Development

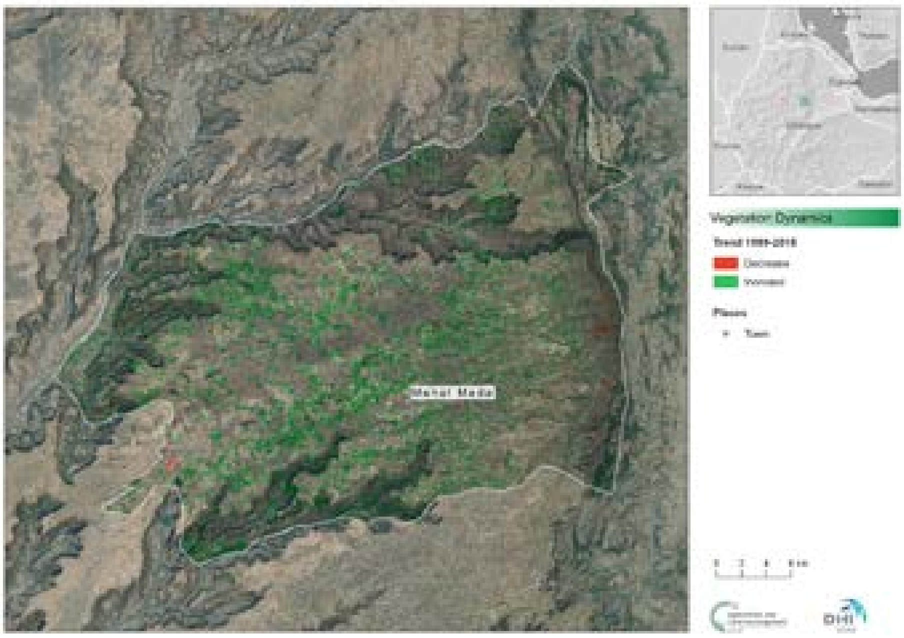
Enhancing evidenced-based planning, monitoring and evaluation of international development work for food security with satellite-based data and information.

Silvia Huber [A], Mads Christensen [A]

A: DHI GRAS

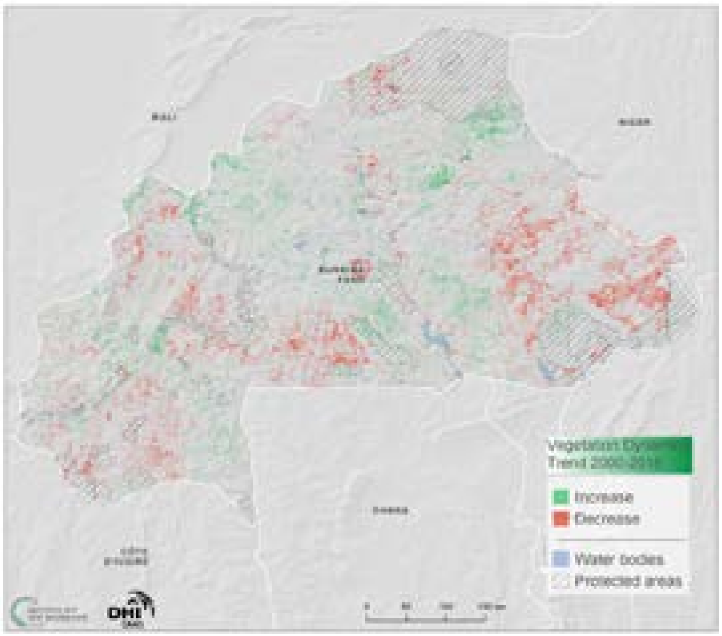
The challenge

Increasing demands for food, water, energy and essential services to fulfil the needs of a rapidly growing population have significantly increased the demand for land resources. As a result of the exacerbated intensity of human activity, many rural areas have experienced significant land degradation, consequently reducing the productive capacity of the land, in other words significantly reducing the production of food per land unit. Degradation is a complex process involving various driving factors, among which climate change, land use/cover changes, and human dominated land management play a significant role. Since land degradation is directly related to food security, international development work puts focus on sustainable land management and land degradation neutrality. However, concrete evidence on the impact of these investments does not exist, and the underlying drivers of land degradation processes



Satellite-derived vegetation dynamics at local scale for Menz Gera Midir (Ethiopia). For vast areas an increase in vegetation cover was mapped. The reason behind this trend is not known. The hotspots of decrease are mostly related to urban growth and steep areas.

Satellite-derived vegetation dynamics at country scale for Burkina Faso. Declining vegetation cover over the period 2000-2018 is mostly related to agricultural expansion and urban growth due to an increasing population. Increasing vegetation cover can be linked to protected areas but also mango and cashew plantations.



are not fully understood. This makes it difficult to identify policies and investments that will effectively combat desertification, to halt and reverse land degradation and halt biodiversity loss.

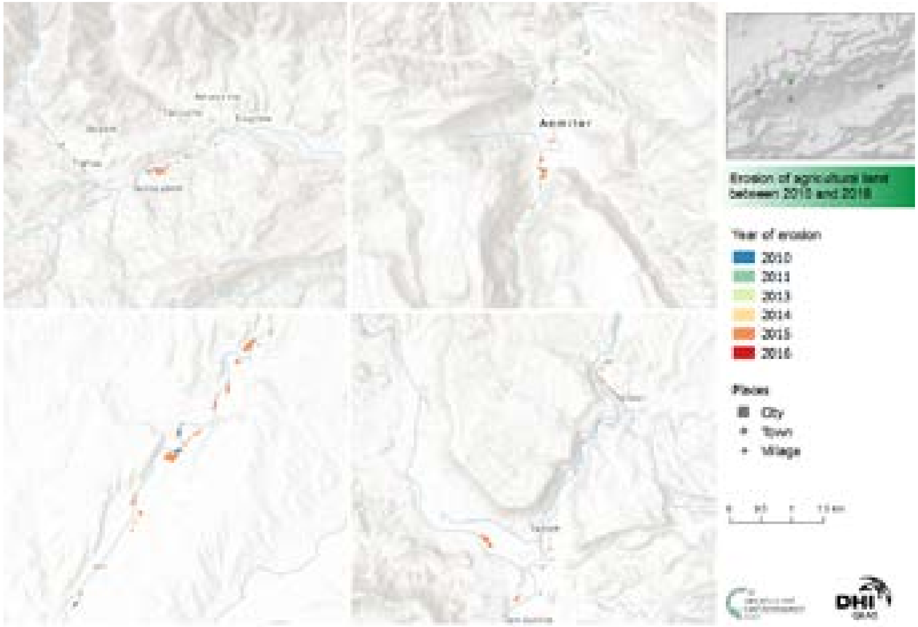
> **EO4SD introduced the satellite-based information collection and analysis to our project and partners. That was an eye-opener for me to think about the use of such information to document our base line and develop a monitoring system. I am still using the sample data EO4SD gave me for 2 districts as an example while I present the value of satellite-based information for our monitoring system. These data I got help me to demonstrate how satellite data, analysed and interpreted can have a meaningful information for policy makers.**
>
> *UNDP Project Manager, Global Environment Facility, IAP Food Security Child project*

The space-based solution

Satellite Earth Observation has major potential to inform and facilitate international development work in a globally consistent manner. EO4SD – Earth Observation for Sustainable Development – is an initiative of the European Space Agency, which aimed to achieve an increase in the uptake of satellite-based environmental information within the regional and global programmes of the Multilateral Development Banks.

Many of the driving factors of land degradation can be monitored using earth observation satellites. With the launch of the Sentinel satellites of the European Union's Copernicus Programme, an unprecedented amount of free and open data has become available which allow monitoring even at local project scale. The integration of information from different satellites that consider land use/cover change, land productivity, long-term vegetation cover dynamics, climatic as well as other contributing factors and combined with local information allows for a comprehensive assessment of the biophysical baseline at project start and progress monitoring during implementation. The same thematic information is available at different spatial resolutions, connecting the regional dimension with national and local processes. Depending on the indicator, the information derived is typically available on a daily, weekly, monthly, or yearly basis, both historically and near-real time. With these characteristics, spatial evidence-based land status indicators can be extracted, and statistics calculated for investment planning and project monitoring and evaluation of projects implemented by Multilateral Development Banks.

In the province Ouarzazate (Morocco), the only arable land often lies close to the rivers in the valleys. Owing to floods, the land is eroded regularly. This map shows the areas eroded and the year of the event. As can be seen, 2015 was the year with major floodings resulting in much of the cultivated land being eroded.



Benefit to the citizens

The engagement of EO4SD resulted in the implementation of earth observation-based monitoring systems in several pilot countries, including in Ethiopia for the *Integrated Landscape Management to Enhance Food Security and Ecosystem Resilience in Ethiopia* Project, funded by the Global Environment Facility programme on food security. The system implemented in Ethiopia provides regular EO-based data and information to underpin the requirement for evidence-based project monitoring and evaluation. The biophysical baseline was also derived from satellites for 2017, providing a good basis to follow progress of the implementation. The results of the final evaluation will be useful to assess which approaches were successful and therefore suitable to be applied in other areas. Earth observation-based approaches to inform evidence-based planning and monitoring and evaluation of international development projects have the potential to significantly improve project planning processes and implementation, while providing a solid and objective justification of public spending on international development work.

Outlook to the future

DHI GRAS will continue to engage in refining tools for monitoring ecosystem health indicators by integrating information from different data sources, including radar, optical and ground surveys. Future missions, such as the Copernicus candidate mission on Land Surface Temperature Monitoring, will further improve the ability of satellite data to underpin land and environmental monitoring in high spatial and temporal resolution in the future. Furthermore, the rapid evolution of deep learning approaches to automate satellite data analysis and identify discrete patterns within the data will be a game changer in the future, paving the way for a new avenue of opportunities to provide operational monitoring systems in near-real time.

Acknowledgements

We thank the European Space Agency for providing funding for the EO4SD project and we thank our partners in the EO4SD agriculture cluster. We also thank the Multilateral Development Banks and the local stakeholders that have contributed to this project through their engagement and collaboration, including the World Bank, the United Nations Development Programme (UNDP), the International Fund for Agricultural Development (IFAD) and the Global Environment Facility (GEF).

Satellite Derived Ocean Current Information for Ship Route Optimization

Satellite altimetry from the Sentinel-3 satellites is a unique tool to improve high resolution near real time estimates of the ocean surface currents important to navigation and route optimization.

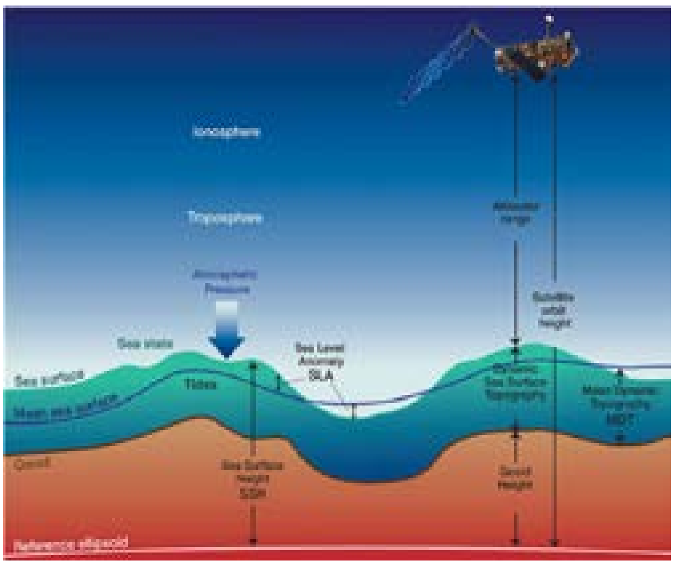
Ole Baltazar Andersen, DTU Space, Technical University of Denmark

The challenge

The operation of ships is affected by a number of environmental influences such as tides, currents, waves and winds. The maritime community has recognized the benefits of exploiting ocean currents at least as early as 1769 when Benjamin Franklin printed a chart of the Gulf Stream to expedite voyages between Europe and USA. In most oceans, there are regular currents that ships may be able to exploit for faster passage. Therefore, it is beneficial to take advantage of ocean currents when they are along the planned route, and to avoid the currents when they are in opposition. Accuracy metocean data are also essential for ship safety and entities performing complex operations during adverse conditions like search and rescue.

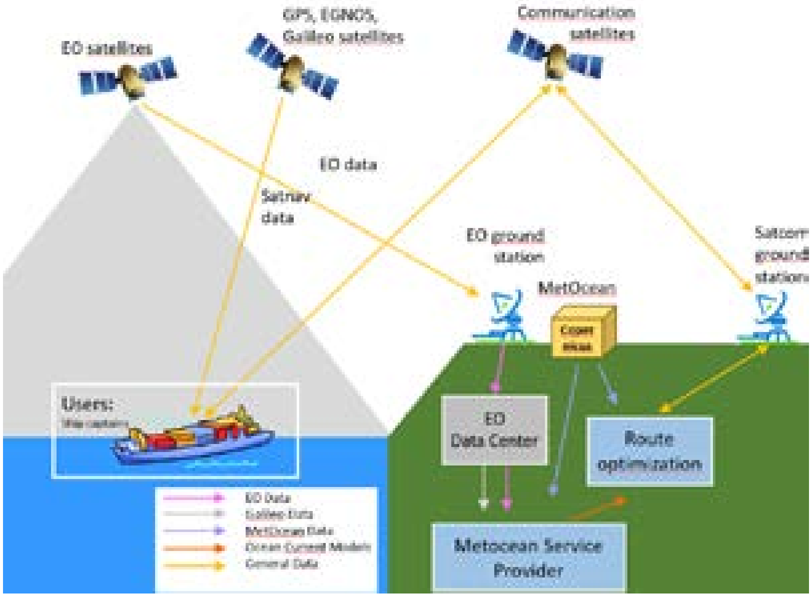
The space-based solution

The effects of dynamic currents have largely been neglected in earlier routing studies due to lack of reliable and timely estimates of dynamic current



Satellite altimetry explained.

Based on information on the dynamic sea surface topography along a transect on the ocean surface, the satellite is able to determine sea surface height and geostrophic currents, wind speed and significant wave height.



Use of satellite earth observation data to inform users like vessel captains.

patterns. However, technological developments in satellite altimetry now offer the potential for providing accurate estimates of currents, windspeed and wave height in near real time which can be used to improved metocean data or act directly as metocean information. The metocean information forms the base for the subsequent route optimization based on model predictions.

Benefits to citizens

With improved use of satellites, the ship is expected to realize significant time and fuel savings leading to improved scheduling even on some coastal voyages, whereas in the past, such savings were mainly realized on trans-ocean voyages. Route Optimization is a growing market, and with the expected increase in maritime activity in the Arctic, it is vital that high latitudes will be included in future systems. Here the dependence on EO information will be even greater, as the general metocean data will be less accurate, and only the European Sentinels will be capable of providing EO information for marine route optimization in the Arctic oceans.

Outlook to the future

Data from the Copernicus and, most importantly, the Sentinel-3 sequel of Sentinal 3A and 3B satellites was initiated with the Launch of Sentinel 3A on February 16, 2016 and Sentinel-3B on April 25, 2018. Today, they provide accurate estimates of currents, windspeed and wave height in near real time. Within a few years, additional satellites in the Copernicus programme like Sentinel-6/JasonCS as well as Sentinel 3C and 3D will continue to provide high quality data into the future.

Acknowledgements

A feasibility study called Blue_Siros has recently been completed with the support from the ESA Artes programme.

MOIST - Managing and Optimizing Irrigation by Satellite Tools

Leading Danish and European experts in satellite applications work with the agricultural sector to develop a system to optimize the use of water resources in farming based on Copernicus data.

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The challenge

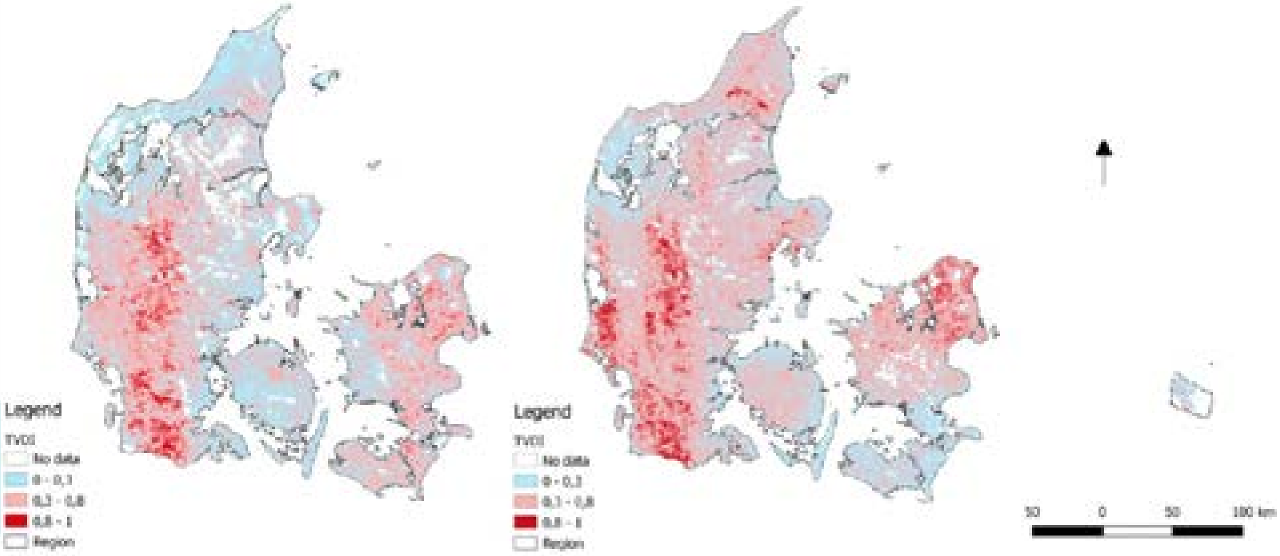
Water resources are under pressure due to the ever-increasing demand from growing populations and thus the need for increased agricultural productivity. Water scarcity is expected to increase in the future, leading to global focus on development of smart water management systems. An operational irrigation management system is in high demand. Currently, the farmers do not have access to spatially distributed information on the water status of their fields or timely information directly related to observations of crops. The MOIST project provides regularly updated maps of water status for agricultural fields and makes them available to farmers online, providing them with information on when, where, and how much to irrigate.

Irrigated potato field, Foulum, Denmark.
Photo: Jens Bonderup Kjeldsen.

> **The system will improve the crop yield from each liter of water used on a field. This will benefit farmers in the form of increased earnings and there are also environmental benefits in the form of reduced leaching from agricultural fields.**
>
> *Mathias Neuman Andersen, Aarhus University*

The space-based solution

MOIST will develop a system driven by time series of satellite data, freely available from the Sentinel sensors via the Copernicus programme. Satellite data replaces and complements conventional meteorological data, with the added value that satellite imagery provides direct observations of spatial variability of crop growth and water status. MOIST will exploit and combine different kinds of imagery each with distinct information content, which enables mapping and updating crop water needs in due time before the crop has been damaged by wa-



Water stress, Denmark May 6th (left) and May 14th, 2018 (right). Based on Sentinel-3.

ter stress. The philosophy behind MOIST is thus to combine multi-sensor satellite products of vegetation, evapotranspiration, soil moisture and crop water stress for agricultural areas. Main data sources are Sentinel 1, 2 and 3 operating in optical, thermal infrared and microwave-bands. Synergies between sensors and wavelengths across products will be exploited. With a cell resolution of 20m, irrigation water needs will be provided on field scale. Testing and validation of the system are carried out in Danish main crops, as well as in important crops in semi-arid Mediterranean climates (Southern Italy and Northeast Spain) where the summers are hot and dry and the winters temperate.

Benefits to citizens

The project will offer farmers a new tool contributing to optimize irrigation of agricultural crops. The project will strengthen the efforts of local consultants for optimization of field irrigation. Irrigation management is an important strategic area. On the 450,000 hectares of agricultural land that can be irrigated in Denmark, irrigation is the single most important factor for increasing crop yield. In addition to higher yields, optimal irrigation ensures much more stable yields and often crops of a higher quality. Based on winter wheat as a case, SEGES has estimated the direct economic potential for the Danish farmers by introducing more precise irrigation to 240 DKK/ha/year, roughly corresponding to a total of 100 mill DKK/year. Whereas water is not a limited resource in Denmark in general, it is indeed the case in southern parts of Europe or other parts of the world – in particular for the 40% of the world classified as semi-arid. Here, MOIST is expected to have a significant potential supporting growth in crop yield and at the same time provide more environmentally sustainable irrigation and water management on regional scale.

Outlook to the future

Overall, a more sustainable irrigation can be expected with less environmental impact, e.g. in the form of leaching of nutrients from soil. Sectors outside the agricultural, such as energy, environment and climate adaptation, may benefit from the satellite products developed in the project.

Acknowledgements

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Global Monitoring of Atmospheric Humidity

Water vapour plays an important role in the Earth's climate system. The Copernicus Climate Change Service now provides global monitoring of atmospheric humidity based on tracking of GPS radio signals propagating through the atmosphere.

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The challenge

Humidity plays an important role in the Earth's climate system due to the strong greenhouse effect of water vapour but also due to its role in the global energy transport between geographical regions and vertically between different layers in the atmosphere. It is central to the formation of clouds and precipitation and determines the fundamental conditions for the biosphere, including distribution of rainfall and droughts.

It is essential for climate researchers to be able to monitor atmospheric water vapour. There are also practical aspects of being able to monitor the climate system on a monthly or seasonal basis. An example is the El Niño phenomenon. Starting as a local warming in the tropical Eastern Pacific, the El Niño events have widespread global consequences, amongst them a general increase of the atmospheric humidity. The challenge is to obtain observations that have a global coverage and at the same time have the required accuracy.

Humidity is difficult to measure accurately on a global scale. It can be highly variable, rapidly changing on short time scales. Local measurements at weather stations or from weather balloons are rarely representative of a larger region of the atmosphere and are too sparse to provide a truly global view. Global monitoring of atmospheric humidity requires observations from space.

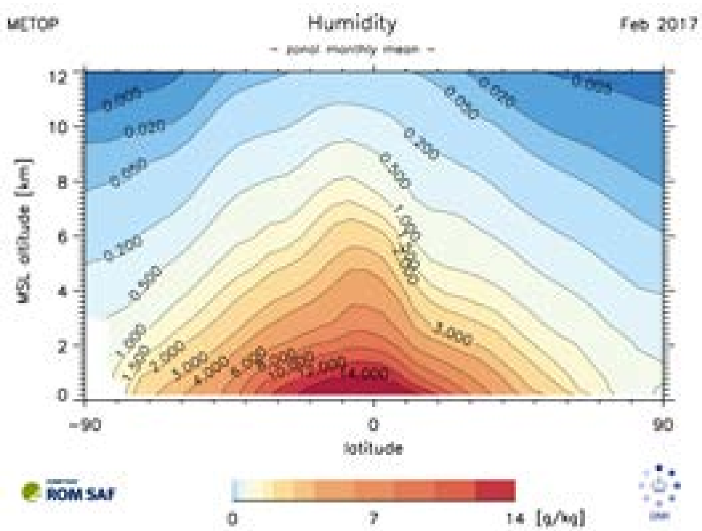

Figure 1: Global distribution of humidity over latitude and height in the lowest 12 km of the atmosphere.

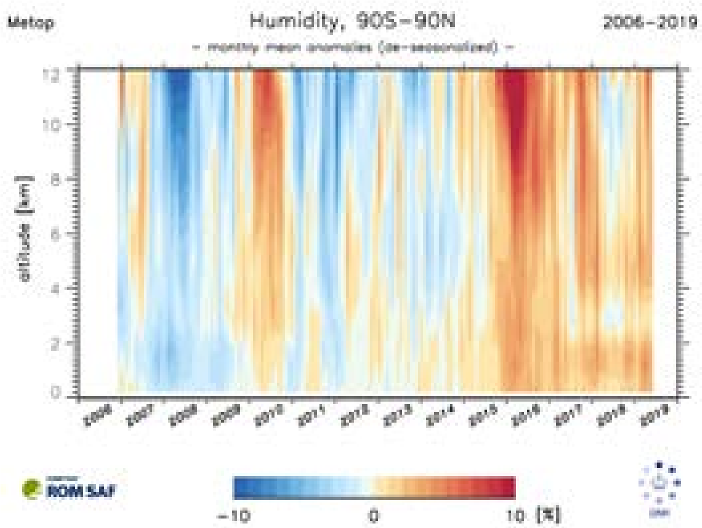

Figure 2: Global humidity anomalies (differences from a mean) in the lowest 12 km of the atmosphere, from 2006 to 2019.

The space-based solution

Such a space-based humidity data record is now available through the Copernicus Climate Change Service. The data is based on tracking GPS radio signals passing through the atmosphere. An advantage with this technique is that it is not affected by the presence of clouds or whether it is above land or ocean – the observations have a truly global distribution.

The humidity data record starts in 2006 and is regularly updated to cover also the latest season. Data is provided on a global latitude-height grid, covering the lowest 12 km of the atmosphere. Figure 1 shows the global distribution of humidity in February 2017 as measured by GPS radio occultation instruments on board the Metop satellites and combined with model data. This is during the northern hemisphere winter when the humidity peaked just south of the equator. Through the Copernicus Climate Change Service, we can view the peak in humidity moving back and forth across the equator as it follows the seasonal cycle of the tropical regions where water vapour is transported into upper air.

The humidity data record available through the Climate Change Service currently covers around 13 years of data. Comparing these data with other climate data records reveals interesting inter-connections in the Earth's climate system. We can follow how the global humidity responds to the El Niño episodes in the Pacific. Figure 2 shows the globally averaged humidity from end of 2006 up to middle of 2019. The major El Niño events in 2009-2010 and in 2015-2016 are closely followed by a relatively large increase of the atmospheric humidity. A closer inspection reveals that the global humidity also reflects weaker variations in the tropical Pacific.

Benefits to citizens

These types of long-term data records provided by the Copernicus Climate Change Service help researchers disentangle the mechanisms behind variations of atmospheric water vapour. This is essential for improving the global climate models that provide important information for policy makers, nationally and internationally. The emerging climate services can use this data to monitor, on a monthly or seasonal basis, how the global climate responds to, e.g., episodes of sea-surface temperature variations. The data is instructive and easily understood, also for non-specialists.

Outlook to the future

The data is based on a remote-sensing technique under rapid development. We can foresee an improvement in the level of detail in the horizontal, geographical distribution of water vapour, as well as on shorter time scales.

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