Satellite-based ROW monitoring solution deployed in full operation: initial results

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Abstract

For the past decades, aerial surveys have been the state-of-the-art solution for right-of-way (ROW) monitoring to protect pipelines from third-party-interferences (TPI's). When TPI damage a pipeline, it can lead to disastrous events. Although aerial inspection systems are still the most widely used approach to mitigate these risks, recent developments in Earth observation (EO) technology have enabled satellite-based ROW-monitoring solutions to become a viable alternative. In fact, it will be shown in this paper that satellite-based monitoring approaches applied in full operation in many cases even outperform aerial surveys with respect to TPI detection performance.

The main drawbacks of traditional aerial platforms relate to unreliability due to weather dependence, a relatively low temporal re-visit rate and reporting subjectiveness due to a human observer. Nevertheless, the industry has been holding on to this technology, as it is a proven concept with a perceived high performance. As an alternative to these aerial inspections, the satellite-based system CoSMiC-EYE (Combined-Sar-Multi-Spectral-Change detection) has been developed by Orbital Eye. This TPI monitoring solution can operate weather independent, offers high temporal revisit rates and delivers objective reproduceable monitoring results without human observers, thus overcoming the major drawbacks of traditional aerial inspections.

In the past year, CoSMiC-EYE transitioned to a fully operational satellite-based TPI monitoring solution servicing thousands of kilometres of pipeline world-wide. In this conference contribution we present and detail our findings based on these operational deployments that were executed together with a number of pipeline operators from across the globe. The results will show, among other valuable insights, that satellite-based ROW-monitoring is fully ready for large scale operational use and, in many cases, can outperform traditional aerial inspection solutions. The combination of SAR and Multi-spectral imagery is shown to be key in this and truly presents a novel solution to manage TPI's more efficiently and sustainable.

1 Introduction

Although many technical innovations have been introduced in the pipeline (monitoring) industry over the past decades, the current aerial monitoring solutions are still very similar to the original concept as introduced in the past century. The technology is widely accepted by the industry but is also sub-optimal in many ways. The main drawbacks of aerial platforms relate to unreliability due to weather dependence, low temporal re-visit rates and reporting subjectiveness introduced by the human observer. Basically, aerial surveys are obsolete technology no longer fit for the 21st century where safety and sustainability are more important than ever. This paper presents an alternative, satellite-based monitoring solution, developed by Orbital Eye. In section 2, a description of the CoSMiC-EYE (Combined-Sar-Multi-Spectral-Change detection) technology is provided. Section 3 presents two operational deployments of CoSMiC-EYE executed in 2021 in Trinidad and the Netherlands, the latter also including a comparison of CoSMiC-EYE to aerial surveys. Finally, the main learnings and conclusions of these operational deployments are discussed in Section 4.

2 Background – Right-of-Way monitoring from space

The satellite-based monitoring technology discussed in this paper has been developed by Orbital Eye, a company specializing in satellite data analytics to detect and monitor activities at the Earth’s surface. Instead of data products, Orbital Eye offers tailored integrated solutions. In the case of Third-Party-Interference (TPI) monitoring, pipeline inspectors and managers are provided with a decision support platform to detect, track and manage TPI’s along their assets. This section introduces CoSMiC-EYE and the technical background.

2.1 CoSMiC-EYE

The CoSMiC-EYE service is Orbital Eye’s main product and is developed as an alternative to conventional aerial inspection methods for pipeline corridors. One of the main concepts at the heart of the CoSMiC-EYE solution is that it optimally combines data from three different types of satellites constellations: (1) Sentinel-1 Synthetic Aperture Radar (SAR) satellites, (2) Sentinel-2 multi-spectral satellites and (3) high resolution[1] optical satellites, such as SkySat, Pleiades and SuperView. Figure 1 shows an overview of the CoSMiC-EYE system.

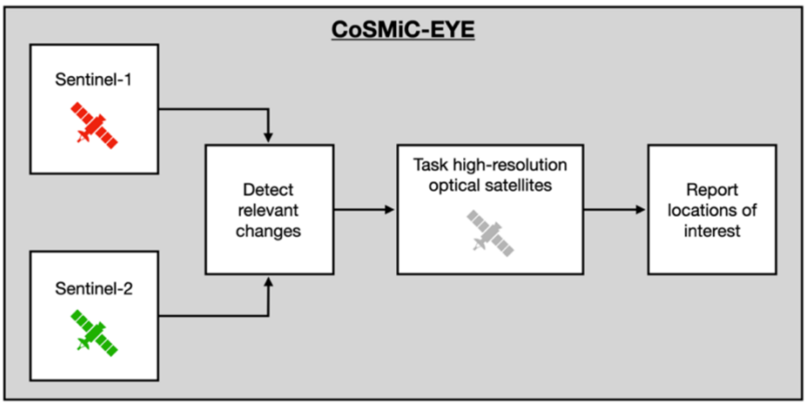

Figure 1: Flowchart of the general operations of the CoSMiC-EYE system. First of all, Sentinel-1 and Sentinel-2 imagery is ingested into the system. An advanced change detection algorithm filters all irrelevant changes. Next, high resolution optical satellites actively task and collect images near all relevant changes. Finally, the relevant locations together with recent high resolution optical images are reported to the pipeline operators.

[1] High resolution is defined as optical imagery with a pixel resolution of 0.5 meter or less.

Both Sentinel constellations are designed for monitoring and capture imagery of the entire pipeline corridor at a fixed high revisit frequency. A single overpass of these satellites often captures the entire network of an operator. Data from the latest overpass is compared to the previous overpass and all relevant changes are extracted. A combination of classical and Artificial Intelligence (AI) filters are subsequently used to remove all irrelevant changes. The remaining locations of interest (LoI's) determine the areas for which high-resolution optical data is collected. When recent high-resolution optical images are available from the global archive, then these are provided to the pipeline operators. Otherwise, satellites are actively tasked to acquire new images at the location of interest. Those activities confirmed to be relevant are finally reported to the customer where the high-resolution optical imagery also serves to support the customer in classifying the reported activity without the need to visit the location. A more detailed description of the CoSMiC-EYE technology can be found in our previous conference contribution.[1]

ROW monitoring systems are often dependent on local conditions to perform their operations. Aircraft, helicopter and drones are for example weather dependent. Heavy rain, gusts of wind or fog can prevent them from taking off or limit the visibility. However, at the heart of the CoSMiC-EYE system is a modified SAR Coherent Change Detection algorithm based on Sentinel-1, which is weather and day-time independent. Although, clouds can obscure the view of Sentinel-2 and high-resolution optical satellites, the CoSMiC-EYE system can always report with a baseline performance based on Sentinel-1. When the clouds disappear or a gap opens up at a location where the radar detected a relevant change beforehand, then the optical sensors are ready to collect their share of information.

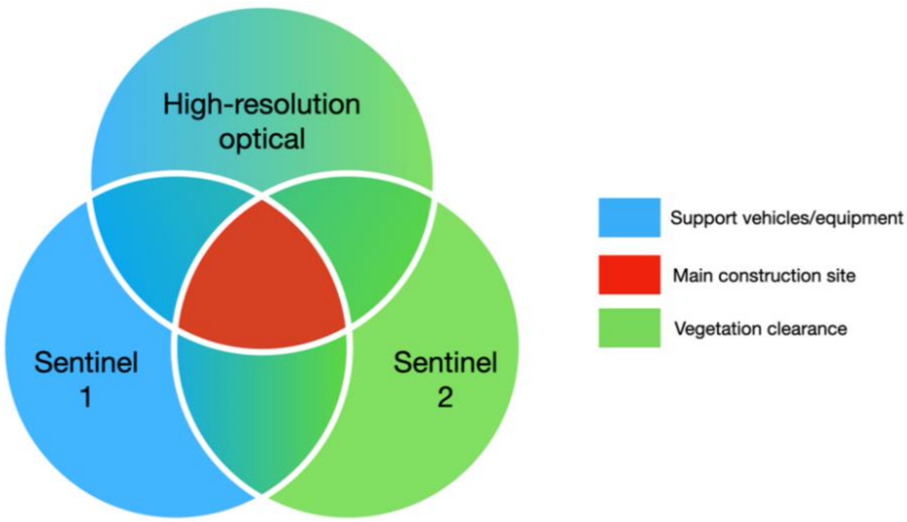

Figure 2: Schematic overview of the type of activities that are captured by the three different types of satellites present in the CoSMiC-EYE system. Sentinel-1 is mainly specialised to capture support vehicles and equipment due to the properties of the SAR signal. The multi-spectral signal payload of Sentinel-2 is best at spotting changes in vegetation. The high-resolution optical satellite can detect support vehicles/equipment as well as changes in vegetation. All three systems have the individual capability to detect the main construction site of a TPI.

The high revisit time of the satellites provides them with the capability to capture long as well as short duration events. Events with a short or long duration consist of different components. Often there is a main construction site which consists of support vehicles and equipment, which cause ground disturbances indicated by vegetation clearances. The different satellites used by CoSMiC-EYE each play their own role to capture these components, which is shown in
Figure 2.

Sentinel-1 mainly detects the presence of support vehicles and equipment, Sentinel-2 is specialized to identify vegetation clearances and the high-resolution optical satellites can capture support vehicles and equipment as well as vegetation clearances. All three types of satellites are able to detect the main construction site by themselves.

Figure 3 shows an example of a larger construction site in the Netherlands which contains all the different types of activities listed in
Figure 2. Figure 3a shows a detailed overview indicating all elements of the larger construction site based on the available high-resolution optical image (SuperView). Figure 3b and Figure 3c shows respectively the less rich Sentinel-1 (SAR) and Sentinel-2 (multi-spectral) image. Both images can't detect all activities, however the combination is able to capture the full extent of the activity. The advanced combination of three different types of satellites grants CoSMiC-EYE with the capabilities to detect all types of activities and offers the pipeline operators the ability to classify any event from the office with high-resolution optical imagery.

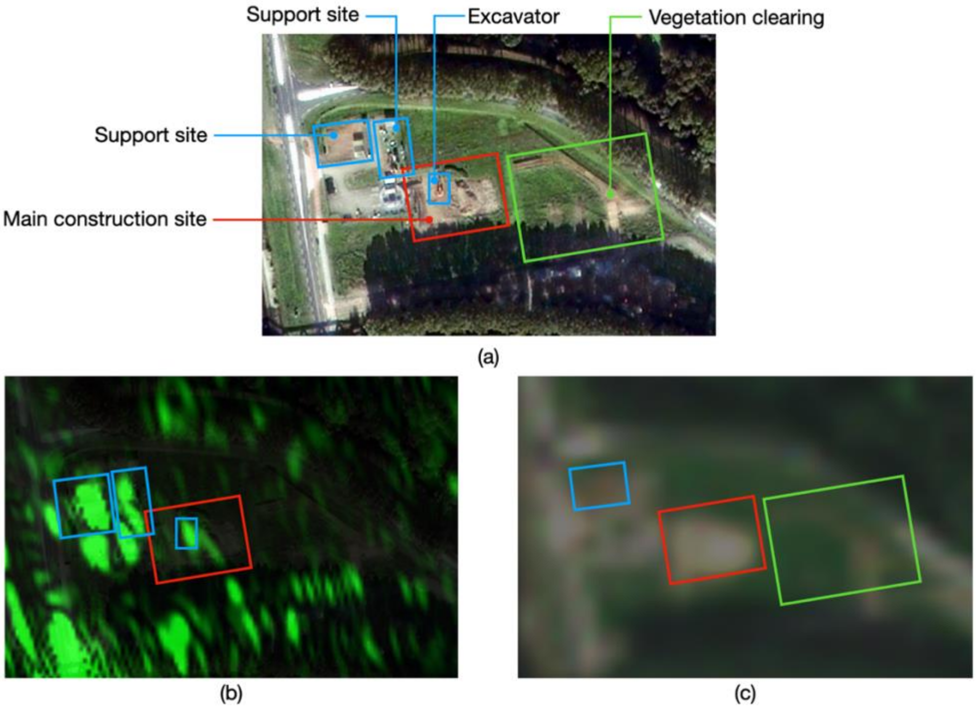

Figure 3: Overview of the types of objects/activities that are detected by (a) high-resolution optical imagery, (b) Sentinel-1 SAR and (c) Sentinel-2 multi-spectral. Combined the Sentinel-1 and Sentinel-2 satellites detect all components of the activity.

2.2 Deployment of CoSMiC-EYE in an operational context

Pipeline operators have long been used to conventional monitoring methods, mentioned earlier in this paper. Implementing a new, innovative monitoring solution can therefore be a challenge – as this requires an adjustment in operational processes. Besides, ultimately, different departments within an organization should benefit from the implementation of new technologies in order to successfully adapt this new technology as an organization. The implementation of the CoSMiC-EYE monitoring solution into pipeline operators' operational processes, and the benefits it brings to different departments within an organization, are therefore important aspects when integrating this innovative technology. In this section, it is described how CoSMiC-EYE usually is implemented into organization and two examples of current implementations are given.

When a pipeline operator has chosen for an integration of the CoSMiC-EYE monitoring service, Orbital Eye assesses the monitoring procedures that are currently in place and how CoSMiC-EYE can complement or substitute these procedures. In this assessment, several aspects are considered, such as, but not limited to, the current monitoring frequency, the type of activities that pose a threat to the pipeline, regulation around pipeline monitoring and the current workflow of operators. The CoSMiC-EYE monitoring service will then be optimized based on the outcomes of this assessment. Besides, the organizational goals for adopting this new technology are discussed, which also serve as a metric for monitoring the performance of CoSMiC-EYE.

Since the start of January 2021, CoSMiC-EYE is integrated into the operational processes of a Transmission System Operator (TSO) in Trinidad and Tobago and a TSO in the Netherlands. The customer in Trinidad was used to monitoring the pipeline network mostly by ground patrol, while the Dutch customer monitored its network using a combination of aerial- and ground patrol.

To the customer in Trinidad, Orbital Eye reports newly detected activities at a weekly interval. New activities are reported in the CoSMiC-EYE application, which the customer has installed on desktops and tablets. Besides, an email is sent with an overview of all newly detected activities. The network of this customer is divided into several regions, with a field inspector being responsible for one or multiple regions. When new activities are reported, the field inspectors open the CoSMiC-EYE application, and check for each activity if it is a known activity, an activity that can be classified based on the available high-resolution optical imagery, or if an on-site inspection is needed for that activity. All activities are thus classified either from the office, or after an on-site inspection.

The Dutch customer receives biweekly updates about detected activities. All activities are checked by a team in the office – checking if activities are known, can be linked to permits provided for ground works (so-called KLIC data) or if they can be classified by analysing the optical data. If an activity cannot be classified from the office, or when an on-site intervention is needed, the team in the office will inform the field staff about this activity, after which the field staff plans an on-site visit.

3 Review of operational service in 2021

The operational services detailed in this paper are summarized in Table 1. The monitored areas covered a variety of land usages from rural regions and forests to dense urban and industrial areas, such as the port of Rotterdam. The operational studies were analysed and different statistics will be discussed to compare the performance of the CoSMiC-EYE system. First of all, the number of detected events is presented in Section 3.1. The types of detected activities are also shown and multiple examples are presented. Next, Section 3.2 provides an in-depth analysis of the performance, discussing in detail the observed true/false positive rates. Section 3.3 compares the CoSMiC-EYE service performance in the Netherlands to helicopter surveys that were conducted in parallel and Section 3.4 discusses the qualitative organizational impact of operational use of CoSMiC-EYE. Finally, the results are summarized in Section 3.5.

Table 1: Overview of the main characteristics of the operational services conducted in 2021.

	Service 1	**Service 2**
Country	Trinidad	The Netherlands
Type	Transport	Transport
Area class	Rural/Urban	Rural/Dense urban
Pipeline length (km)	450	250
Corridor width either side (m)	30	15
Duration	12 months	12 months
Anomalies/month	4.8/100km	4.2 /100km
Aerial surveys	no	yes

3.1 Reported activities

In 2021 many activities were detected within the monitored pipeline corridor for the services provided in Trinidad and The Netherlands. When longer duration events are detected, then they can consist of many significant temporal changes which are reported to the pipeline operators. Only the first report of an activity was taken into account during the analysis of this study, as the purpose of this study is to present the total number of relevant activities within the corridor. Figure 4 and Figure 5 show the total number of reported TPI’s over time in 2021 for the services in Trinidad and The Netherlands.

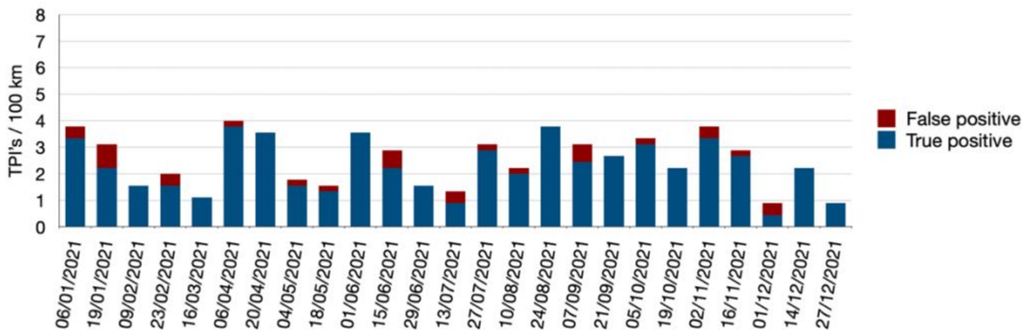

Figure 4: Reported activities by CoSMiC-EYE during the operational service provision in the Trinidad.

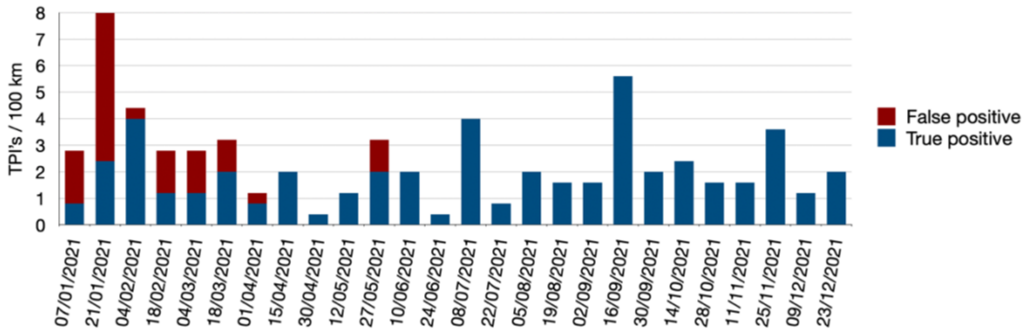

Figure 5: Reported activities by CoSMiC-EYE during the operational service provision in the Netherlands.

The service in Trinidad quickly established a consistent performance with respect to the number of reported activities and false alarm rate (see Figure 4). On the other hand, the service in the Netherlands initially needed some time to be calibrated. Mainly, the dense urban area near the port of Rotterdam initially resulted in a large number of false alarms. The CoSMiC-EYE systems learns from the user classifications. The feedback was used to optimise and train the system to achieve the expected service performance from March onwards. CoSMiC-EYE was able to report for many consecutive reporting intervals without any false alarms by the time of June for the service in the Netherlands.

Both the services presented in this study were not only running in completely different parts of the world, they also consisted of slightly different types of land cover. The pipeline in Trinidad covered more rural areas consisting of agricultural land to dense forests. The monitored corridor in the Netherlands crossed many industrial and dense urban areas. The rural areas in the Netherlands were often still subjective to intensive agriculture and, therefore, continuously in flux. In general, agricultural activities are not of interest to the pipeline operators in these studies. Changes caused by normal agricultural activities, such as harvesting and ploughing, are therefore filtered by the CoSMiC-EYE system.

The types of reported activities are shown Figure 6. Trinidad has relatively more combined storage/heavy loading and vegetation/agriculture events than working sites in comparison to the Netherlands. The main differences are due to different land cover types that are crossed by either pipeline. For example, vegetation clearances happen more often in rural areas and vice versa works happen more often in urban neighbourhoods. Figure 6 provides an overview of the true positive detections. All of the false-positive detections were due to traffic or transportation activities detections. A more elaborate analysis of the true-positive/false-positive ratio will be presented in Section 3.2.

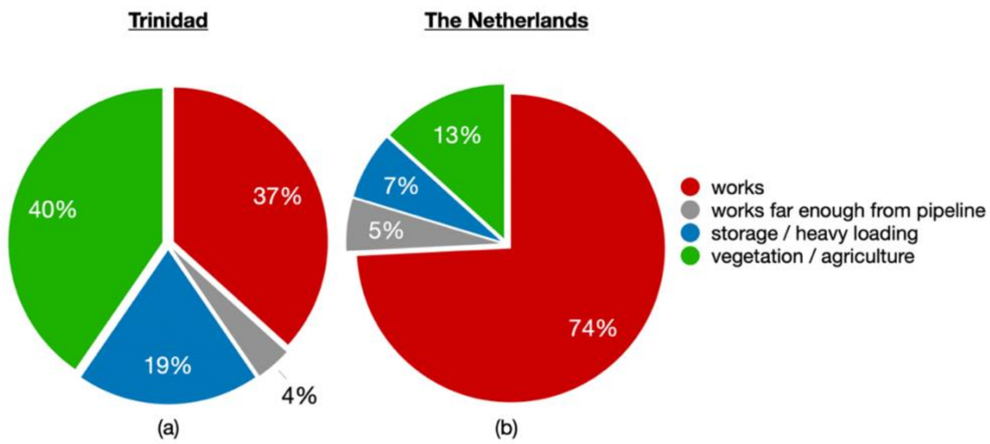

Figure 6: The share of each type of relevant activity reported by CoSMiC-EYE during 2021 in Trinidad and the Netherlands.

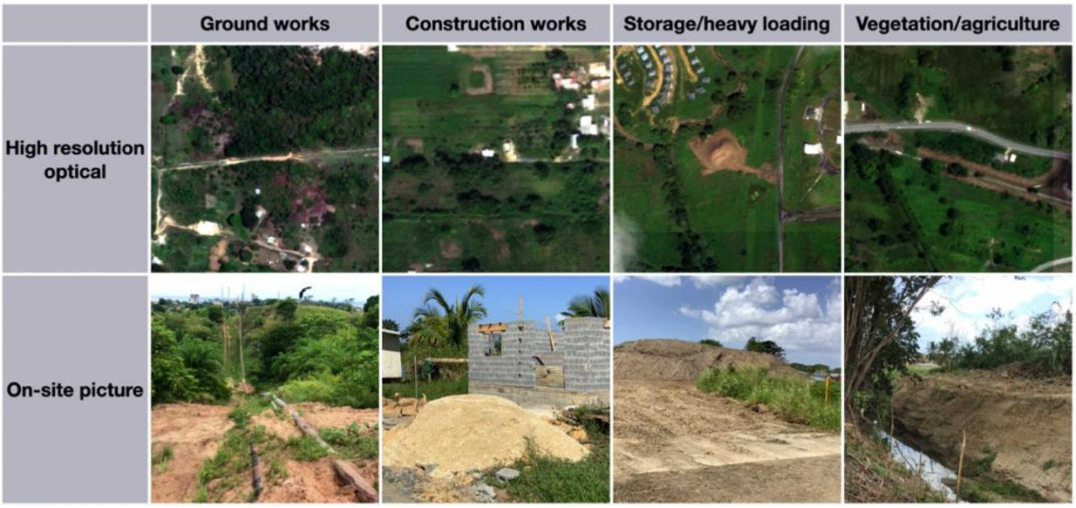

Figure 7: Examples of different types of reported activities in Trinidad.

Figure 8: Examples of different types of reported activities in the Netherlands.

Figure 7 and Figure 8 show examples for the main categories of the relevant events shown in Figure 6, and relate to activities detected in respectively Trinidad and the Netherlands. First of all, the works-category was divided in ground works and construction works. Ground works always disturb the ground and therefore are the most immediate threat to buried pipelines. Construction works mainly cause external loads on the pipeline, and cause immediate damage due to the heavy equipment used on-site. In Trinidad, illegal settlement and encroachment also happens, which is another incentive to monitor the corridor actively. The third category is related to storage/heavy loading activities near the ROW. Stockpiles on top of the pipeline can cause external loads on a buried pipeline and also make maintenance activities in the vicinity more difficult. Storage activities are often part of site preparations before construction takes place and therefore are a good early warning trigger for future activities that may take place within the corridor. Finally, the fourth category consists of vegetation clearances and other agricultural activities. As examples, vegetation clearance and dredging activities (Figure 7), and a temporary pathway construction leading to a vegetation clearance (Figure 8) are presented. These activities are often unknown to the pipeline operators, but do interfere with the ROW. Hence, they are reported to the operators. Activities related to vegetation are well visible in the provided optical imagery and can often be classified from the office.

3.2 Operational performance

The operational performance of CoSMiC-EYE in this study is presented in Figure 9 and based on the true-positive rate. The operational deployment of the satellite-based service resulted in a consistent true-positive rate at 90%. The start-up phase of the operational service in the Netherlands took slightly longer and soon a similar performance was achieved as in Trinidad. During the last 4 months of 2021 there eventually were no false alarms and a true-positive rate of 100% was achieved.

The backbone of CoSMiC-EYE is the SAR coherent change detection algorithm that works weather and daytime independent. This is an absolute necessity as both Trinidad and the Netherlands are very cloudy from time to time. Figure 10 shows the average cloud cover for the Sentinel-2 overpasses in both locations. Clouds appear all the time, hence radar must always be a key component in any reliable ROW monitoring service.

Despite the high levels of day-to-day cloud cover in both Trinidad and the Netherlands, CoSMiC-EyE was still able to provide frequent recent high resolution optical imagery at any location of interest. Multiple high resolution optical satellite constellations were collecting imagery for the monitored locations and pass over the defined areas of interest multiple times per day. This is a strong contrast to the Sentinel-2 constellation, which consists of just 2 satellites with a 5-day repeat cycle. High resolution optical satellites target specific areas where changes were already detected by the SAR coherent change detection algorithm. When there is a gap between the clouds at the targeted location, then an image can be acquired and delivered to the customer. As a result, almost all reported changes by CoSMiC-EYE are accompanied by recent high resolution optical images.

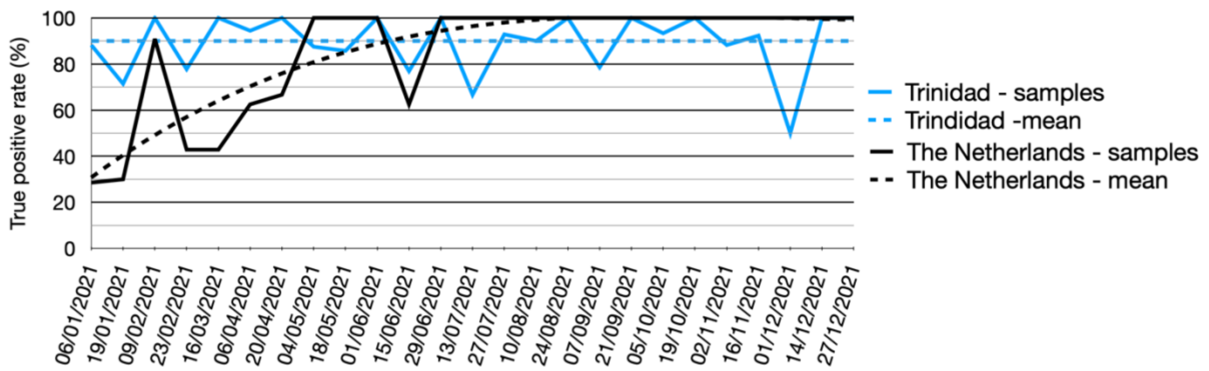

Figure 9: Overview of the ratio of accurate reported events by CoSMiC-EYE during 2021 in Trinidad and the Netherlands. The true-positive reports were determined based on the pipeline operator classifications of the reported events.

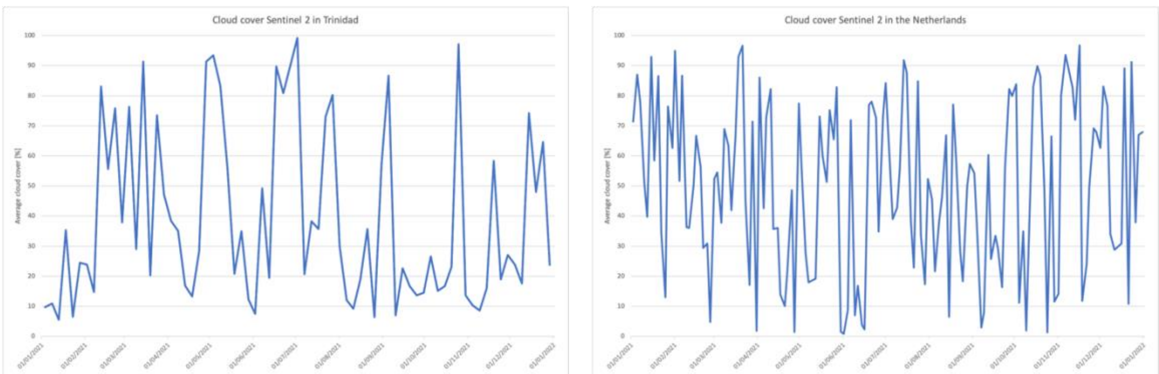

Figure 10: Cloud coverage of the Sentinel-2 images collected over Trinidad (left) and the Netherlands (right) in 2021.

3.3 Comparison CoSMiC-EYE to aerial surveys

Helicopter surveys were conducted in the Netherlands in parallel to the satellite-based service. The helicopter flights took place at a similar bi-weekly interval and were scheduled 4 days after the CoSMiC-EYE reports became available. Therefore, both ROW monitoring solutions can be compared, because they operated at an equal temporal frequency. The results of the comparison are shown in Figure 11. The first bar of Figure 11 shows the relevant activities that were detected by both systems. These mainly concern the large and long duration activities that are well observed from both flight altitude and space. The second bar contains the activities that were only detected by CoSMiC-EYE and contains significantly more activities compared to the third bar, which shows the activities that were only reported by the helicopter. The difference is very significant, as CoSMiC-EyE reported over twice the number of relevant activities that were not reported by the helicopter surveys. The activities of the second and third bar mainly consist of small and short duration events. These activities can be difficult to spot and mainly depend on the overpass time of the system, as they are sometimes only active for a few hours. The high revisit frequency of the Sentinel-1 constellation in the Netherlands (i.e. every 1.5 days on average) allows for more detections of short duration events. The human observer in the helicopter may have a higher resolution view of the corridor, in this case higher overpass frequency is clearly most relevant. Increasing the overpass frequency of aerial platforms is not a scalable or commercially viable option. However, this is not a problem with the current and rapidly growing number of satellites orbiting the Earth.

Furthermore, Figure 11 indicates whether the reported activity was registered at the necessary Dutch governmental institute. All ground works must be registered at a national database in the Netherlands. Known activities were registered, while unknown relates to unregistered activities. The results show that CoSMiC-EYE was able to report more unknown activities than the helicopter. Possibly the helicopter surveys did not report consistently all activities that were already known to the pipeline operators, which may explain part of the difference between both systems. On the other hand, the helicopter also often did report activities that were already previously known to the operators but consistently a lower frequency compared to CoSMiC-EYE.

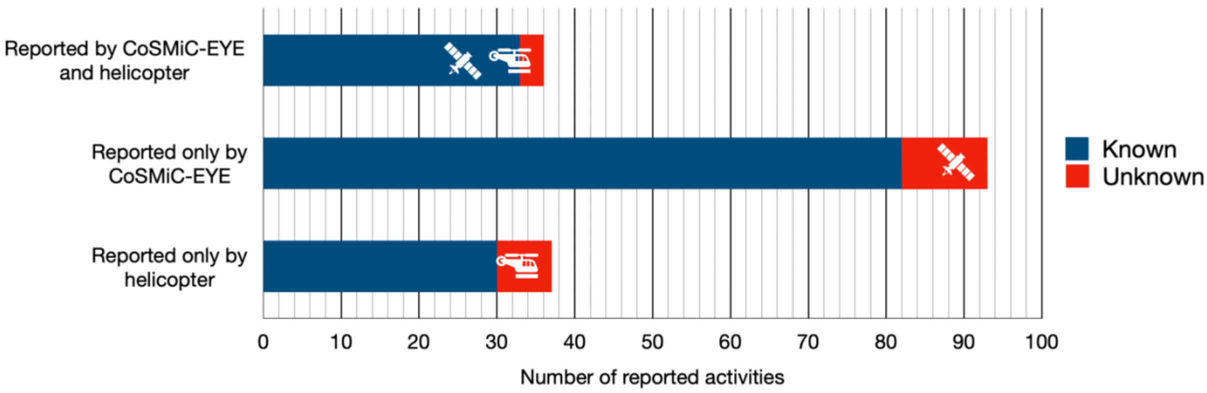

Figure 11: Overview of the activities reported by CoSMiC-EYE and the helicopter during 2021 in the Netherlands. The activities are organized by the type of survey that detected each event. Blue and red respectively indicate whether the activity was beforehand known or unknown to the pipeline operators, because works should be registered beforehand in the Netherlands.

3.4 Value of deployment of CoSMiC-EYE into operations

In previous sections, it was shown that many relevant activities were detected by CoSMiC-EYE and that low false alarms rates were achieved, both at the customer in Trinidad as well as in the Netherlands. However, the important question is how these pipeline operators benefit from the performance of the system, and how a satellite-based monitoring system adds value to the monitoring procedures of a pipeline operator and increases overall safety.

After one year of operational deployment, several benefits are recognized by both customers. First of all, the integration of the CoSMiC-EYE monitoring service into operational processes was not difficult, although there was a small learning curve at the start of both projects. Besides, the situational awareness has increased for both customers. In Trinidad, multiple activities were detected that would not have been detected if the pipeline was only monitored by car patrol, as some activities took place in difficult-to-access places, and due to the high monitoring frequency of satellites. In the Netherlands, where the pipeline network was also still monitored by the helicopter, multiple activities were detected that were not seen by the helicopter (see Figure 11), or that were not registered in the database of permits for groundworks (KLIC-database). Lastly, integration of CoSMiC-EYE into operational processes has also led to an increased efficiency – many reported activities could be checked and classified from the office, through the analysis of the optical imagery. For the customer in Trinidad, this meant that less field visits were required, herewith saving time and money. For the customer in the Netherlands, the improved efficiency was mainly achieved through the integration of KLIC-data into the CoSMiC-EYE software, which enabled the customer to link detected activities to registered activities in the KLIC-database and focus their efforts on those activities not properly registered.

3.5 Summary

The satellite-based monitoring service CoSMiC-EYE was provided operationally to pipeline operators in Trinidad and the Netherlands during the year 2021, covering a total of 700 kilometres of pipeline. A summary of the results of these operational services is provided in Table 2. The main difference was the type of reported activities in both countries: the corridor in Trinidad covered vast rural areas, hence a larger share of relevant events was caused by vegetation clearances and unexpected agricultural events. The dense urban and industrial sites that are crossed by the Dutch pipeline caused more events related to working sites. When the CoSMiC-EYE system was compared to the aerial surveys conducted in the Netherlands for 2021, then the satellite-based solution reported almost double the number of relevant activities in comparison to the helicopter surveys. In addition, both pipeline operators reported improved situational awareness around their assets, which provides some efficiency gains and in turn is expected to have a positive impact on the overall safety level.

Table 2: Summary of the main findings of the operational services provided in Trinidad and the Netherlands.

	Trinidad	**The Netherlands**
Pipeline length [km]	450	250
Mean # TPI's reported per month	4.8 TPI's / 100 km	4.2 TPI's / 100 km
Mean true-positive rate after 3-months	90%	95%
Top 3 reported types of TPI's	1. vegetation/agriculture 2. works 3. storage/heavy loading	1. works 2. vegetation/agriculture 3. storage/heavy loading

4 Conclusion & Discussion

The satellite-based monitoring solution CoSMiC-EYE was successfully deployed as an operational service in Trinidad and the Netherlands during 2021. The technology provided an accurate overview of ongoing activities within the ROW. Therefore, CoSMiC-EYE was found to be a mature and trustworthy ROW monitoring solution. The advanced combination of radar, multi-spectral, and optical satellites ensured that monitoring can be conducted all year long. Despite any weather or day-light conditions, the system proved that it could provide pipeline operators with information on activities taking place within their ROW.

Due to the combination of SAR and multi-spectral satellites, the system can detect all key components of relevant activities to pipeline operators. Radar-based sensors have the ability to detect support vehicles and equipment on-site and multi-spectral sensors are specialised to capture changes in vegetation. In Trinidad, more relevant vegetation clearance and agricultural activities were reported, while more general working sites and excavations were reported in the Netherlands. This was expected based on the varying environmental conditions in either country and confirms that CoSMiC-EYE is fit to be deployed globally.

CoSMiC-EYE showed to report twice the number of relevant activities in the corridor compared to helicopter surveys conducted in the Netherlands. Recent high resolution optical imagery accompanied the reported events. Therefore, reported events could almost always be classified from the office, only reported activities that were unknown had to be followed up in the field. Presented in an intuitive user-interface, the CoSMiC-EYE solution was shown to be a tool that can easily be integrated into pipeline operators' monitoring workflows.

At the moment, industry is still holding on to conventional aerial surveys as the main ROW monitoring solution, although more and more companies are also adopting satellite-based monitoring technologies. Aerial surveys were introduced decades ago to increase the safety of pipeline corridors, even though there was no legislation that forced the use of these aerial surveys. One of the reasons why these aerial surveys were introduced, is because pipeline operators are likely to hold themselves to higher safety standards than they are otherwise legally obliged to, due to the hazardous nature of their activities. Aerial surveys evolved over the years in countries to become the norm and sometimes even legally the prescribed ROW monitoring method (e.g. by national regulatory institutions such as the DVGW in Germany). As a result, the pipeline industry misses out on valuable technology of the current century, as satellite-based monitoring solutions are proving to be, and already are, a more powerful tool to survey the ROW. Therefore, the norm should shift in the upcoming years to allow a more rapid introduction of satellite-based monitoring systems as a valid ROW monitoring solution.

When protecting communities, the environment and assets are the main goal of a ROW-monitoring solution, then satellite-based technology of is the way forward. EO-solutions no longer behold for the future, as the industry has been assuming. The contrary is true, as a satellite-based solution is already here and can compete to become the industry's standard.

5 References

1. Blauw, Alexander and van Haver, Sven, *Operational performance validation results for a satellite-based ROW monitoring solution*, Pipeline Technology Conference 2021 (March 2021)