Future Satellite and Drone Monitoring of the Baltic-Adriatic Corridor, Harbors, and Motorways of the Sea

Roadmap

TENTacle Blekinge pilot case 3.1, Blekinge Institute of Technology, Sweden

Version: final report, 2019-08-31

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Baltic Sea Region
EUROPEAN REGIONAL DEVELOPMENT FUND
EUROPEAN UNION

Project: Roadmap - Future Satellite and Drone monitoring of the Baltic–Adriatic Corridor, Harbors, and Motorways of the Sea.

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Abbreviations

BAC	Baltic Adriatic Corridor
CD	Change Detection
CEF	Connecting Europe Facility
CNC	Core Network Corridors
DLR	German Space Agency
ESA	European Space Agency
GMTI	Ground Moving Target Indication
INEA	Innovation and Networks Executive Agency
ITS	Intelligent Transportation System
MoS	Motorways of the Sea
MS	Member States
SAR	Synthetic Aperture Radar
ScanMed	Scandinavian – Mediterranean Corridor
TEM	Trans-European Motorways
TEN-T	Trans-European Transport Network
UBC	Union of the Baltic Cities
UAV	Unmanned Aerial Vehicle
VTM	Vessel Traffic Monitoring

Summary

The effects of a system's implementation can be difficult to analyze and measure without appropriate metrics, not least from a more general perspective. Insight identifying the need for new objective metrics for the European transportation network gave rise to the idea of using Earth observation satellite systems equipped with a high-resolution imaging Synthetic Aperture Radar (SAR). This insight became the starting point for a pilot study, in the Interreg Baltic Sea Region project TENTacle, established within the framework of the INTERREG EU-Program 2014–2020. The aim of this study was to improve mobility, intermodality, and interoperability on the major transport axes across Europe. The goal of the TENTacle project was to develop suitable recommendations for decision making on transport policy for the Baltic Sea Region.

Global Earth observation satellites equipped with advanced radar technology (SAR) has emerged in recent years. Today, there is a major shift towards increased availability of radar data, and this trend is set to continue with a significant increase over the coming years. In parallel, drone systems for local observations are also emerging. Today, advanced drone systems can track logistic activities in a harbor, for example, in a very cost-efficient way. Both global observations using satellites and more local observations and measurements with drones can provide valuable information and contribute to increased knowledge and insight on European networks, both along the paths as well as the TEN-T nodes.

This report contains results from field measurements in the north of Europe (Southern Sweden), where the German satellite system TerraSAR-X[1] and TanDEM-X (operated by German Space Agency DLR) and a drone (provided by a Swedish company) were used. The first aim was to establish the methodology (which is required in a full-scale satellite measurement). Thus, the methodology included the following aspects: how to select the measurement range, ordering measurements for the selected area, and downloading satellite data from specific outlets. The second aim was to verify how the measurements could contribute to pre- and post-analyses in various ways, when any improvements to the new extension of the Trans-European Transport Network (TEN-T) system are introduced. The third aim was to evaluate drone data, as the study was conducted in an area where drone measurements could be performed.

The report presents the overall objective to link key ratios, which in turn are considered relevant for evaluating the effects of goods transportation along key corridors (such as traffic flows, intramodality, and capacity in ports and terminals). The main focus of the report is to show how satellite-based systems enable measurement, but also to show how to estimate the ability of other surface-covering systems (such as drones and airborne systems) to deliver a measurement system, based on an analysis of accessibility, quality, cost, and usability.

[1] TerraSAR-X, and TanDEM-X are imaging radar Earth observation satellites, and they are a joint venture being carried out under a public-private-partnership between the German Aerospace Center (DLR) and Airbus Defence and Space

1. Introduction

This report is a part of the EU TENTacle project, a flagship project of the Baltic Sea Region Programme initiated in 2015 by Region Blekinge. The TENTacle Baltic Sea Region INTERREG project focuses on the relationship between transport and regional development. It seeks to capitalize on major EU investments in transport infrastructure such as the Trans-European Network, (TEN-T). The TENTacle project aspires to involve public and market stakeholders in a joint effort, to develop policy and action recommendations, enabling benefits to be drawn from the TEN-T core network corridors. This will provide prosperity, sustainable growth, and territorial cohesion.

1.1 Background and motives

The expansion of the TEN-T has a positive impact on society in several different ways, and not necessarily just changes in goods movement patterns. It is difficult to measure and evaluate how such an expansion can change or affect heavy traffic on the TEN-T on a large scale. In recent years, the opportunity to study the effects on a large-scale have emerged from the development of new technology and methods. The effects of the extent and implementation of a system can be difficult to analyze from a more general perspective, and overall analysis can play a key role in improvement and expansion of the system. This report intends to highlight such opportunities.

Unlike older systems, new analysis techniques based on surface measurements from platforms at both high and low altitudes mean that it is now possible to present new types of information in a very efficient way. High altitude platforms (aircraft and satellite) with advanced radar equipment can not only depict specific parts of regions, but also map movements and changes (such as heavy vehicle movements) in the Core Network Corridor (CNC) transportation system in a more comprehensive way. Using external measurement, traffic is measured at different points simultaneously from high altitude over a large geographical area. In this report, the trial in southern Sweden included geographical areas the largest of which was approximately 700 km², with a corresponding altitude or orbital height of the satellite taking the measurements at 514 km. The introduction of new routes and intermodal terminals in the TEN-T CNC can contribute to new, difficult-to-predict, complex movement patterns and chain reactions of human activity. It is important to analyze such changes, and new advanced satellite measurement technologies has the potential offer a breakthrough for post-analysis. Low altitude platforms (drones) equipped with cameras can monitor intermodal terminals by visually recording any changes in the port. Thus, these systems can contribute to optimizing harbor efficiency. Bottlenecks can be handled as they appear, and inflow is easy to measure. In the experiments carried out within the framework of this project, the operating altitude of the drone was approximately 120 m.

What primarily characterizes the satellite system technology in this report is that both measurement and analysis can take place at any time (day or night) and it is based on radar technology, which, unlike traditional satellite-borne optical systems, can also operate under difficult weather conditions. Another important characteristic for high altitude platforms is that a single measurement involves a scan of a very large area (such as a larger part of a terminal, port, or part of the TEN-T CNC). Previous studies involving satellite observations of traffic with satellite-borne optical sensor systems have indicated that there are difficulties with light conditions and optical artefacts (such as shadows from trees or cars) [1]. However, a synthetic aperture radar (SAR)-based satellite system is very robust, because it can measure during both day and night, regardless of weather conditions. However, with regard to drone measurement, the optical systems commonly used are sensitive to severe weather conditions. In the same way, haze and fog at low altitude can impair the drone system's ability to take measurements effectively. The advantage of the drone (compared to high-altitude systems) is that it is not significantly affected by compact cloud base in the same way as optical satellite systems, because the drone normally flies low (usually at 100–200 m above ground), far below the clouds. In this context, the combination of a low-flying optical system with a high-altitude radar system is a successful combination.

Measurements and analyses with SAR technology [2] from satellites can, in a more accurate way, compare differences and similarities across the entire geographical transportation system in different respects. Before, during, and after the introduction of investments in the road network, it is possible (in a completely new way and with a completely different understanding) to assess changed behavior patterns and traffic impact. Currently, in many cases, the basis for traffic change is derived from measurements that are calculated based on information from different measuring systems. Despite accuracy and a lot of work, this unfortunately can lead to inevitable discrepancies that surface-based measurements do not suffer to the same extent. Satellite measurements with the proposed radar system are taken with the same measuring system at different locations across Europe, in the same way, all year round. Surface-wide measurements of inflows can provide new important information and possibly replace existing measurements and measuring systems; at the very least they can supplement existing data sources in a very efficient manner.

The ability to study, analyze, and evaluate the effects of new routes and extensions of the road network and terminal development reliably will not only effectively contribute to future decision-making processes, but also include how future corridor improvements can be made to the transportation system.

Therefore, the focus of the pilot study lies in how new technology can create a better understanding of how a transportation system contributes to change. It tries to identify the importance of developing new, necessary tools for systematically understanding and comparing implementation, by measuring before, during, and after the change.

1.2 Purpose of the Pilot Study

The purpose of this study is to contribute to new methodologies for identifying changes along our TEN-T and CNC transport corridors. The report focuses on how measurements from satellites with

SAR technology and drones with optical sensors can contribute to the evaluation of new roads, routes, or intermodal terminals as they are introduced.

SAR is a specialized advanced radar system, in which a large number of conventional radar images are compiled to produce a radar image with higher resolution. The focus of this report is on goods and traffic movement, and how measurements from satellite, as a completely new method, can establish an approach using totally new principles. This presents a significant opportunity for traffic measurement that can contribute to measuring relevant identified factors considered important for the development of a corridor.

The measurement method used in this study is unique, and the purpose to exemplify how an objective mapping method for traffic measurements can contribute to further develop of traffic corridors. The intention is to establish knowledge about the ability to measure traffic in larger areas (throughout Europe) in the future, using the same measuring system. A key objective here is to understand how this approach can contribute to analysis, indicators, or forecasts in the context of the development of the TEN-T.

In addition, a further objective is to understand the methodology required for full-scale measurement (for example, a comprehensive order and data collection, with analysis, and its contribution to automated pre- and post-studies in investments or new routes, such as before/after an expansion of TEN-T). Another important aspect of this part has been to verify that an order of measurement data from a satellite can be derived from a specific environment (port, road, or terminal) at a given time when a measurement takes place, as shown in Figure 1.

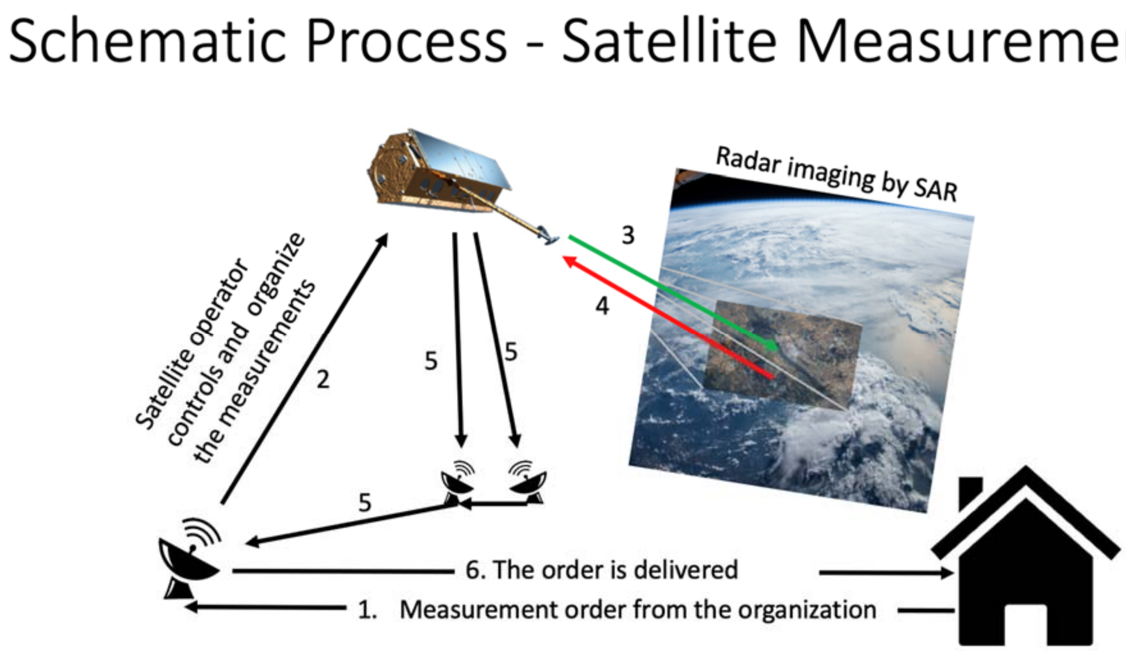


Figure 1. Schematic description of satellite measurement. The client requires traffic measurements over a large geographical area e.g. all roads and intermodal terminals around a port. 1. The client's order is sent to a service provider (the satellite operator). 2. The satellite is directed towards the measured area. 3. Radar sends out the pulses frequently when the satellite passes the area. 4. Reflections from vehicles (radar echoes from the area) are recorded. 5. When the satellite passes reference stations on Earth, the

data from the measurement is dropped from the satellite to the stations and then forwarded to the satellite operator. 6. After processing, the satellite operator delivers high-resolution radar "images" back to the clients. These "images" then form the basis of a computer processing by the client, which results in information on traffic measurement.

Traffic changes usually affect an associated geographical area, and satellite measurements over larger areas in different regions are therefore important for analyzing these changes appropriately, and interpreting within the correct context. For example, such changes might be the effects of new paths.

2. New measurement methods for TEN-T Core Network Corridors

The development of corridors is an important part of the EU's infrastructure investments. This section of the report presents several examples of how new satellite/airborne metrology could be used in future. In this section, we define the different types of paths, which include roads, motorways of the sea (MoS), and important railways that intertwine important transport nodes within Europe. In this context, nodes are particularly important features of the corridor, typically from located in more urban or more transport logistically significant environments, such as ports or intermodal terminals.

2.1 Path efficiency

For a functioning corridor, efficient paths between nodes are required in the network. In this context, “effective” means that the given volume of goods or vehicles expected to travel from one point to another can do so without unnecessary detours or delays. In several different ways, this study has deepened our understanding of how satellite or drone measurements can effectively contribute information to achieve even more efficient and sustainable transport chains.

It is important to point out that this report contains several different possibilities; it is also the case that, for example, a satellite can conduct data collection in slightly different ways. Different procedures can contribute to special and very useful measures, depending to an extent on what the decision-makers want to study. It is also the case that the subsequent processing of data needs to be adapted to conform to previous methods of analysis, to maximize measurement carried out over the specified area.

When it comes to studying traffic between nodes, this usually occurs with paths or routes of some kind. For example, it might take place along roads or motorways, along fairways or on the open sea, or along the railways. For studies between nodes in the corridor, it is usually the maintenance of flows that are considered most important. In most cases, obstacles along a transport corridor add unnecessary extensions to transport times, which is why establishing a flow is so important along a path. A bottleneck in a single place can lower the efficiency and flow of an entire route.

A further point of interest for decision makers is how investments and regulations (legislation) affect the transport fleet's composition. For example, a team that stimulates more departures from key ports may eventually contribute to a fleet of smaller vessels. In the same way, requirements for filling levels can affect vehicle fleets, eventually consisting of smaller trucks but with an increase in the number.

These issues depend on differing criteria when it comes to measuring technical aspects. Flows over surfaces or flows along corridors of different lengths are more suitably measured with high resolution capture of movement and speed. Such measurements are usually very reliable, at the expense of a relatively low-detail solution.

If decision makers are interested in studying changes in vehicle fleet composition, then a higher-resolution measurement mode needs to be ordered and applied. A future possibility with the high-resolution method is that it is possible to achieve classification, and with the support of advanced methods for analysis and AI, create the basis for changes between the measuring occasions.

An important parameter that cannot be selected afterward is which measuring mode to use. This needs to be clearly stated by the authority before being able to move on to conducting any large-scale measurement.

2.2 Node efficiency

Here, it is the case that a transportation chain is no better than the weakest intersections or nodes that exist along the way. It is of note that the size and efficiency of vessels does not matter if the corridor is unable to handle them. This applies to all types of transportation, and whilst not typical of seaways, is applicable to land-based transportation. In this context, nodes are usually intermodal terminals, ports, truck ports, parking spaces around harbors, and the extensive transport network that usually supplies the port with freight transport.

When it comes to nodes, there may be a slightly different starting point for the focus of this study. It could be about node activity in the form of surfaces occupied by goods and trucks, or the activity that takes place during loading and unloading. It is important to decide in advance whether to study instantaneous activity on a specific occasion, or the difference between two different occasions.

Change detection (CD) is a technical term that is central to these contexts. Simply put, it can be said that CD is the ability of a given system to compare the same surface on two different occasions. There are many different possibilities when it comes to this type of measurement technique, and there are great opportunities to conduct comparative studies between nodes such as ports, supports, and terminals. As the measuring system is carried by a satellite, such studies can easily be made between Member States, but other continents can also contribute to such comparative studies.

2.3 Satellite measurements of path and node efficiency

As previously mentioned, radar satellite measurements are not necessarily taken with the same resolution; hence, the ordered measurement mode is an important parameter. With regard to paths, SAR satellite measurements can contribute with completely new dimensions that are also very powerful. This means it is not only the ability to measure over large parts of a corridor, but also the advantage is that measurements can be taken over completely different geographical parts of a corridor and all over the EU.

By measuring larger areas, a better estimate of flows in a particular region can be measured in a completely new way with high accuracy, which also enables future comparative studies. The only requirement is that the estimation must be in a well utilized part of the corridor to be able to convey relevant information to decision-makers accurately and with good statistics.

Our study exhibits a fair ability to measure the speed of heavy vehicles and make good flow estimates over large areas.

Regarding the ability to measure static goods in important nodes, it seems effective to change the measuring instrument on the satellite to one of higher resolution. This provides the fantastic ability to measure and see small changes in freight handling in terminals and ports.

Our measurements and verifications within the framework of TENTacle show a good potential to study the movement of vehicles, very small changes, or movements from one day to another. Our experiments have been validated with measurements from a drone.

2.4 Drone measurements of path and node efficiency

A drone can be used as an amazingly powerful measuring instrument that is very flexible. There are very few disadvantages of using a drone, which mainly related to taking measurements in a corridor. Specifically, the altitude and weather conditions can become problematic. The altitude is something that is normally regulated by the authorities and is a parameter that cannot normally be changed. In addition, there are restricted zones within the corridors (such as near airports), where flying is either severely restricted or forbidden. Regarding the weather, drones are much more sensitive to weather than satellites. Heavy rain or snow are perhaps the most difficult weather conditions for drones to negotiate, but strong winds also need to be addressed and taken into consideration. While satellites with radar measuring instruments have no such limitations, drones are a very powerful and cost-effective method of collecting large amounts of information for a relatively low cost. Drones are widely available today, and in TENTacle they have been used to document radar satellite measurements. Within this project, different types of methodologies have been developed with regard to goods and transport measurements. We have also explored the ability to count cars from the air or carry out simple classifications.

3. Pilot study technical results

During the TENTacle project, a pilot study was conducted to test the use of satellites and drones to measure transport in the TEN-T network. From this study, we have derived many conclusions, many of which are technical, and some are at a higher level. In the previous chapters, we have drawn general high-level conclusions, while in this section we will present more technical results. Important conclusions about the measurement philosophy are also provided in Appendix A.1, and a background of the satellite-based measurements used is provided in Appendix A.2. In the pilot study, we performed physical experiments with drones and satellites, and we developed processing tools to measure parameters of interest in the TEN-T network. The first experiment was conducted in 2016, and the last measurement was made in 2019. In Karlshamn, we took road traffic measurements close to the port using drones, cameras, and satellites. We also took drone and satellite measurements in the ports of Karlshamn and Karlskrona.

3.1 TENTacle traffic measurement experiment

Many traffic measurements have been collected relating to the harbor in Karlshamn. Here, we present some of the general results obtained from these experiments, which are divided into satellite measurements and measurements made by drones equipped with a camera.

3.1.1 Satellite-based SAR traffic measurements

In the harbor, the measurement campaign was carried out within TENTacle, as expected by the Swedish authorities. Both the Swedish Transport Agency and the Swedish Transport Administration were interested in the study and supported the ground-breaking initiative to measure traffic with satellite SAR. Within TENTacle and in national initiatives, there has been a great deal of interest in measuring changes in truck traffic across larger areas (measurements at different time instants over large road networks). For this reason, the measurement campaign included 20 satellite measurements over the road network in the western part of the province of Blekinge. The measurement campaign took place during 2016, after which time the operator changed to a new satellite measurement mode. An advanced measurement solution such as an SAR satellite can be reprogrammed to create specific measurement properties (Appendix A.2) that fit exactly with what is to be measured. In the large-scale road network case, modes for movement detection and speed estimation were used (of great interest for vehicle measurements in the road network). The purpose of the campaign was to collect data for an initial evaluation of the ability to monitor traffic flows based on SAR technology. As part of the campaign, a dedicated experiment was conducted with four different trucks. Truck 1 was a tank trailer, truck 2 was with a cabinet and cabinet trailer, truck 3 was tank truck with tank trailer, and truck 4 was only a truck tractor. All truck routes were logged with GPS, which allows you to see the exact location, speed, and direction of each truck when the satellites passed.

In the experiment, the twin satellites (TerraSAR-X and TanDEM-X) [4] flew very close to each other, with a separation (space between the satellites) of only a few hundreds of meters. The measurement period was approximately 7 s, and an area of approximately 35 km × 35 km was depicted. However, each spot on the ground was illuminated for less than 1 s. This short illumination time limited image properties such as resolution. Further, because the illumination of each truck lasted for a period of less than 1 s, the trucks only moved a short distance (less than 25 m). The assumptions (or approximations) used in SAR processing that the trucks moved in straight lines at constant speeds were appropriate for this type of measurement.

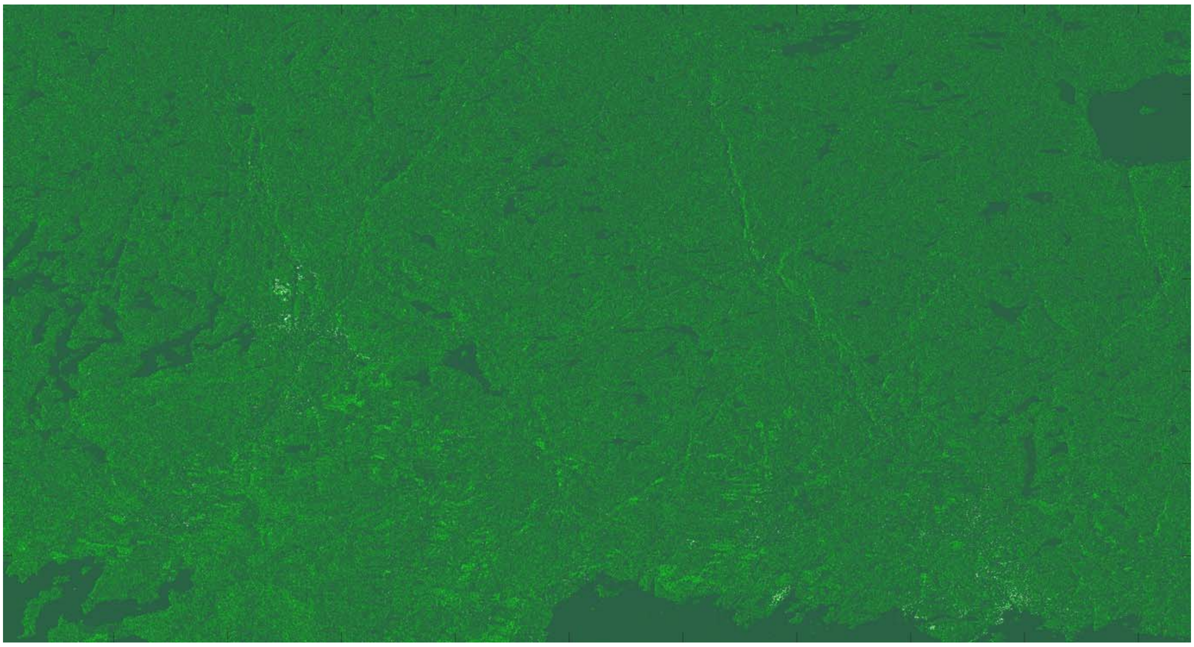


Figure 2. One of the TerraSAR-X images used in the experiment. In the upper right of the image, Lake Mien is located, and in the lower right, the harbor of Karlshamn in located.

One of the SAR images from the campaign is shown in Figure 2. The SAR image covers a large area, from Ivösjön in the southwest to Lake Mien in the northeast of Sweden. In the image, the cities of Olofström and Karlshamn are easily identified. Figure 3 shows a truck close to the port, and also shows how a moving truck appears in an SAR image.

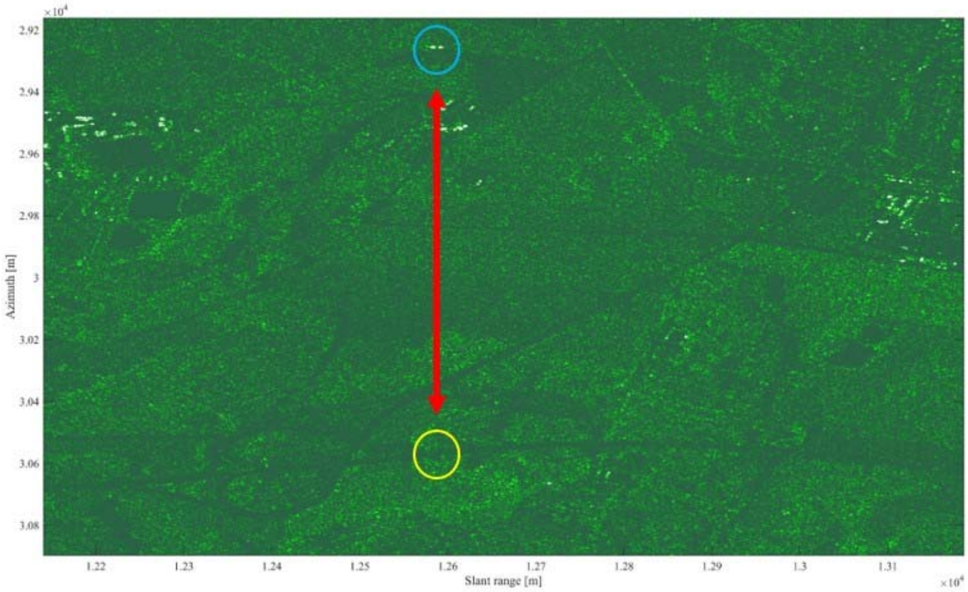


Figure 3. In blue is the truck with trailer appearance in the SAR image and yellow is the truck in its true position.

The truck appears far from the road where it is moving. This is an effect of SAR image formation. Stationary objects on the ground appear in the right place, but anything that moves in the scene will be displaced from its location in the image. In the experiment, all trucks could be detected, except the truck tractor. This is not surprising, because the measuring mode and method have been developed to extract vehicles moving in the range direction optimally. To increase performance, the software must be developed further to handle cases with targets that move parallel to the satellite. This is indeed a development potential in this regard.

The project also focused on adapting and developing algorithms to the new format of TerraSAR-X as provided. Several steps were required to achieve this aim. The initial step consisted of building a simulation environment for the TerraSAR-X and TanDEM-X systems. The purpose of this was to ensure that the algorithms worked well in the specified manner, and to enable assessment of abilities such as detecting and estimating vehicle speeds in the later stages. One objective of the project was to make a test sample (order) of satellite data and implement the simulation environment to verify that trucks can be measured as specified. In this type of project, there is always a risk that the goals specified in advance will not be reached. Real experiments are always accompanied by a great deal of uncertainty with respect to time planning, and tasks usually take longer than expected. This project has already taken considerably longer than we anticipated in our original project plan. The simulation environment works and delivers at a satisfactory and sufficient level. We have even conducted a real experiment with measurements over Sweden, where we demonstrated that the technical proposal works. The time limitations meant that we relied on relatively robust estimation methods; however, despite the relatively primitive algorithms used, the experiment showed future potential, and at the very least great development potential. In the next part of the report, some of these results are presented. However, to understand the significance of the test measurements, these must be put into context. Therefore, we start the description by clarifying the used measuring principles, which were mentioned to some extent previously. The first principle is CD, and the second is ground moving target indicator (GMTI) using radar detection [5]. We start with GMTI, which was our main focus during the experiment.

In simple terms, GMTI measurements occur at the same place in space but with two or more measurements in time. The method has been used in traditional radar technology since the 1940s. The technology evolved for high-resolution radar (such as SAR), where GMTI gained its impact just 20 years ago. Then, it was only available as a research tool, primarily with a military focus. Today, it is used operationally in military systems and the technology has just been introduced for civilian applications.

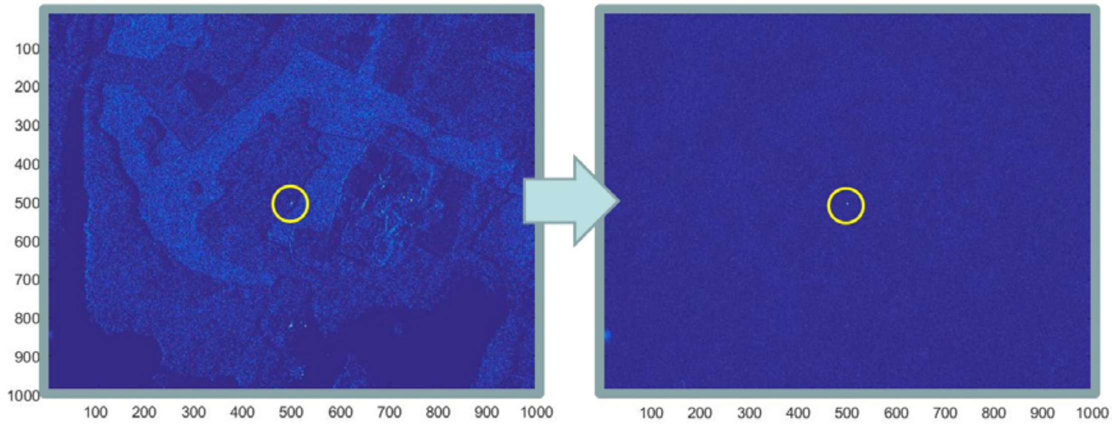


Figure 4. Unfiltered SAR image of moving truck and filtering of moving truck, to the left and right, respectively.

The TerraSAR-X satellite can divide its antenna into two parts, which means that the front antenna takes the measurement a little earlier than the rear antenna. The antenna is 5 m, and the speed of the satellite is approximately 7.6 km/s. This means that the time difference between the measurements is approximately 0.2 ms. This time shift gives the radar a strong sensitivity to speeds of 80 km/h, which is a regular truck speed.

By using both satellite channels, the stationary objects in the radar image can be suppressed, as shown in Figure 4. To the left, an area with a moving truck is shown, and to the right (after filtering), the moving truck is the only strong target. What happens in the filtering is that the stationary targets are so similar in both measurements that one channel can be used to remove the echo in the other. However, the truck has moved a few millimeters between the time of the measurements; hence, it does not look the same in the two measurements. These changes can easily be detected by the radar. The length of the truck can be measured from the picture, which is estimated at 14–20 m. However, there is an uncertainty because we do not have a good method for length estimation. In general, radar measurements tend to underestimate the length of the vehicle. Accordingly, more work is needed to obtain more accurate length estimates, and to estimate the uncertainty in the estimates.

3.1.2 Traffic measurements by drones and cameras

In parallel to the Satellite measurements, a drone and camera measured the road. In Figure 5, we see an exit on the E22 highway close to the port of Karlshamn. This measurement was made at the same time as the satellite measurements, and the vehicles detected by the satellite are also detected by the drone. We have also developed a detection algorithm for this measurement, so that the vehicles could be automatically detected and counted in the drone videos.

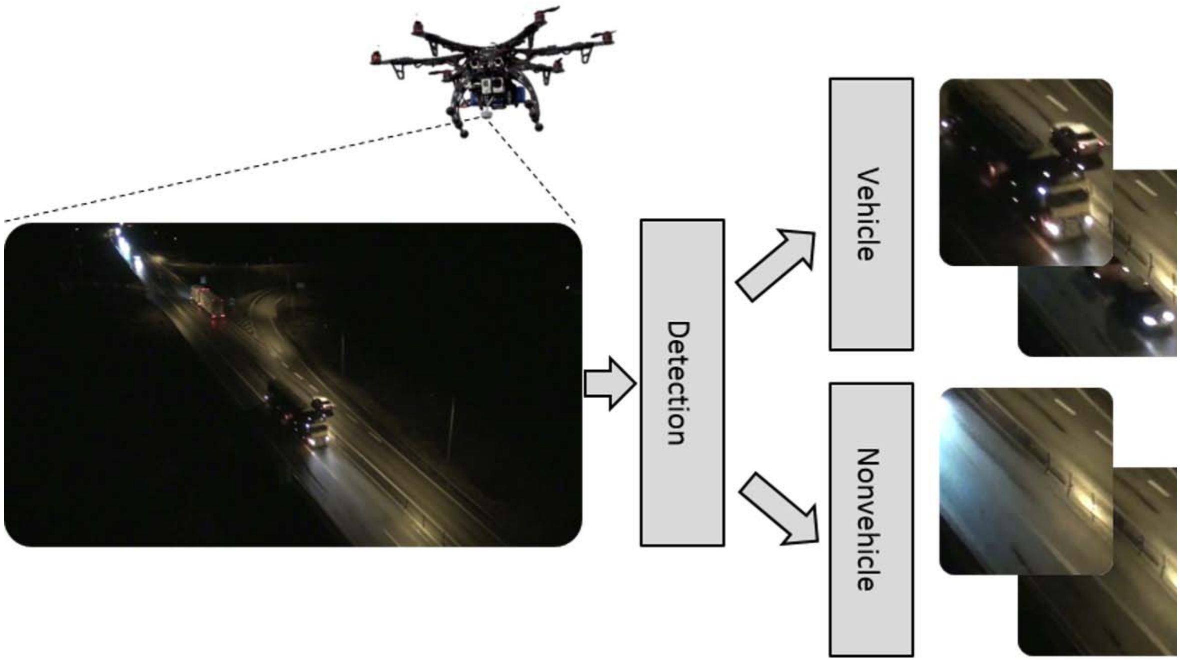


Figure 5. Drone measurement made on an exit on the highway E22 close to the port of Karlshamn. For the measurements, an automatic car and truck detection algorithm was developed.

Drone measurements of traffic are efficient in some cases, for example, when drones automatically take measurements for a shorter period of time in some areas. If a longer measurement period is needed, there are other much more efficient and cost-effective methods available. Today, there are good digital cameras available that are inexpensive and have sufficient technical performance. Figure 6 shows traffic measurements made by a low-cost GoPro[2] camera. This test was also conducted on the highway E22 at one of the two major exits to the port of Karlshamn. In this test, we developed new techniques to measure speed and to count and classify different vehicles (such as lorries, truck trailers, buses, passenger cars, and motorcycles). The classification was made totally automatically with AI technology, as shown in Figure 6 and Figure 7.

[2] *GoPro, Inc. is an American technology company manufacturing action cameras.*

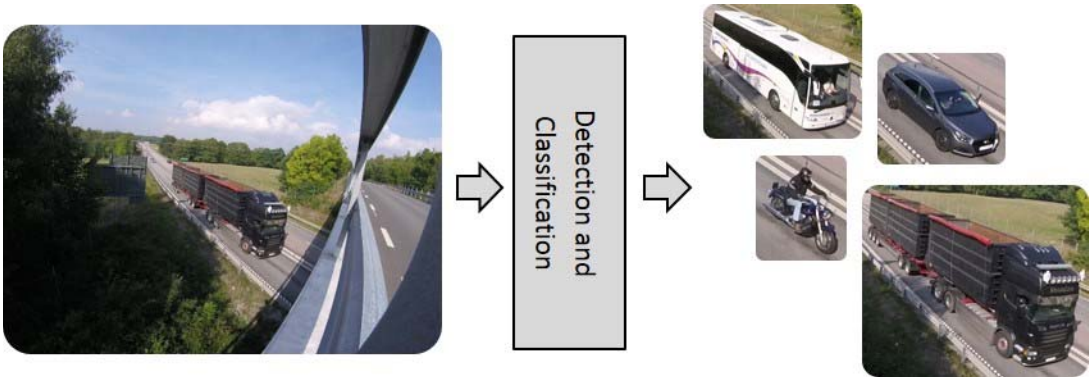


Figure 6. Automatic vehicle detection and classification using machine learning techniques and a roadside camera.

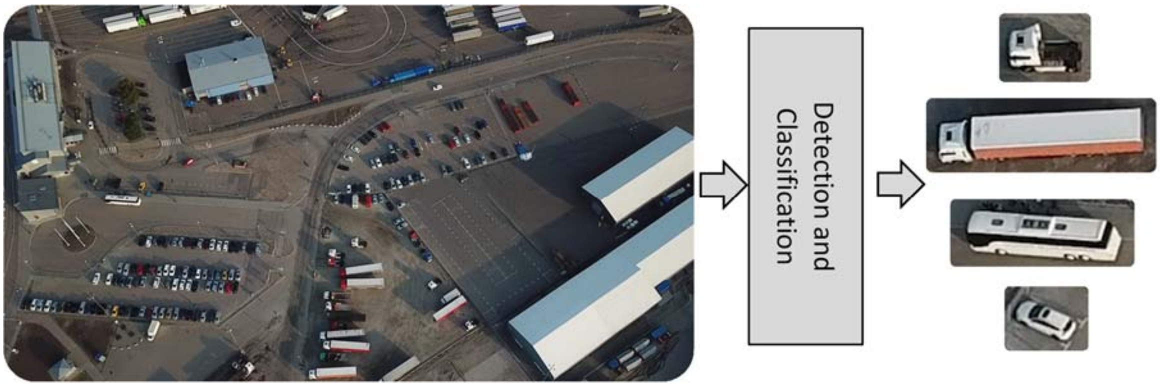


Figure 7. Automatic vehicle detection and classification using machine learning techniques and a drone.

3.2 TENTacle node Experiment

In the pilot study, we studied ports that are TENTacle nodes. Therefore, we can also give good examples of how the techniques can be used on TEN-T nodes. We used drone and satellite measurements in both ports to investigate changes, such as the trucks in the ports. In the previous section, we reported on TENTacle truck traffic measurements. This experiment was conducted to measure the intensity of truck traffic in the TEN-T and its surroundings (i.e. the TENTacle network). In the node experiment, we concentrated on the activity in one TEN-T node, or in a TENTacle node associated with a TEN-T node. There are two such nodes In Blekinge: Verköhamnen and Stillerydshamnen. In the TENTacle Blekinge pilot case, measurements of the truck traffic/parking situation around these two harbors were of interest.

3.2.1 Port of Verkö

In Verkö harbor, measurements were performed with a satellite-based SAR and a drone based optical camera. The satellite measurements were supplied through an agreement with the company Airbus Defence and Space, and took place at approximately 07:15 on the measurement days. One highlighted satellite image over the Verkö area is shown in Figure 8. The image is simply a zoom over the harbor, and all of the harbor is seen except some areas belonging to NKT[3] in the north of the port. All buildings give strong reflections, while the road and the sea give low reflections (on this day). There is no ferry present in this particular image, but many trucks have gathered in the primary and secondary parking places (marked in yellow and red, respectively).

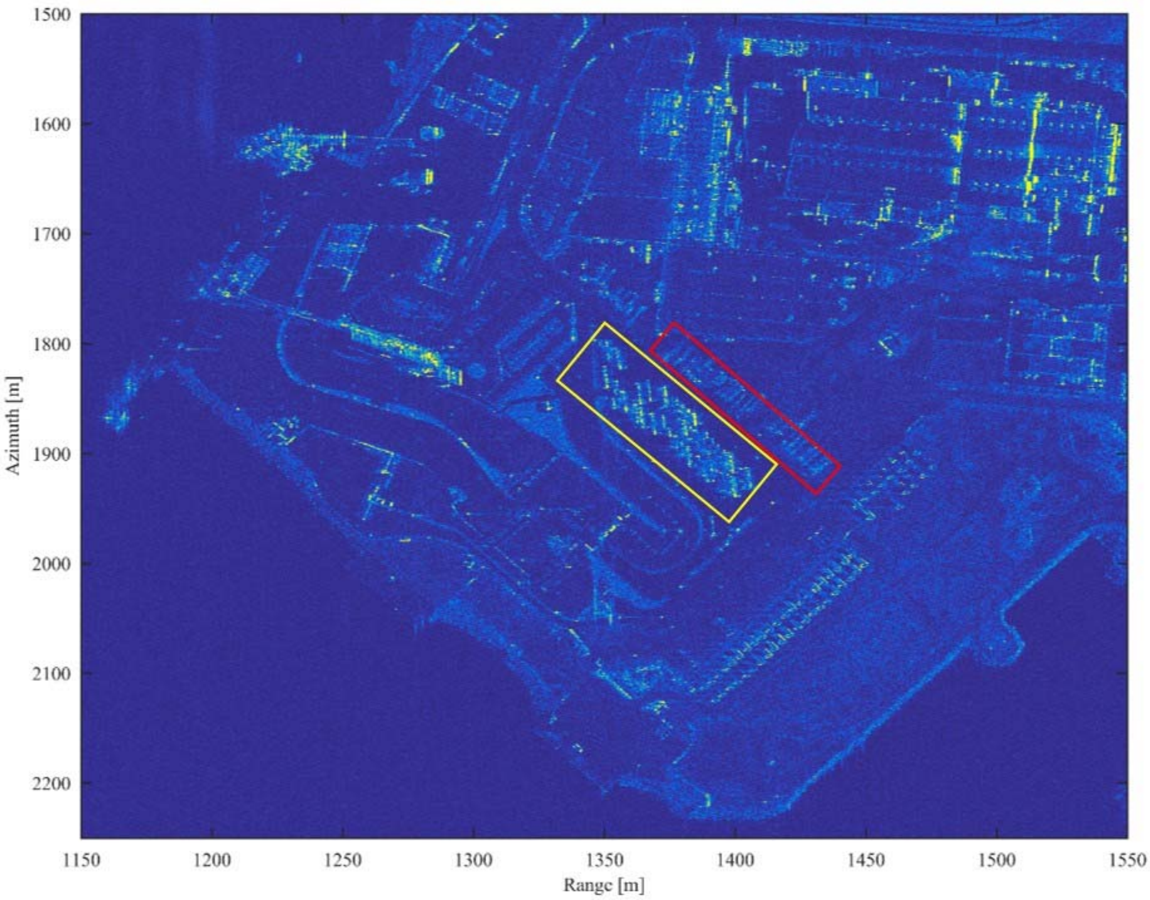


Figure 8. A TerraSAR-X image of the port of Verkö in Karlskrona. The resolution of the image is less than 1 m. In the image, one yellow and one red rectangle is shown. The yellow is the main parking for trucks, and the red is a secondary place.

In Verkö, the drone measurements were taken between 07:00 and 08:00 (approximately) from drone videos of the harbor area. For most measurements, one ferry arrives during this time. The number of trucks is high on many days, but for some measurement days the truck intensity is rather low. Figure 9 shows one picture from the drone showing the Verkö harbor, just as the ferry arrives. Drone measurements are valuable for the on-site harbor investigation, while the satellite measurements

[3] *NKT A/S is an industrial holding company manufacturing power cables.*

support the long-term evaluation of large harbors or several harbors in Europe at the same time. In the future, both technologies will be the subject of further development, and the satellite-based technology will be increasingly available to make evaluation measurements of transport chains over large areas of the EU. Based on these measurements, Figure 9 reflects a typical situation from one of the days when the port areas for cargo traffic were heavily loaded. The large number of trucks and trailers were allocated to almost all available spaces, waiting for the next departure.

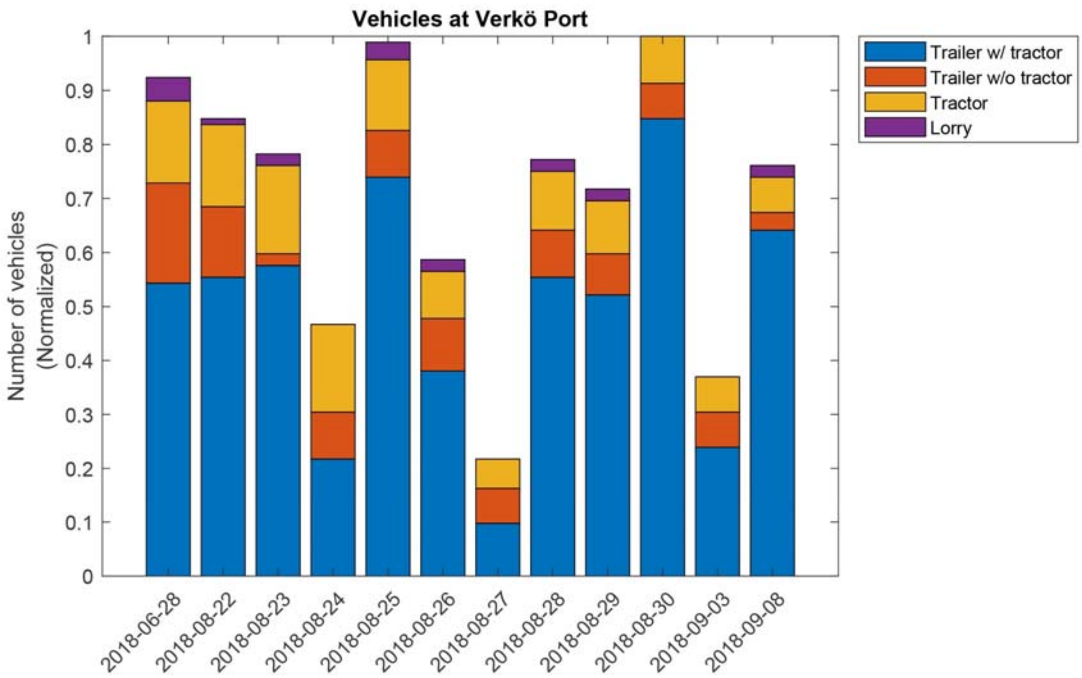
Figure 9. Verköhamnen 2018 in Karlskrona, Sweden.

Within the framework of the TENTacle project, a test measurement campaign was simultaneously conducted with the TerraSAR-X satellite and a drone. The campaign was conducted over ten days in August/September 2018 and reinforced the perception that a significant amount of goods transportation occurs along this MoS road (Karlskrona–Gdynia). From Table 1 and the infographics in Figure 10, it is even more evident (notwithstanding the limitation of the study) that Satellite and complementary drone measurements can add and clarify when it comes to supporting the development of a port and parts of corridors.

The results of the satellite and drone measurements further reinforce the shortcomings and needs highlighted in this report, meaning they indicate the importance of establishing Blekinge's connection to TEN-T.

Another more comprehensive and important result from this part is the methodology for regularly using satellite-based SARs and drones to evaluate transport chains across large areas of the EU. This new measurement method is very promising. Further, the purpose of this part of the pilot study has been to investigate how a selection of well-chosen measurement areas (such as intermodal terminals, harbors, and central roads and railway tracks for goods) can provide much information about the actual transportation flows within the EU, from an evaluation and development perspective.

Table 1 Normalized load in the Verkö harbor. A short-term analysis based on measurements with an SAR satellite and a drone.



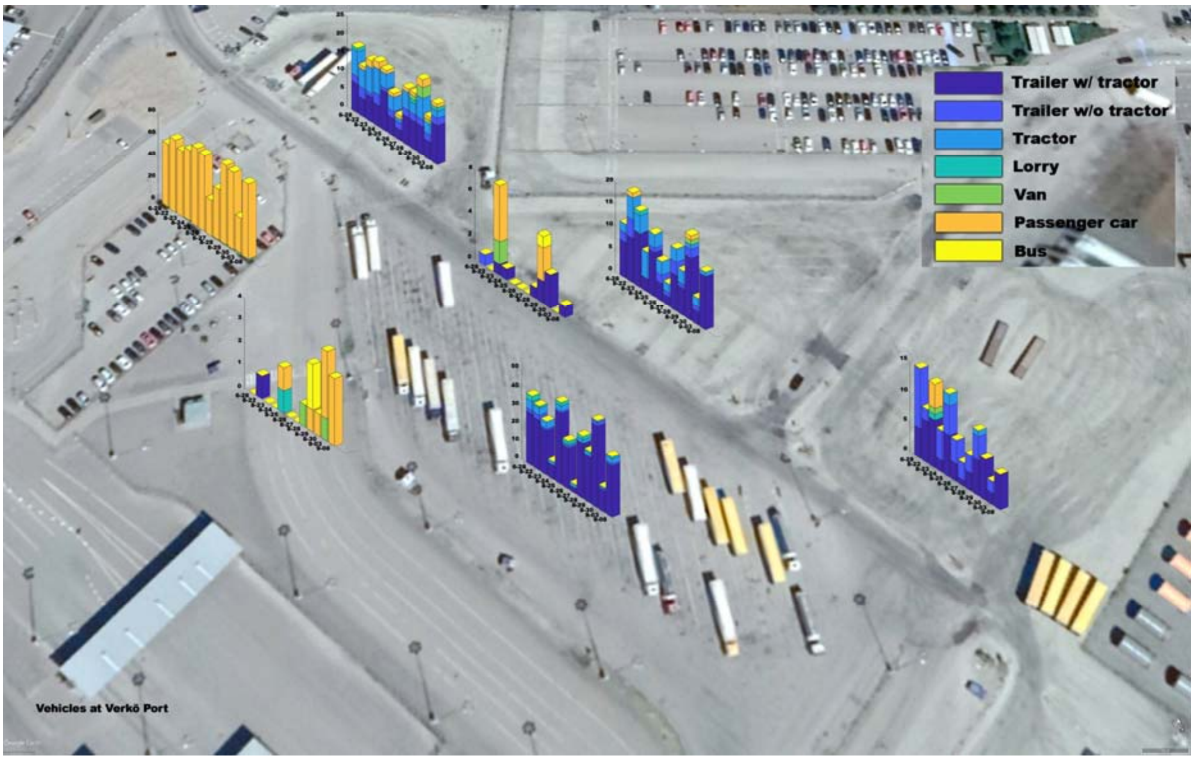


Figure 10. Infographics showing the allocation for the respective surface. This Infographics example also illustrates the significance of the TENTacle developed measurement methodology of the satellite and drone measurements.

3.2.2 Port of Karlshamn

In the port of Karlshamn, we took both drone and satellite measurements. In Figure 2, we can see one full size TerraSAR-X image used over the port. The satellite measurements were taken during a period from January to February. Almost all the images were taken in darkness, and many were taken in bad weather conditions (such as snow and rain). The TerraSAR-X images were provided by the German Space Agency (DLR). The resolution is approximately 2.5 m (thus the measurements of flows and vehicle speed estimates along the access roads were the focus of this study); therefore, the images over Karlshamn harbor cannot provide the same level of detail as the ones used in Karlskrona. However, we still think that the images give very useful results. Figure 11 is a zoom over the harbor, in which we can see the main pier and the pier for the ferry to Klaipeda (marked with a yellow arrow). As seen in one of the images, the ferry is in the port, while it is not present in the other images. The red arrow denotes one of the available truck parking spots. There are some trucks visible in the top image, but there are almost no trucks at all in the lower image.

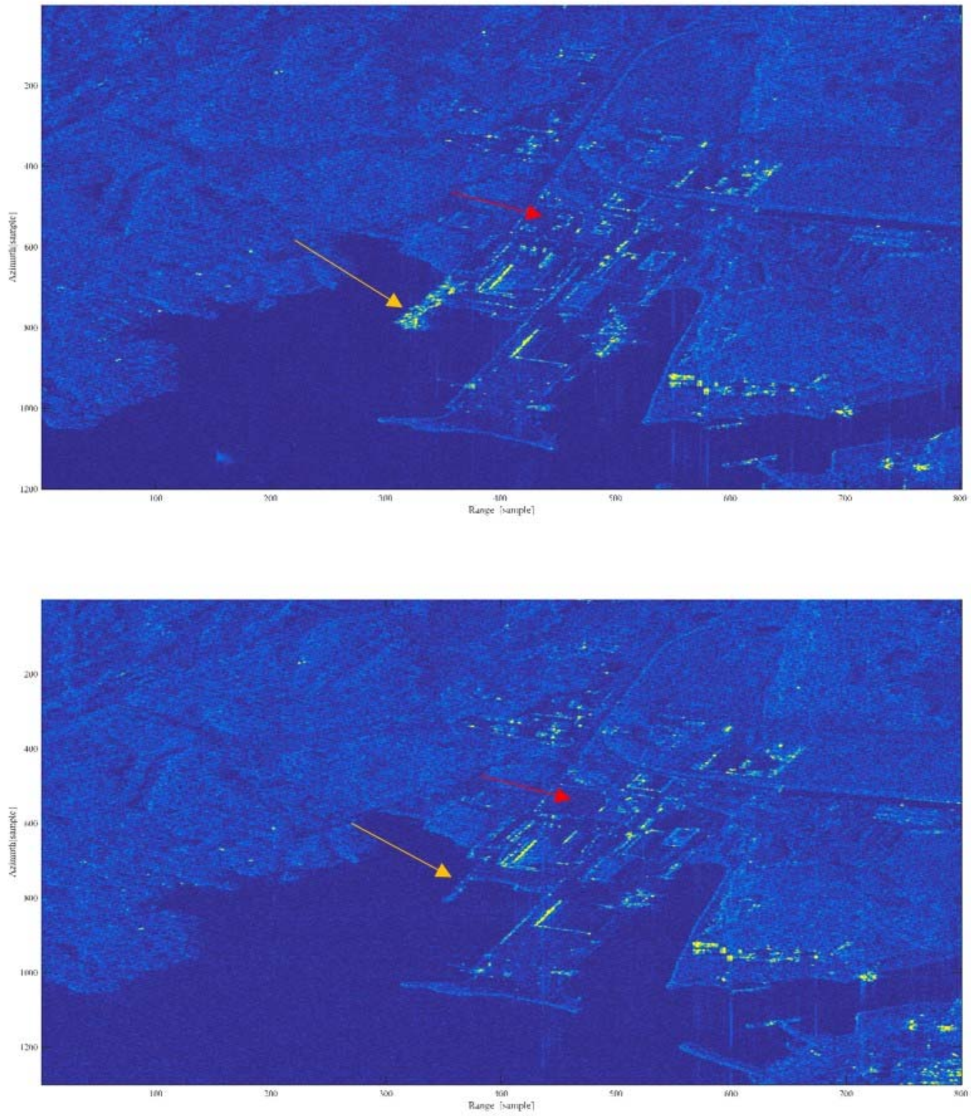


Figure 11. The port of Karlshamn Stillerydshamnen. Open water has low backscattering (i.e. low intensity) in the image. The yellow bar indicates the ferry location when it is in the harbor. The red arrow shows one of the available truck parking spaces.

At BTH, we have developed routines (computer based algorithms) to detect moving and parked vehicles, where large vehicles such as trucks are the main focus. As mentioned in the traffic measurements, there are many methods for detection, and each method has its advantages and disadvantages. In Figure 12, one result for a change detection algorithm is shown. This algorithm uses the change between two radar images: one slave image and one master. As can be seen in the image, most changes in the harbor occur in the different parking zones. Over the port of Karlshamn, we had a total of 40 satellite images from 10 different days. One example of the results is shown in Figure 13, where truck parking at the parking lot is measured by the satellite. It can be observed that the parking has different occupations for the different measurement days. Further, the measurement time is different for the different measurement days, which is a natural reason for the change.

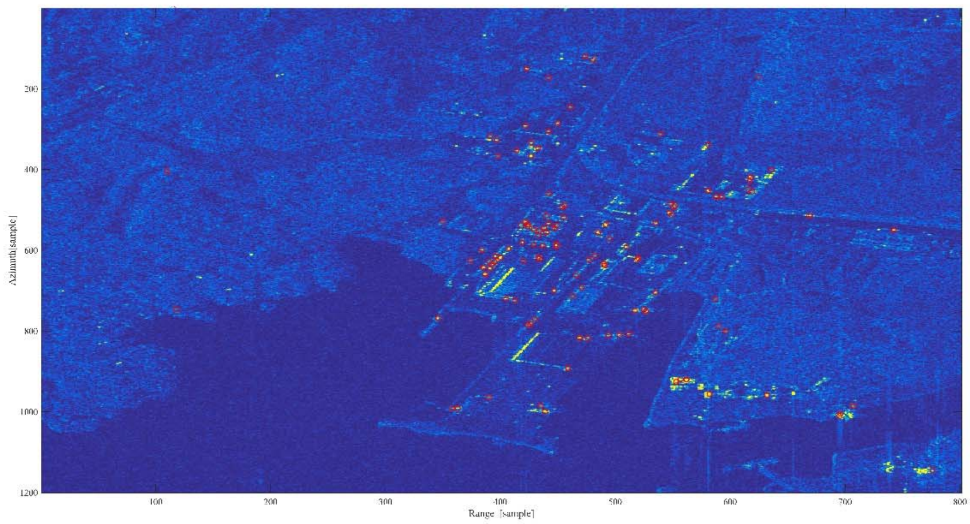


Figure 12. A change detection image based on two TerraSAR-X images. The small red markers indicate changes between the images.

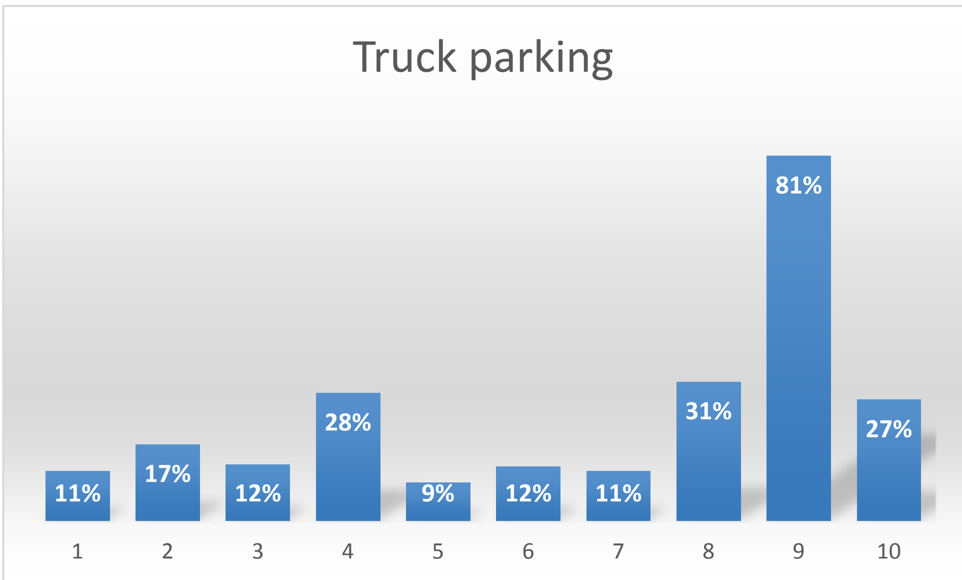


Figure 13. Truck parking in parking area with yellow arrow in percent, where parking space is full at 100%. This measurement is based on satellite for ten days during January to February.

In addition, several drone measurements were taken over the Karlshamn port during different periods. Some of the drone measurement were taken at the same time as the satellite measurements, and some were taken later during spring/summer. In

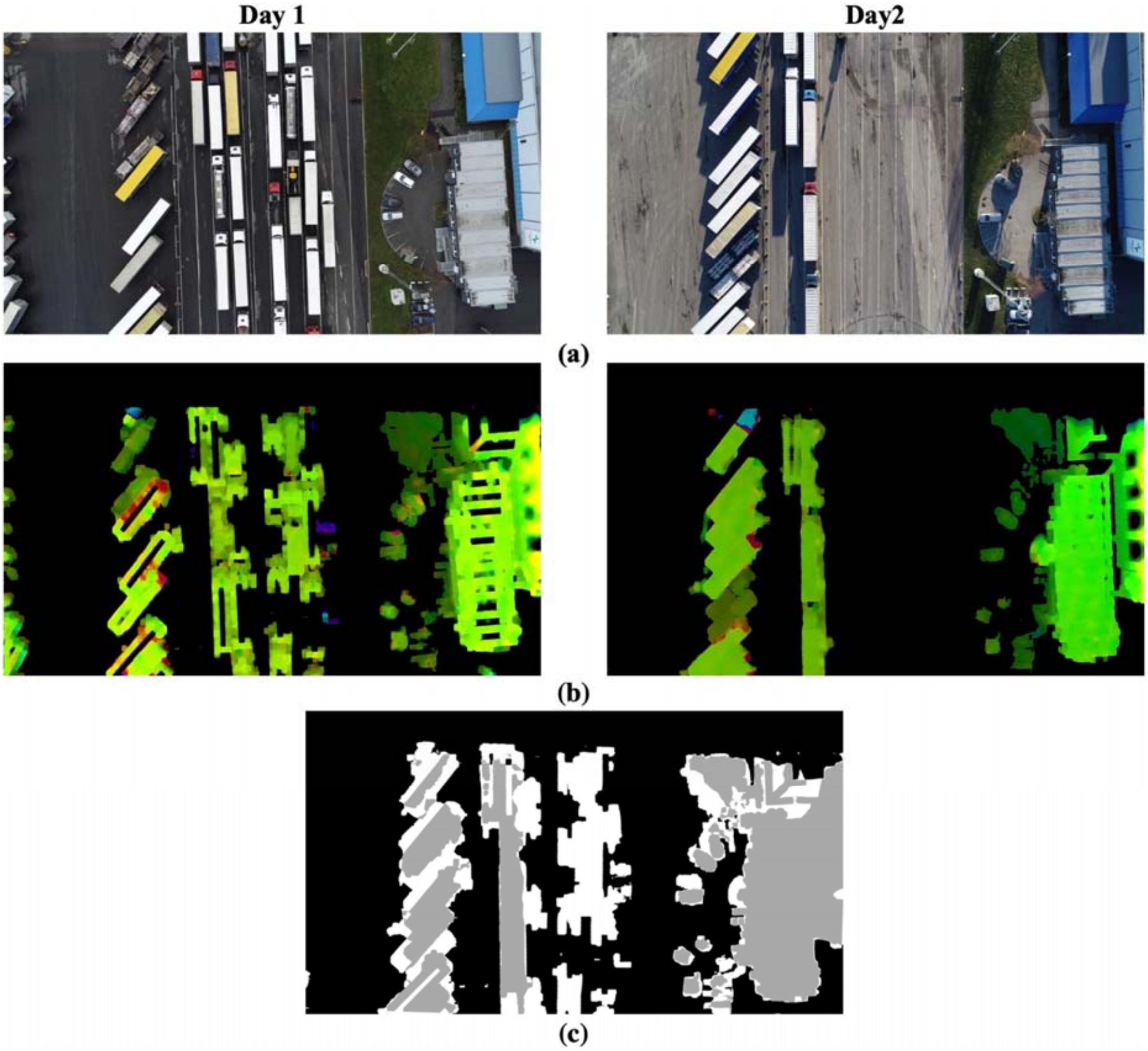


Figure 14, a change detection image is shown for the area that in the satellite image is marked with a red arrow. The change detection was made using two different drone flights. For each flight, a 3D feature map is constructed for the scene that illustrates 3D objects above a reference surface. By comparing generated 3D feature maps for each day, a 3D comparison model is created that is used to detect changes in the port's parking spots in aerial images over time. Because this method uses extracted 3D features of the scene, it is robust towards variation in illumination and brightness of the scene in aerial images taken at different days.

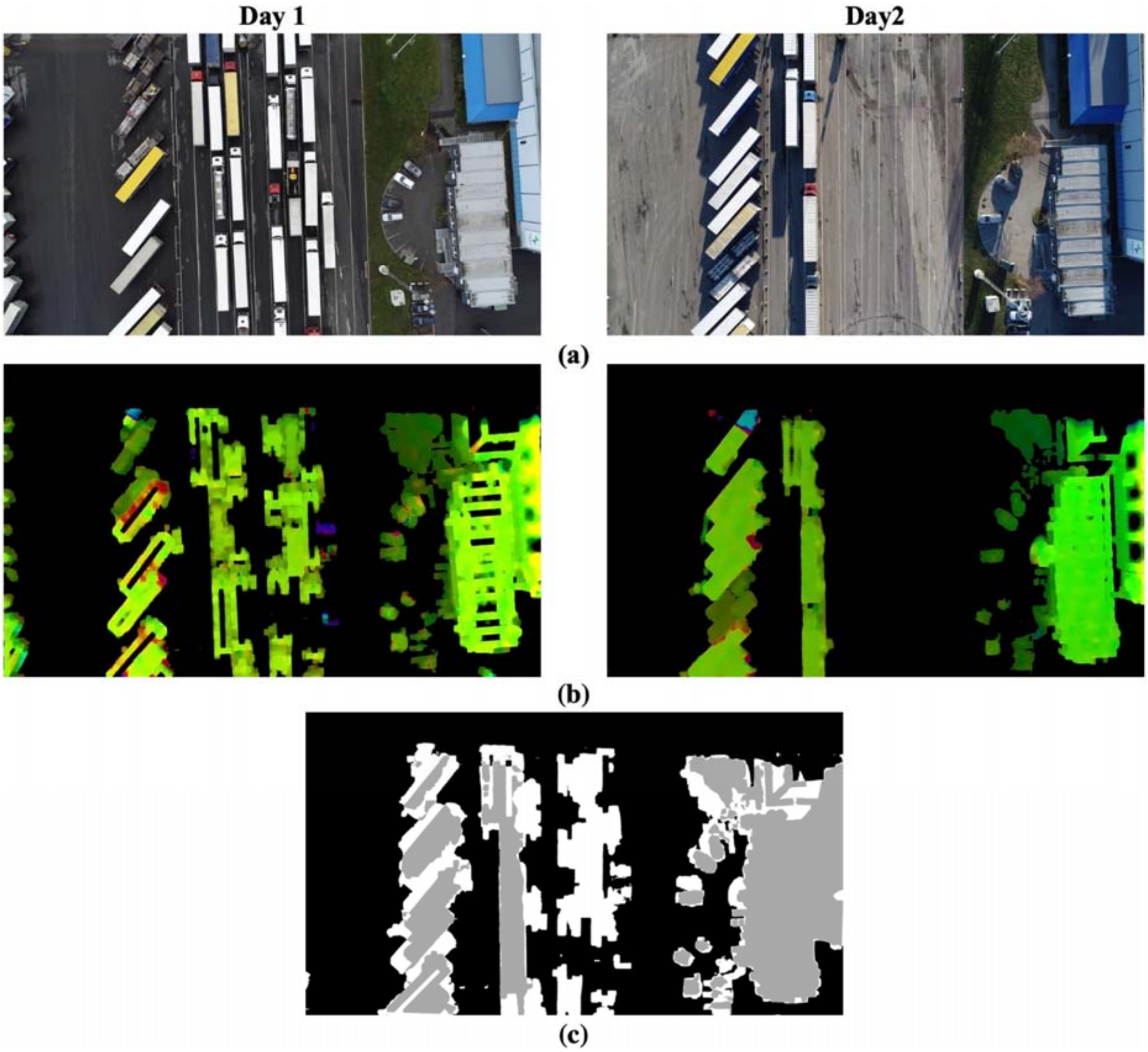


Figure 14. Change detection using aerial images from the drone (a) the sequence of aerial images, (b) 3D feature extraction of the objects in the scene (c) detected changes in the port's parking spot are in white, no object in both images is in black, and an object in both images is grey.

In a later period, drone measurements over the Karlshamn port were again taken over a 7-day period. These measurements were conducted particularly over two areas: Karlshamn port's parking spaces and Karlshamn pier, where various goods are placed for shipping. In the first stage, maps of these areas are generated using consecutive aerial images, and keypoint extraction and matching techniques are used to create a large high-resolution mosaic image. These maps are then aligned with each other according to a google map reference. Hence, corresponding regions at different images cover the same area, as shown in Figure 15 and Figure 16.

Figure 15. Aligned mosaic images consisting of drone measurements over the Karlshamn port's parking space over several days.

Figure 16. Aligned mosaic images consisting drone measurements over the Karlshamn pier over several days.

These maps contain crucial information about the placement of various types of goods and items within the port area in one single image that can be used for management and development purposes, see Figure 17. The advantages of drone maps in comparison with satellite images are having low cost, high resolution and very fast to obtain that are key factors particularly in emergency situations.

Figure 17. A mosaic drone map of the harbor with indication of various items and goods.

Figure 18, shows the number of trucks and trailers parked in the port's parking space in 7 days at 16:00. In addition, Figure 19 demonstrates the portion of covered area for each category at the pier in 6 days. This information can be used for further development of the port's parking space and the pier.

Figure 18. Infographic of the port's parking space and number of trucks/trailers in 7 days using aerial images.

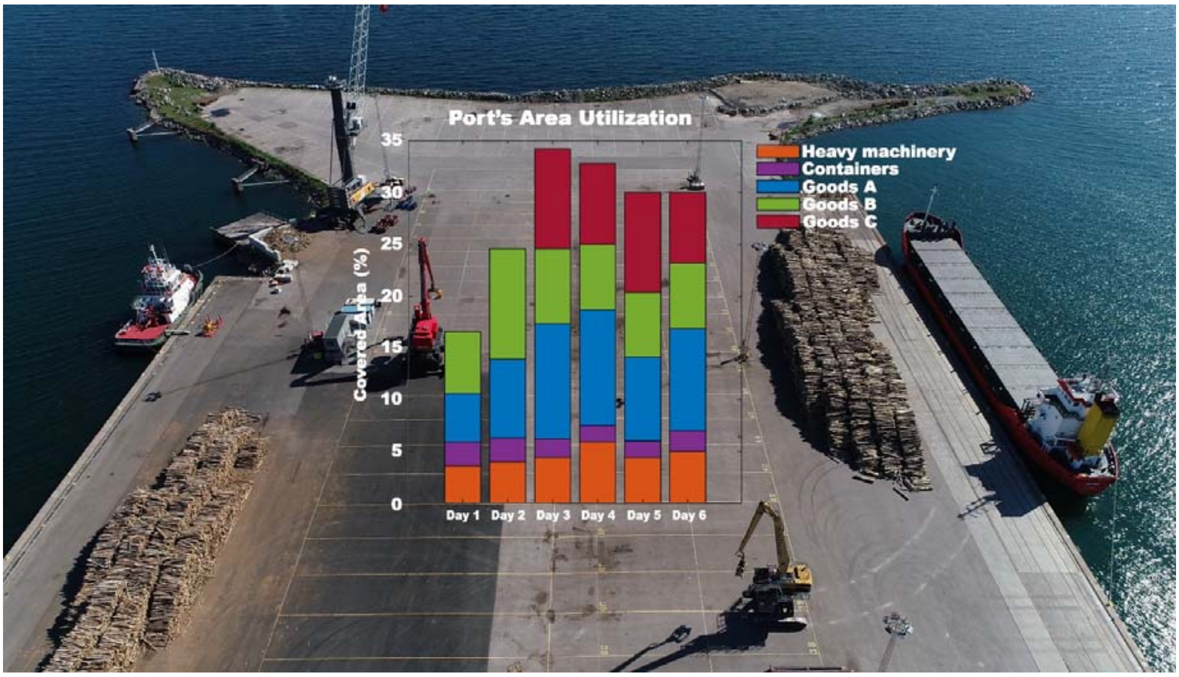


Figure 19. Infographic of the covered areas for each category at the pier space in 6 days using aerial images.

Furthermore, these mosaic images of the port at parking space and the pier are compared with each other day by day. The comparison between aligned maps can be done using texture analysis, 3D comparison model or machine leaning techniques. The result of this procedure shows many useful information including the most utilized places within the port, the types of goods at each of these places, the movement of vehicles and goods in the port over time and so on. Figure 20 and Figure 21 show the heat map of used spaces in the port's parking space and the pier over several days, respectively. It gives a clear picture of how the port is utilized day by day with various items using drone measurements that otherwise would be very hard to see.

Figure 20. The heat map of the utilization of the Karlshamn port's parking space using drone measurements made over seven days.

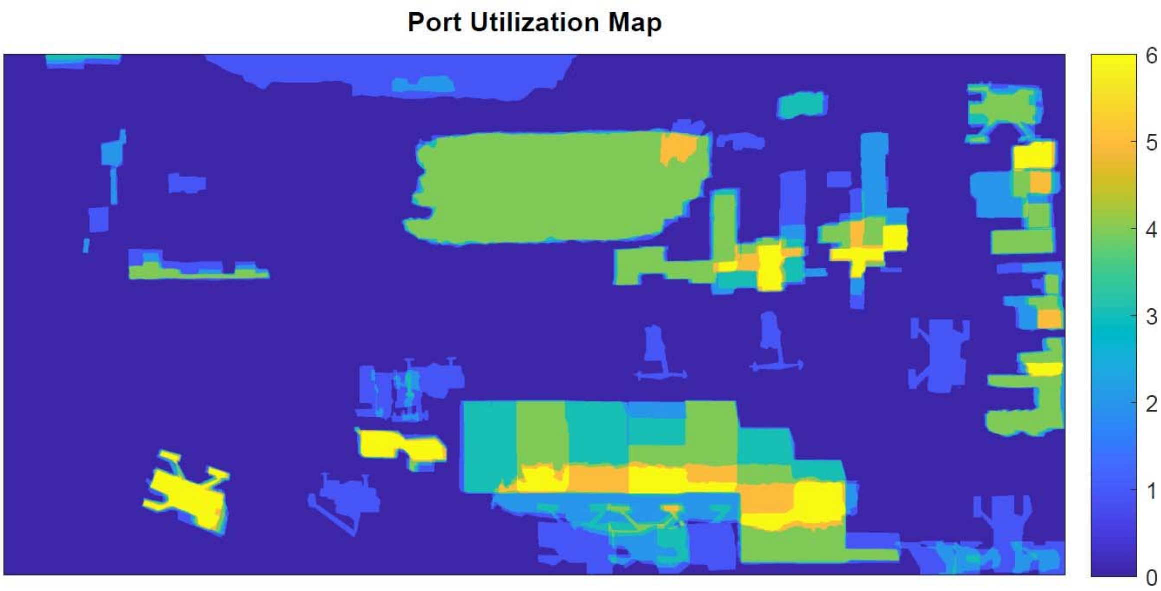


Figure 21. The heat map of the utilization of the Karlshamn pier using drone measurements made over six days.

For object detection at the harbor, we used a machine learning (artificial intelligence) technique called deep convolutional neural networks to detect and classify trucks and various types of trailers (without trucks). To do so, first, the architecture of the network is designed according to our goals and data. Then it is trained using labelled data obtained from the drone footage. The trained classifier was able to receive aerial images as input and then locate possible trucks and trailers in the image. This technique was highly efficient for the detection and classification of various objects of interest automatically, using deep end-to-end networks, as shown in Figure 22.

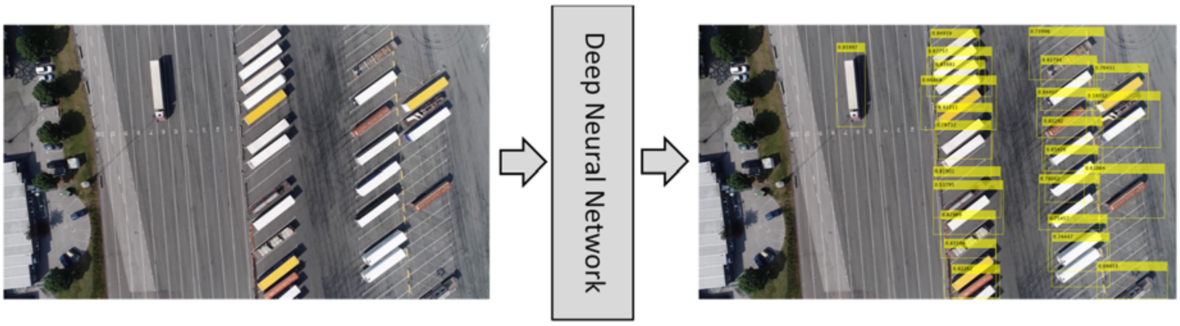


Figure 22. Trucks and trailers detected using deep neural networks with bounding boxes and confidence level for each detection.

4. Results and discussion

Karlskrona and Karlshamn are two port cities in the province of Blekinge in the southern part of Sweden, where traffic across the Baltic Sea and Europe plays an important role via the connection to Gdynia and Klaipeda. The ports (and traffic connected to the ports) represent a major economic development, not only in Blekinge but also for parts that lie to the north and west of Sweden. In the future, these ports will be developed, and extensive changes in land use can be expected in and around the ports, (including access roads and various types of communication) due to the rapid development of transport. Correct planning in a sustainable efficient manner and development, such as port areas, leads to new possibilities for the development of corridors and communications within the EU. This study evaluates the usefulness of remote sensing with satellites and drones, where satellite measurements are completed with radar (SAR) and analysis from the drones is completed with a camera. The idea of satellite measurements of this kind is that the radar images can provide a direct image as well as multi-temporal satellite data. Via the multi-temporal SAR satellite data, the change analysis of the terminals can be performed, and in this test study, surfaces allocated by goods and vehicles could be observed. The future significance of an overall understanding of this type of change is important for planners to achieve planning as smart as possible.

APPENDIX Surface traffic measurements

This appendix deals primarily with how surface-covering measurement systems can be used for traffic measurements. The idea is to use an imaging sensor based on a flying platform like a drone or a satellite. In particular, SAR satellite-based measurements can add completely new knowledge about our European transport networks. This presents a completely new opportunity to study changes in a broad sense, and in the future, it can constitute new methodology in the area of traffic measurement. This technology is not only suitable for power evaluation, but can also be used in other contexts, not illustrated here.

A.1 Surface measurements

Technically, surface measurement means that you can simultaneously take measurements over a larger area, meaning larger areas can be considered. If we choose to measure with a satellite, it can cover large areas of approximately 700 km^2 in a one single measurement. In principle, this means that measurement can include heavy vehicles (truck traffic), boats, trains, and movements of goods within intermodal terminals and ports in the covered area. It should be noted that even larger areas can be ordered. All the activities of the measuring area are measured for a short period, meaning that you measure everywhere where there are goods or vehicles at the moment of measurement. There are special options or modes that can be ordered, which in turn provide an expanded analysis opportunity to monitor the momentaneous movements (speed of vehicles) in the area.

For surface-covering measurements, a given area is measured repeatedly at different times of the day over a year. This method is basically weather-independent (if you use radar), and all measurements are the basis for final estimates and calculations. The method is also suitable for making satellite data collections at different given times, allowing subsequent analyses. Therefore, one can use analysis methods developed at a later date, rather than just at the time of measurement. This means that the analysis method becomes very powerful, not only because it covers large parts of the traffic network at each measurement, but also because it is possible to save extensive data and finally compile the results. Therefore, measurements can be taken at several times during the day, or just a few times a year. External measurements do not require measuring equipment to be installed at a specific measuring site, which means that a minimum staffing is needed for the actual measurements, as this would be performed by a supplier of measurement data from the measuring system. These measuring systems are continuously being developed, and new satellites that can support this type of measurement are continuously being established and projected, which we will touch on later in this report. In principle, we are in a transitional period, where many new satellite systems are planned. Therefore, data of this kind will be much more accessible in the future, and we will be able to access data more often and more frequently. Accordingly, analysis can become available a day or only hours after a change in the CNC has taken place.

The satellite system does not measure at a specific point or only on road sections in the surface-covering measuring area, but rather over entire surfaces (such as ports and terminals) along the CNC. It is not just a given measurement site (or cross section), but rather many road sections that together make up a gigantic measuring site. In this way, a single satellite measurement can measure several road sections, a port, and an intermodal terminal simultaneously.

Conversely, the system does not capture all vehicles over a single day; however, over time it would be conceivable that all the data collection would be spread over all hours of the day, all year round. However, it is highly possible that concerning road wear, it is of more interest to take measurements at a corresponding time annually, recurring before, during, and after its introduction. Over time, the measurement of entire distances or of vehicles traveling along a path will not only result in accurate flow estimates, but also in map velocity profiles over the entire distance. Thus, it becomes a knowledge-building process, not only at a single portal/spot at the measuring site (which is the case with traffic portal measurement), but actually a measurement over the entire distance.

A satellite measurement over a given surface is difficult to compare with measurements that take place at a measuring station or portal along the road. However, it is possible that there is some kind of connection between the measurements that take place at the portals and those taken by satellites.

Compared to what surface-covering systems can measure, measurements that are currently taken via portals along the TEN-T have different starting points and are not just purely technical. It could be said that measurements taken along a road measure traffic more intensively in a cross section (more locally a specific measuring site). A satellite system is required to measure all traffic on many entire routes concurrently, less intensively, and over the day. However, it has the potential to do this repeatedly on a daily basis over the year, which from the point of view of analysis is advantageous. It is worth noting that this same measuring system can cover the entire corridor (e.g. the whole BAC or Baltic-Adriatic Axis over Poland, the Czech Republic, Slovakia, Austria, and Italy).

Portals along the corridors can carry out classification of vehicles by using different types of technology. The satellite system also has the prerequisites for being able to classify vehicles, but this is more in terms of length and composition of heavy vehicles rather than axle configurations of various kinds. This report for reasoning based on what one might expect from the technology if the post-analyzes for a measurement with satellite systems would be relevant to use. The strength of the satellite system is that it measures consistently from year to year with the same accuracy, which contributes to the possibility of compensating for systematic measurement errors in evaluations of various kinds. However, for optimum results, we recommend that the possibility of combining local measurements (such as portals and drones) with the SAR satellite systems is reviewed.

It is important to distinguish between what is possible to measure and what is required to evaluate improvements to the TEN-T. It is not necessarily absolute measurement values that are the most important, but probably flows (or differences in flows) between different parts of the network at the comparison times are of more interest. Regardless of the measurement system, an estimation is required and there is no principle difference between measurements on the ground compared to those made with satellite. In other words, all measurements require dedicated and adapted post-processing when data from the systems is collected. Both portal and satellite measurements result in knowledge about EU freight transport in harbors, terminals, and along the roads. In retrospect, several different types of analysis can be performed, which in turn can answer questions relevant to the present focus.

Today, in most countries, there is a well-developed methodology and technology for collecting and processing traffic data in portals. For satellite measurements, new products are continually being developed that can provide answers to completely new issues (and at the same time measure over large areas) in the foreseeable future. An important parameter in the construction of roads is the choice of location of the portals. This is because it is costly, and the location should be effective. A satellite-based system has no such aspects to consider [6,7].

An important consideration when reading this report is that from an evaluation perspective, the aim is usually to identify deviations, bottlenecks, or changing behavior, and not necessarily about the absolute flow. Rather, it is about being able to compare different years or examine different parts of the network and make fair comparisons. For example, the satellite method is not particularly sensitive to the construction of new roads or new road sections, as long as these are within the measured geographical area.

The measured areas over the TEN-T should be well-chosen, based on the criteria of constituting an important part of the traffic system from the corridor perspective, and ensuring that the geographical measurement surfaces together have as little overlap as possible.

As with all traffic measurements, it is important to study different seasons and divide the measurement year into different measurement periods (such as weekends and weekdays for a week). Usually, at country level, there is a strategy for how measurement periods should be selected for portal measurement; thus, it is important to have the same approach to surface-covering measurements.

Measurement sites for surface-covering measurement should be selected with a focus on goods and targeting traffic that in some way reflects the areas that are known in advance to contain large quantities of goods being recharged or stored.

Satellite measurements require data post-processing, post-analysis, and simulation of order selection to carry out estimates of various kinds. For natural reasons, it should be remembered (whether estimating goods flows or making a comparative study between countries), that uncertainty largely depends on the flow, and a relatively low flow generates a relatively large degree of uncertainty. Studies of flow changes are, from the point of view of evaluation, more advantageous, because a comparative study can dispel variations in traffic more accurately, and instead can focus more on variations that are probably due to the introduction of road wear tax (for example).

Regardless of whether we measure with portals or satellite systems, it will be impossible to maintain up-to-date information about the traffic on the entire road network continuously, as it would be very costly and storage intensive. Therefore, it is important to make good choices regarding measurement sites and surfaces in advance. Further, post-processing should also be conducted with effective and as statistically reliable methods as possible obtain relevant information.

In this context, it may be worth noting that a more comprehensive picture of changes in corridors can be made; therefore, this may place demands on non-aggregated measurement data from aircraft, drones, or more local portal measurements.

Surface-covering methods principals and selection of platform

Surface-covering measurements have many advantages compared to point measures, as they provide the possibility of studying many roads at the same time over a large area. Accordingly, traffic over a large area will be measured. To achieve this area coverage, airborne or even space borne electromagnetic sensors are preferable. A distinction should be made between active and passive electromagnetic sensors: passive airborne options include ordinary or infrared cameras, and active sensors include laser or radar. The principle differences between passive and active systems are the size of the measuring area, and speed sensitivity, which is much greater for active sensors.

The measurement area (or ground coverage) of the surface-covering system is directly related to the altitude of the sensor platform. To illustrate this, we take the example of a drone. The highest altitude for a drone in Sweden is 120 m, and we assume it is carrying a regular camera (passive sensor) and it is located directly above the geographical area of interest. A camera lens only sees the area directly beneath (and slightly peripherally), with the best resolution being achieved when pointing straight down. If we further assume an image angle of 45°, which approximately corresponds to the diagonal of the image having the same length as the height of the sensor, this means that when flying at a height of 120 m, an area of approximately 100 m wide is captured by the camera. However, if an active sensor is chosen the coverage will be different. Radar can illuminate a wider area (from 20° to 70° either side of the platform). This is because an active radar sensor has the best resolution at a greater distance. At an altitude of 120 m, the corresponding illuminated area will be 280 m, and if the radar illuminates both sides of the platform, it will be more than 500 m. Thus, the scanned area becomes larger than with an optical sensor. We conclude that the covered area becomes larger as the sensor platform height increases. With this in mind, the covered area is approximately given by the sensor's height for a passive sensor and is a few times larger for an active sensor. With this simple assumption, we realize that one drone can monitor small harbors, an aircraft can monitor large harbors (or a big town), while a satellite can measure an entire country. Let us now assume that we want to measure many harbors (small and large) in Europe. Therefore, we would need either one satellite system or many drones. However, if we extend the measurement area to a region or a TEN-T corridor, the only choice is to use the satellite system.

Surface measurement technical restrictions

In the previous section, suggestions were made about how surface-covering measurements from drones and satellites could be used for logistics measurement. Where the evaluation area covered by a satellite is large, there are restrictions in terms of data and measurement time. The previous example assumes that there are continuous sensor updates in both time and space. Accordingly, a European logistic measurement (or TEN-T corridor measurement) is planned and timing and areas that have the greatest relevance for the measurements should be considered. This is because access to the sensor and to large amounts of data that are generated. Let us initially assume that we will map changes in transport along a corridor. Let us further assume that we do not have continuous measurements available without updating the national vehicle mode "just" once per second. We also assume that the sensor's resolution is 1 m^2, which is suitable for vehicle measurements. Because a corridor extends over thousands of kilometers and the main area of interest is along the sides of that corridor, it is not only the road that should be measured. However, let us assume the area besides the corridor is 50 km wide on both sides and that the corridor is 2000 km in length. This means that the sensor has to cover a surface area of 200,000 km^2. This would generate data at approximately 4 TB /s. Because the evaluation is required to capture data over several years, this would mean that very large amounts of data are generated. If we assume that data is stored for 4 years, this would mean that a sensor would generate 500 million TB of data throughout the entire measurement period. One personal computer commonly has memory storage of 1 TB, and therefore the data has the same memory size as 500 million computers, which is a significant proportion of currently existing personal computers. Therefore, data collection needs to be optimized in both space and time to obtain the data needed for evaluation.

Today, availability of satellite data is restricted in both space and time. In many situations, the main interest is in logistics (and changes); accordingly, we believe it is possible to limit the errors that occur even if limited measurements in time and space are used. If we use the technique to study changes in logistics of cargo at European ports, information can be retrieved using the same type of measurements before and after. However, it is important that there is a randomness in the measurements to avoid systematic errors. It is therefore important to have a measurement strategy.

A.2 High resolution Radar for surface measurements of traffic and logistics

If the radar is more advanced (coherent between pulses), the precision of the radar pulses is very high. Radar measures distance using the parameters of time and the speed of light. Therefore, some radars are synchronized to atomic clocks that have very high frequency and time accuracy. Coherent radar can be used to detect moving objects and to determine their speed (Doppler). If the radar platform is moving, the coherent radar can build a synthetic aperture to increase resolution if long synthetic apertures are used.

Radar principals

Radar (which is an abbreviation of **Ra**dio **D**etection **A**nd **R**anging) was developed in the early 1900s [8], but it was mainly during the Second World War that it gained prevalence. Radar has some excellent advantages compared to optical systems. Radar uses electromagnetic radiation (just like optical systems) but with a much longer wavelength, and radiation generated by its own sensor. Radar is therefore independent of daylight, and weather conditions. Even in rain, fog, snow, or even storm, the radar can detect and produce images. These characteristics have resulted in a significant impact not only in the military sector but also in civilian society, such as within shipping and aviation.

If the radar is more advanced (coherent between pulses), the precision of the radar pulses is very high. Radar systems resolution follows the same principles as an optical system, whereby the lens (antenna) size in relation to wavelength is the physical limit of its resolution [9]. A larger antenna gives higher resolution. Because the radar operates with much larger wavelength than optical systems, a radar system must have much bigger antenna than an optical lens to reach comparable resolution. This requirement means that traditional radar systems have much lower resolution than optical systems. However, the radar, unlike the optical sensors, also has a high resolution in the third-dimension range, or distance. To increase radar resolution, synthetic apertures were developed (Wiley). The idea was to use the sensor platform movement and record the radar pulses as the platform moves. From the recorded data, a very long synthetic antenna could be built by adding pulses coherently. By forming a large antenna, high resolution is achieved. SAR increased in popularity in the 1970s with the advent of computer processing. However, it has since become problematic to access sufficient processing power and storage space for the large amounts of data generated, a problem that remains for many radar systems [10]

Radar resolution in three dimensions relates to the physical properties of the antenna and the bandwidth of the transmitted pulse. A camera sensor has an angular-resolution limited by the camera lens size. Because it is an angle-resolution, the resolution in meters decreases with distance. This is something we experience when our eyes follow the same principle. At closer distance we can see the details and at a larger distance we need binoculars (a bigger lens). The same principle applies to the resolution of a radar sensor in the two dimensions that are limited by the size of the antenna. Larger distances with the same antenna result in poorer resolution, while resolution at a distance is always the same and given by the radar pulse.

The TerraSAR-X used in this study has a resolution below 1 m [11], and today there are some radar systems that have a resolution of 300 mm from a platform in space (i.e. onboard satellites). To gain range resolution of 300 mm is difficult, but possible. This requires 500 MHz bandwidth, which is an available frequency for traditional radar. However, it is very difficult to build a physical antenna needed for the required resolution. For example, let us suppose the satellite travels in orbit at an altitude of 800 km. Having resolution of 300 mm in azimuth would correspond to an approximate antenna size of 50 km, depending on the operational radar frequency. Even if it were possible to build such an antenna on Earth's surface it would be a great challenge to place this antenna in orbit and connect it to an orbiting satellite. To solve this issue, SAR technology is used. While the satellite is moving at high speed, data is stored from the received radar pulses. The resolution is then created by adding collected pulses together to form one high-resolution image. In practice, data collection takes several seconds, where an increased recording time improves the resolution. Data are then eventually sent to Earth for processing. Unlike optical sensors, the SAR has a resolution regardless of distance. However, the length of the SAR increases with distance, which means that the amount of data also increases, and problem of inversion magnifies.

Today, SAR technology is used in a variety of areas and for a variety of applications. The technique has been crucial in various military conflicts, and it is used today for a variety of civilian applications. A very important area of application for civilian SAR systems is global climate monitoring from satellites, where, together with optical sensors, they are sometimes the only source of information available to study changes that take place on the Earth's surface. This might be with regard to changes in rainforests [12], or changes in ice masses around the Earth's poles [13]. These areas are difficult to access, and often have severe cloud conditions. There are a variety of geoscientific parameters that can be measured with SAR satellites, and today methods have been developed for using the technology to record changes that happens in cities, such as shifting buildings or to measure road surfaces with high precision for (potential) future autonomous cars.

Developments in the field are still addressing both military and geophysical needs. However, there are many new fields developing, one of which is to measure behavior change of people in open spaces [14,15]. Another field is to measure traffic and trade through ports, and to analyze changes over time, which can be related to investments needed for infrastructure. From a traffic perspective, today's SAR system possesses the capability to consider truck traffic flows or to estimate trade through ports.

Satellite measurement modes

This appendix will briefly describe available satellite measurement modes and give examples of available satellite systems. Several different satellite systems could deliver useful radar data for measurements proposed in this report. Radar remote sensing from satellites is facing an expansion and there are many new consortia that plan new satellite systems, which may be available within the next few years. All systems have in common the ability to order data in different measurement modes. In TENTacle, two different type of modes are used, that will be described in the following passage. To provide insight into the area, we have presented a short and very general description to describe the difference between measurement methods.

All satellite radar systems today have a variety of measurement modes. These modes have been developed to optimize performance in various applications. For example, if you have an application that needs a high resolution, you choose that mode. However, you will then lose coverage and the imaged area will be smaller. Another mode might be maximum coverage, where you lose resolution. This could be compared with a camera where a photograph at a given location with a zoom lens gives a very detailed picture of a smaller area, compared to a wide-angle lens that gives a large view but not with same amount of detail, due to the lower resolution. For traffic measurements, resolution is important, and in this case, it is interesting to distinguish between measurement methods that generate one or several measuring channels. For logistics at one harbor, the measurement resolution is important, where the highest possible resolution available is required.

One channel SAR image

This is the most common way to operate a satellite system. Only one SAR image is generated where the polarization[4] and the resolution are selected. Long aperture (that is, long measurement time) gives high resolution, which is often combined with high bandwidth. Usually, high resolution means that the imaged area decreases. Some available modes are Spotlight, Stripmap, and ScanSAR modes, each of which has slightly different properties. For example, the resolution in Spotlight can be less than 1 m, for Stripmap it is 3 m, and for ScanSAR it is 15 m.

Multi-channel data

By separating radar measurements in time, objects that move can be emphasized. If the time difference is long (hours or days), one can emphasize the changed objects in the area (CD). If, on the other hand, the time difference is short (millisecond), one can emphasize objects that move (GMTI) [5]. In CD, we can use one-channel SAR images by combining two images generated at two different orbits by the satellite. In GMTI measurements, the radar antenna on the satellite is divided into two or more parts. An antenna measures the same area but slightly offset in time to the other antennas. This time difference is used to acquire time-separated SAR images. CD and GMTI is very effective in highlighting changes or moving targets, such as trucks.

Available satellite systems and data products today and tomorrow

Today there are a variety of available satellite-based SAR systems. These are owned by large space organizations such as the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA), and smaller space organizations such as the German Space Agency (DLR), Canadian Space Agency (CSA), Japan Aerospace Exploration Agency (JAXA), and Korea Aerospace Research Institute (KARI). Broadly speaking, all satellite systems deliver SAR images with varying resolution, wavelength, and polarization. Virtually all these systems have enough resolution to make traffic measurements, but only few have high resolution for logistic measurements and the ability to generate multi-channel SAR images, which are probably much better suited for measuring traffic. The multi-channel mode and high resolution has previously been restricted to military use. Here, we describe some of these systems.

Radarsat 1,2 and Radarsat NG

Radarsat are a series of Canadian remote sensing satellites used for both civil and military purposes. Radarsat-1 [16] was launched in the mid-1990s with a main objective of monitoring ice and sea in the Arctic, essential for a country like Canada. For this reason, C-band (wavelength 60 mm and frequency 5 GHz) was chosen as it has a less sensitivity to sea clutter than the more commonly used X-band. Probably for the same reason, HH polarization was chosen for Radarsat-1. Almost 10 years ago, the Radarsat-2 was launched. Radarsat-2 also uses the C-band and has (in part) the same mission as

[4] The polarization of the transmitted and received radar wave has great importance. Visible light also has a polarization but that is not so clear to us because we do not have polarization-sensitive eyes. One illustrative example is polarized googles to reduce reflections in traffic or by utilizing the polarization effect for experiencing 3D visual effects in a move. In radar the transmitted wave has a polarization and a possibility of receiving with two different polarizations. Many satellite systems offer full polarization, i.e. transmit and receive with all combinations and they are designated (VV (V transmitted and V received), VH, HV and HH), and it is called full-polarimetric. The polarization is an important choice and it is used in many different applications.

Radarsat-1. However, Radarsat-2 is more useful as it is fully parametric with better resolution than Radarsat-1. Therefore, Radarsat-2 is often used for military applications. Radarsat-2 is able to divide the satellite antenna into two and thus is also suitable for traffic measurements. However, a disadvantage compared to X-band systems is its sensitivity due to the longer wavelength at C-band. It is also known that multichannel Radarsat data is difficult to order for civilian purposes. In 2019, the Radarsat Constellation [17] satellite mission is planned for launch into space. The system consists of three satellites that will fly in formation. The system operates in the same way as the other Radarsat satellites at C-band, and is fully polarimetric; that is, it can both transmit and receive different polarizations. A likely development is that the military modes will become more accessible over time; however, this will depend very much on the level of interest for these modes and the security situation around the world.

TerraSAR-X, TandDEM-X and TerraSAR NG

TerraSAR-X [3] and TandDEM-X [4] are two German satellites operating at X-band (wavelength 30 mm or 10 GHz frequency). The satellites are commonly used for civil and military purposes. The satellites are owned and operated in a public-private partnership between DLR and the Airbus Defense Research Agency. The radar is fully polarimetric, and the satellite's radar antenna can be divided into two parts, which gives good properties for detecting and measuring movements (multi-channel data). A few years after TerraSAR-X was launched, the twin satellite TanDEM-X was developed, which has the same measuring instrument as Terra SAR-X. Both TerrSAR-X and TanDEM-X can be placed in many different constellations in relation to each other, see Figure 23. The satellites can operate close in space or far apart, depending on the application. Therefore, the satellites are often placed very close together, and during the experiment related to this report, they were in a formation flight with only a few hundred meters between them. Their most important mission has been to make high-resolution topographic maps of the Earth. This task means that the system has a well-developed phase sensitivity, which can be very useful when using the satellite for traffic measurements. Because each satellite has two channels through the shared antenna, it is possible to use different channels for space and time measurements. In a few years, TerraSAR-X will be replaced with TerraSAR-X Next Generation [18], meaning the system will continue until at least 2025. This new system will have a much improved performance.

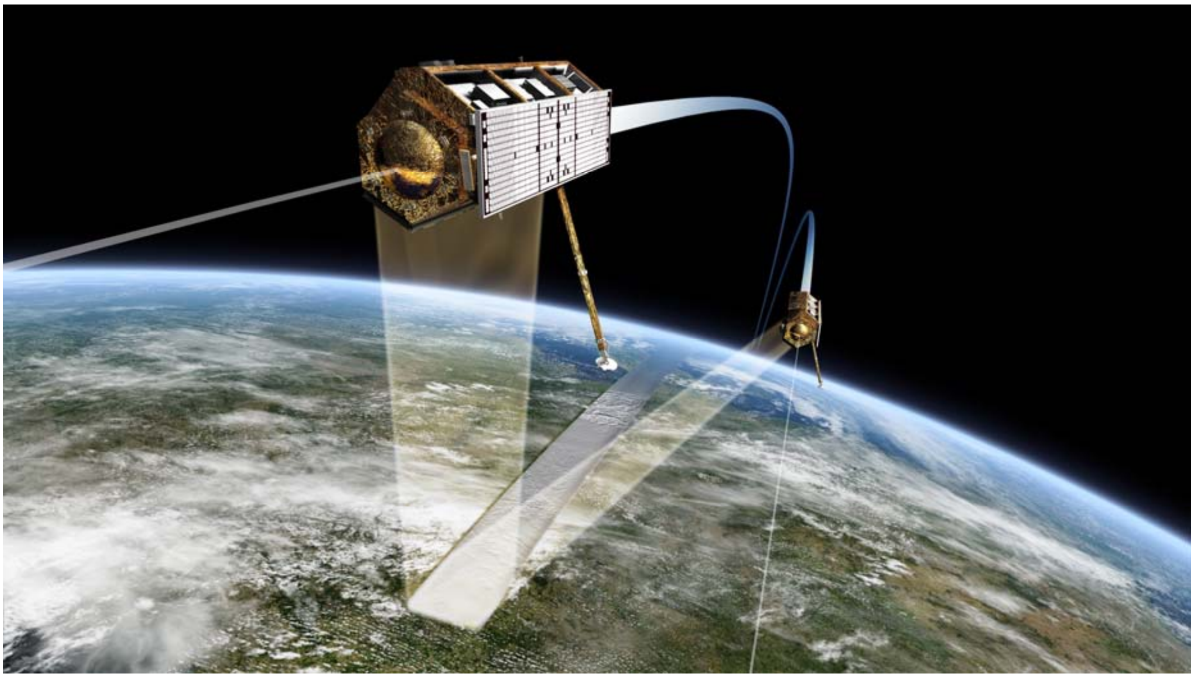


Figure 23. TerraSAR-X and TanDEM-X flying in formation. This satellite system was used for the evaluation in the report. Credit: German Aerospace Center (DLR).

COSMO-Skymed

COnstellation of small **S**atellites for the **M**editerranean basin **O**bservation (COSMO)-SkyMed [19] is a satellite system consisting of four satellites ordered by the Italian Ministry of Defense and the Italian Ministry of Research. The Italian Space Agency is responsible for operation. The system has both military and civilian modes and operates on X-band. The system can operate in different polarizations such as VV, VH, HV, and HH. The idea of the constellation is to achieve good coverage of the Earth's surface in both space and time. In the constellation, the satellites have the same orbit but are displaced in time for maximum coverage. The constellation repeats itself every 16th day. This means that one of the four satellites will return to the same position four times within the 16-day orbit. By directing the antennas to a specific area, the measurements can be made much more often, but they then occur with slightly different measuring geometries. COSMO-SkyMed will be replaced by COSMO-Skymed Second Generation (CSG) [20], with the first satellite being launched in 2019. This will have improved performance compared to the first generation.

PAZ and KOMPSAT-5 and 6

Peace in Spanish (PAZ) [21] was launched in 2018, and the satellite is operated by the Spanish Space Agency, having both civil and military missions. The radar system on PAZ is a "copy" of the TerraSAR-X radar, enabling both PAZ and TerraSAR-X to be interconnected. PAZ operates on the X-band and is fully polarimetric and has good properties for making traffic and logistics measurements. KOMPSAT-5 [22] is a satellite from Korea, which is a SAR system similar to COSMO-Skymed. KOMPSAT-6 has a more advanced SAR system, planned for launch in 2020.

New satellite systems with new business model

At this moment, the market for high-resolution radar images is rapidly changing. Around the world, there are many private investments being made and new consortiums being established. Tomorrow, high-resolution SAR images will not need to be ordered from a governmental organization, but instead will be bought from a private company making profit on the images. Two of these new satellite systems are the Finnish ICEEYE [23,24] and the American Capella Space. ICEEYE is a microsatellite with a SAR system onboard. The first satellite was launched 2018 and has received a lot of attention from the community and stakeholders.

Capella Space is an American company that has the ambition to make similar satellite measurements as the big governmental systems mentioned previously; however, with a completely different price, according to a new business model. One of the basic ideas is to launch considerably more satellites into orbit. Currently, Capella Space is planning to launch 36 satellites flying in formation [25,26]. This would result in much lower manufacturing costs for the satellites and would make the operation much cheaper. The aim is to reduce the cost of data and thereby enable completely new applications and application areas. Another effect of the large number of satellites is the updating of measurement over the same area.

Satellite systems such as TerraSAR-X have an update rate of two passages a day. Capella Space believes that they could update as often as once per hour. One of the reasons for the development of Capella Space is said to be that the US has changed its legislation, which means that American companies will have the opportunity to sell high-resolution radar images of the United States, which was not the case before. Many believe that this industry will grow in the next few years. Capella Space operates on the X-band like most other satellites described here. The first of its satellites was launched into orbit in December 2018.

Price for evaluation of traffic or logistics based on SAR satellite data

Satellite SAR data for traffic or logistics measures is of course associated with cost. However, it might be very cost effective, when considering the large areas and the quality of measurements that the system can provide. Generally, we see two main different types of costs: 1. Development costs to process satellite data. The technology is new, and therefore there has to be some development made on the user side. 2. Satellite data. The data is bought from a provider that delivers data for some agreed price.

Data processing on the user side has low cost when the software is developed, and the methods are fully established. However, because the technology is new and untested, new software to process the data for analysis is required. This software must be developed, and that development is associated with a cost. This will require further study to get a reasonable estimate. We should therefore only discuss the cost of satellite data from the supplier and not the development of the computer environment on the user side.

According to this reasoning, the price would roughly correspond to the cost of buying data. Today, there many sources providing data for traffic and logistics; however, but to date it has only been possible to identify pricelists available online that are rather old. Conversely, we took note of prices for satellite data from 2016 for some of the suppliers mentioned previously, and for some, the same pricelist is still available. In a few years there are considerably more suppliers of data. Some of these promise a considerably lower unit price than current suppliers. This will put pressure on all suppliers, and it is therefore likely that prices will be reduced in the coming years. The prices we have taken note of are a unit price, which is why the prices should be considered as a very high estimate. This is due to the large order needed for the evaluation, which will most probably reduce the price sharply. In connection with a measurement mission, it is necessary to initiate a negotiation with the supplier to secure a good price. It should be possible to reduce the price in real terms, but it is difficult to say by how much. We have, as already mentioned, taken note of unit prices for SAR images from 2016, when prices were between 10,000 and 60,000 Swedish Krona (€100 to €600). Higher resolution demands a higher price. All the suppliers chose to differentiate between the image that is taken from the archive and the image that you order with a time and space assignment. If archives images are selected, the price is less compared with images generated on request. However, for the evaluation proposed in this report, it is probably the case that archived images cannot be used.

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