# 10 Years of Satellite-Based Right-of-Way Monitoring: Reflecting on the Past and Shaping the Future

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# 1 ABSTRACT

In the past 10 years, satellite-based monitoring has been breaking barriers. Back in 2014, monitoring started off with one satellite in a single constellation (Pipeline integrity management from space, Jan Ridder, PTC 2014)[1]; the latest operational deployments use over 100 satellites (Gasunie and Orbital Eye - Operational assessment of satellite-based right-of-way inspections, Alexander Blauw, PTC 2024)[2]. The growing number of satellites has gone hand in hand with the rise of Artificial Intelligence (AI). Satellites have the capability to monitor all pipeline networks in the world. However, a solid system is necessary to translate these vast amounts of data into insights all the way down to the operators. This study breaks down the necessary technical developments of COSMIC-EYE (Combined-Sar-Multi-spectral-Change detection) in the past years into a scalable system for the future to integrate satellites in the day-to-day workflow of operators all around the world.

A reflection is provided on the technology backbone of COSMIC-EYE and how it has integrated different satellite sources over time to monitor the earliest signs of potential threats. A study of different operational deployments with operators is provided. Multiple threats are discussed that were followed up in the field by operators when satellite-based monitoring was integrated into their routine. These activities highlight why the mix of radar, multi-spectral, and high-resolution optical satellites is necessary to create a scalable solution.

The number of satellites in the foreseeable years keeps increasing, and therefore, the reliability of satellite-based monitoring will also increase. Conventional aerial patrols are becoming increasingly expensive as costs go up and sustainability disrupts the Right-of-Way monitoring industry. Satellite-based monitoring is already a proven alternative in the industry operating on networks over 10,000 kilometers. Especially, the scalability of the presented solution with the network size is shown to be a key driver for success.

# 2 INTRODUCTION

In the last 10 years the most frequent cause of damages to underground pipelines is coming from Third Party Interference (TPI), like excavation damage of external parties or other external loads, as the latest publications by EGIG in Europe and PHMSA in North America show.[3,4] Increased monitoring to prevent damages and improved construction technologies showed to reduce the number of incidents for major gas Transmission System Operators (TSO's) in Europe in the past decade.[3] Key drivers to reduce the risk of third party incidents are a combination of monitoring, more stringent enforcement of land use planning and the application of one- call systems for the digging activities of external parties.

Satellite-based monitoring emerged as a valid alternative to aerial patrols in the past decade and plays a crucial part to reduce the risk of TPIs. COSMIC-EYE was developed over the past 12.5 years to support operators worldwide to be in control of any activity in the Right-of-Way (ROW). In total during 2024, 250,000 kilometres of pipeline were monitored by COSMIC-EYE.

In this paper, we provide an overview how the emergence of different satellites has played an important role for the accuracy of satellite-based monitoring. The technology and impact of radar, multi-spectral and high-resolution optical satellites are discussed in Section 3.2. The scalability and accuracy of satellite monitoring has gone hand in hand with the rise of Machine Learning (ML). An overview of this technology's impact on the detection capabilities of COSMIC-EYE is provided in

Section 3.3. The integration with multiple operators in Section 3.4 highlights the capabilities of satellite monitoring after 10 years of intensive research and development.

The review of the current state of the art is followed by a discussion on the next generation of satellites and the advancements that are coming to satellite monitoring (Section 4). Improved detection capabilities and lowering the carbon emissions of the current industry are among the discussed topics.

Lastly Section 5 concludes this paper highlighting the robustness of satellite-based monitoring among large networks extending over 10.000 kilometers. Especially, we show that the versatile nature of the presented COSMIC-EYE solution leads to successful monitoring results even in cases of increased operational demands.

# 3 REVIEW OF SATELLITE TECHNOLOGY IN THE PAST YEARS

Satellite-based monitoring is a high-tech solution fusing multiple satellite sources to detect TPIs near critical infrastructure. Machine learning allows the system to understand the situation at ground-level and filter relevant from non-relevant activities. Therefore, a high detection and low false alarm rate are the most important statistics to review when evaluating a monitoring solution. COSMIC-EYE has shown to perform on the same level or even exceed the performance when compared to traditional aerial patrol methods.[2,5,6] The experience built together with pipeline operators all over the world has led to an extensive dataset of verified TPIs in the past decade that is used to train the machine learning algorithms behind COSMIC-EYE. This section introduces how COSMIC-EYE was founded (Section 3.1), how the satellite developments in the past years have contributed to satellite ROW monitoring (Section 3.2), how machine learning enables satellite data to be translated into actionable insights (Section 3.3) and finally a summary of multiple operational projects highlights how satellite monitoring matches matches the needs and demands of different operators. (Section 3.4).

## 3.1 HOW COSMIC-EYE STARTED

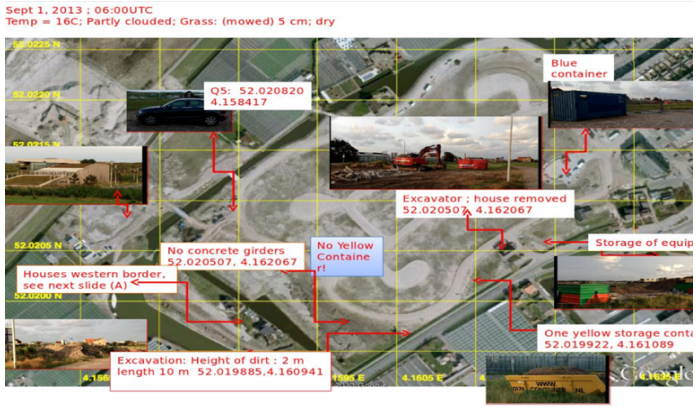
In 2012, the foundations for COSMIC-EYE were built and research started at the time the Sentinel program was announced. However, the satellites were not launched yet. There was just the idea that these satellites could change ROW monitoring. This period marked the beginning of overcoming key challenges in satellite monitoring, including limited satellite availability, low revisit rates, and minimal integration of advanced technologies like machine learning. COSMIC-EYE's development addressed these hurdles and set a foundation for integrating multi-sensor capabilities into global-scale monitoring systems.

At that time there were few satellites available as well as limited constellations with open data, high resolution and/or a high revisit rate. Therefore, the foundations were built on research using the TerraSAR-X constellation. Multiple tests were carried out in the field to understand how TPIs could be detected using remote sensing (see Figure 1). During the test actual TPI's as well as simulated TPI's were placed at these test sites. Early results highlighted both the potential and the limitations of the technology at the time, guiding further research to develop a reliable and scalable monitoring solution.

COSMIC-EYE was developed based on the physical understanding how remote sensing works and how the actual signals interact with objects on earth. The lessons learned formed the basis of

COSMIC-EYE and soon were developed further with operators to create a service detecting activities that are encountered by operators all over the world daily.

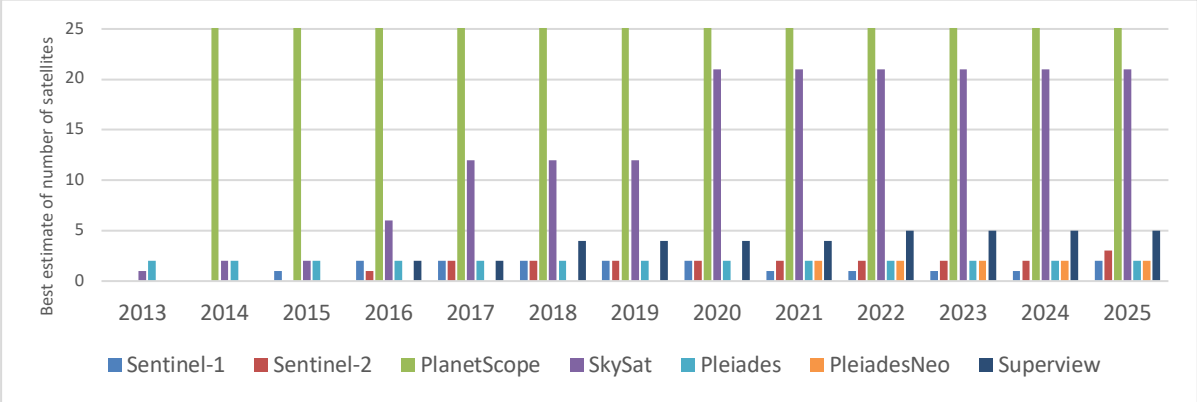
*Figure 1: Map of a test site during one of the field research projects with real and simulated TPIs back in 2013.*[1]




## 3.2 SATELLITE DEVELOPMENTS

During the past 10 years, multiple satellite constellations were launched that created a new market for Earth Observation (EO) products. Figure 2 shows the development of the most impactful satellite constellations that form the backbone of COSMIC-EYE. Most of these EO satellites are in an orbit around 500km altitude and monitor with pinpoint precession. The EO industry has grown over the past years to consist of many constellations and is foreseen to grow even further (Section 4).

*Figure 2: Overview of the satellite constellations used by COSMIC-EYE in the past years. The PlanetScope (Dove and SuperDove) constellation quickly grew past 100 satellites since 2015 and is cut off from the figure for readability.*




The main three types of satellites are:

- Synthetic Aperture Radar (SAR) satellites consist of the Sentinel-1 constellation of the European Space Agency (ESA). Radar satellites are key to detect man-made objects such as excavators, support equipment and structures. Not only are they active sensors working day and night, but they are also capable of seeing through clouds, constituting a mandatory part of the monitoring mix.
- Multi-Spectral (MS) satellites were introduced with the PlanetScope and Sentinel-2 constellation by respectively Planet and ESA. Sentinel-2 is part of the backbone of COSMIC-EYE as it is openly available with a 10m resolution. When needed, PlanetScope is used to zoom in as it provides daily coverage globally at 3m resolution. Multi-spectral satellites measure a wide variety of wavelengths in the light spectrum. Especially the near-infrared

range plays a crucial role to detect changes in vegetation. Clearing of vegetation if often an indication of many groundworks or an early sign of construction works that are about to start. Therefore, MS satellites can detect TPIs very well whether the works are ongoing or already finished. These satellites are always able to see the remnants of the works when there are no clouds.

- High-Resolution optical (HR) satellites are commercial satellites operated by a variety of companies providing images with high details between 30 to 50cm resolution. Due to the high revisit rate of multiple times per day, these satellites can quickly provide optical information under cloud-free circumstances. COSMIC-EYE uses these satellites to verify the activities that are detected in the lower resolution data and to allow the operators to classify the activities from the office.

An overview of the main capabilities is also summarized in Table 1.

*Table 1: Overview of the main characteristics of the three satellite types used by COSMIC-EYE.*

| Type | Synthetic Aperture Radar | Multi-Spectral | High-resolution optical |
|---|---|---|---|
| Resolution | 10 meters | 3 to 10 meters | 0.3 to 0.5 meters |
| Revisit time | 2 to 6 days | 1 to 5 days | multiple times per day |
| Cost type | Free | Free / Commercial | Commercial |

The number of satellites has grown tremendously as well as the variety in sensors and resolutions. The combination of radar, multi-spectral and high-resolution optical data makes sure all parts of a TPI are detected as can be seen in Figure 3. A decrease in vegetation and the presence of equipment makes any site potentially relevant as a TPI. As soon as COSMIC-EYE detects relevant signals from the lower resolution radar and multi-spectral sources, high-resolution optical satellites are tasked to zoom in and confirm the activity. Figure 4 shows an example of groundworks that are visible in a high-resolution optical satellite image where the different elements of the works are detected by the radar and multi-spectral satellites. The radar, multi-spectral and high-resolution optical satellites have enabled satellite ROW monitoring to become a viable alternative or additional to traditional aerial patrols. Where TPIs can be reported reliably with a high accuracy and precision. The growing number of satellites over time has only strengthened the value proposition as more satellites directly translate to more opportunities to detect TPIs within the ROW.

*Figure 3: Breakdown of the type of activity per satellite sensor that together make up a TPI. Man-made objects (blue) are detected by the radar and high-resolution optical satellites. Vegetation related activities are mainly detected by multi-spectral and high-resolution optical satellites.*

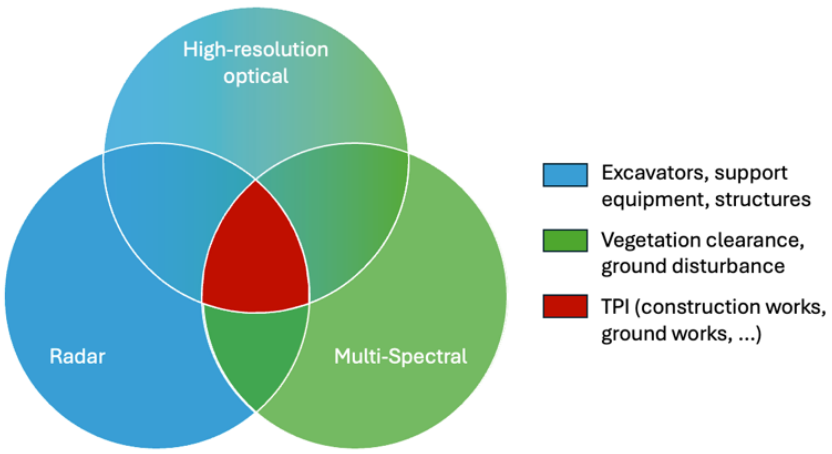
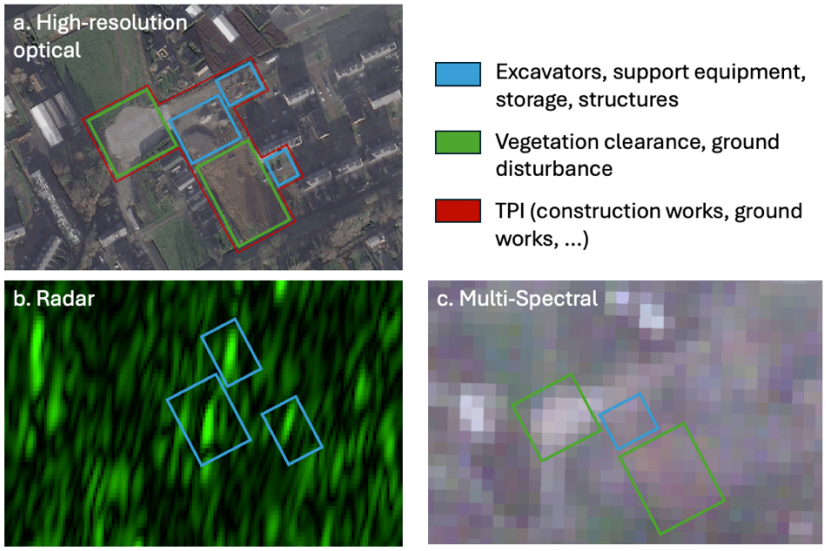


*Figure 4: Satellite images per sources showing the parts of a construction site detected by each sensor type. (a) shows a high-resolution optical image of the entire construction site, (b) shows the amplitude of the radar signal detecting an excavator, storage site and support equipment and (c) shows a multispectral (RGB) image detecting ground levelling, a storage site and vegetation clearance. (a. © Airbus DS (2025), b/c, Copernicus Sentinel data (2025))*




## 3.3 TECHNOLOGY DEVELOPMENTS

The rise of Machine Learning was fundamental to enable satellite ROW monitoring to take off. More satellites mean more data. This does not need to directly translate into higher performance unless there are the infrastructure and algorithms in place to (1) efficiently handle large data flows and (2) automatically detect the features of a TPI. Cloud computing and machine learning have made these advancements possible in the past years. As a result, COSMIC-EYE is a highly scalable system that was trained on almost a decade of classification and feedback from operators all around the world.

The TPI monitoring solution consists of many different models performing tasks such as segmentation, regression, classification and object detection. At any moment in time, the employed machine learning models extract feature representations from the available data and produce useful prediction insights in the form of binary masks or bounding boxes that point to potential threats. In Figure 5 we illustrate various data sources that are exploited in different tasks performed at any time by the machine learning models. The machine learning models can at any time generated the specific features that they need for their specific task. Each model requires a different data source as input. The detection of road works for example can greatly benefit from the road network annotation mask. The integration of machine learning allows the system to also scale with any network size. Currently, COSMIC-EYE operates with the same efficiency on networks of 100 to 10,000 km.

The increasing robustness of machine learning models has allowed the successful management of difficult tasks such as the detection of tiny objects. This is an especially challenging problem as vehicles or excavators can be the size of 10 pixels in satellite images of 30 to 50cm resolution. For a long time, this was near or at the limit of what was possible. Any excavator near the ROW of underground infrastructure can be an immediate threat. Therefore, any excavator or suspicious vehicle within the ROW can be immediately reported to an operator and mitigation measures can be taken. Satellites scan the pipeline networks on almost a daily basis and can often detect potential threats significantly earlier than conventional aerial patrol.[2] Satellites cannot land at immediate risks like a helicopter. However, operators can still interfere earlier using COSMIC-EYE as satellites on

average detect potential threats before the aerial patrol. Figure 6 shows an example of an excavator that was detected at near the ongoing groundworks. The presence of the excavator can be immediately escalated to the operators. They can review the situation from the office based on the accompanied high-resolution image and take appropriate actions to mitigate any risk.

*Figure 5: Example of different data sources exploited by the machine learning models. From left to right, high-resolution optical, radar VV, radar VH, multi-spectral, multi-spectral cloud mask, road network, land-use classifiction. (© Airbus DS (2025), Copernicus Sentinel data (2025), OpenStreetMap. TOP10NL))*

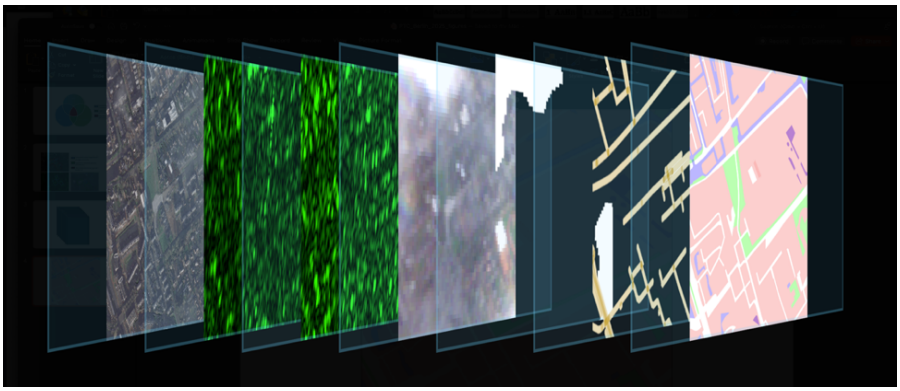
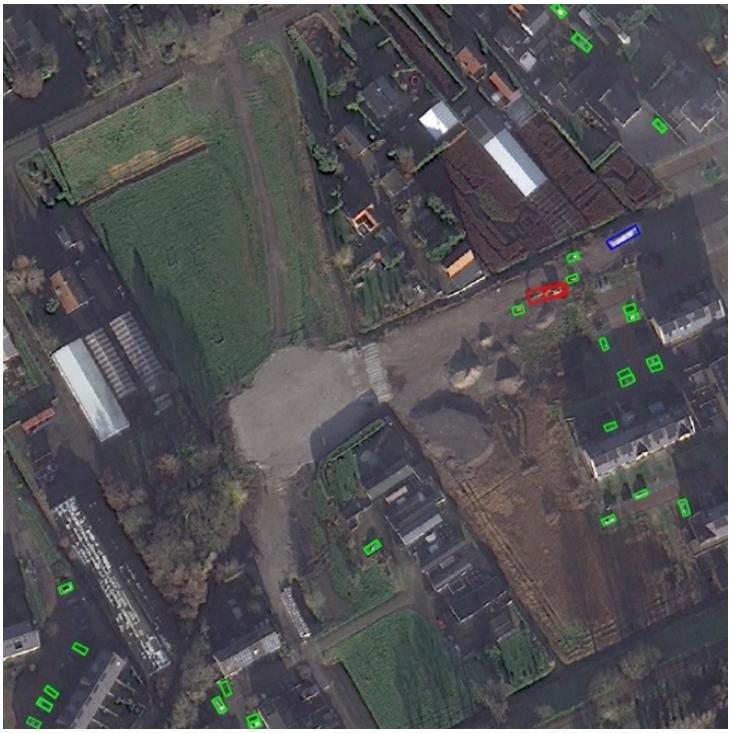


*Figure 6: High-resolution optical image model predictions of the vehicles based on the latest advancements in tiny object detection. Excavators are shown in red, green highlights small vehicles and blue indicates large vehicles. (© Airbus DS (2025)*



## 3.4 OPERATIONAL USE CASES

During 2024, COMSIC-EYE monitored 250,000 kilometres of pipelines. The following section highlights some operational cases proving why the combination of radar, multi-spectral and high-resolution optical satellites is mandatory for a reliable monitoring service. All cases were verified by operators and visited in the field. These examples illustrate how COSMIC-EYE's advancements have translated into effective operational monitoring in diverse scenarios.

1) **Snow and clouds**
   Some of the worst conditions for traditional monitoring methods are snowstorms. The weather reduces the line of sights and often prevents aerial patrol from taking off. Under these circumstances radar satellites excel as they are the only sensor that can keep monitoring without being affected by the weather conditions. Figure 7 shows how the radar satellites are capable to detect starting groundworks in these winter conditions. These cases highlight the reliability of radar satellites, demonstrating how COSMIC-EYE ensures consistent monitoring under adverse weather conditions, overcoming a key limitation of traditional methods.
2) **A farmer in the field or groundworks**
   Many pipelines run through rural areas where the main day-to-day activities consist of farmers out in the field. Any farm equipment out in the field is detected by the radar satellite as a potential risk. However, most agricultural activities never pose a risk to underground infrastructure. COSMIC-EYE uses the context of the surroundings to flag the presence of heavy equipment and potential groundworks using the combination of satellite sources. This approach enables COSMIC-EYE to distinguish between normal agricultural activities and genuine risks, ensuring precise monitoring and minimizing unnecessary interventions. Figure 8 shows an example of groundworks taking place in a field that at first sight might be confused with a farmer out in the field. The groundworks are detected through the combination of the radar detection followed by a multi-spectral clearance covering only part of the field. High-resolution optical satellites are tasked to confirm the works. These use cases show how the capabilities of COSMIC-EYE enable operators globally to be in control of TPIs.

*Figure 7: Example of a radar detection during a heavy snowstorm in 2024, where (a) shows the radar amplitude before the works started, (b) shows the first equipment being placed, (c) shows a heatmap of the change being detected by the radar model and (d) confirms the works taking place in a high-resolution optical image a couple days later when the storm cleared up.(image acquired from © 2024 Planet Labs PBC, Copernicus Sentinel data (2025))*

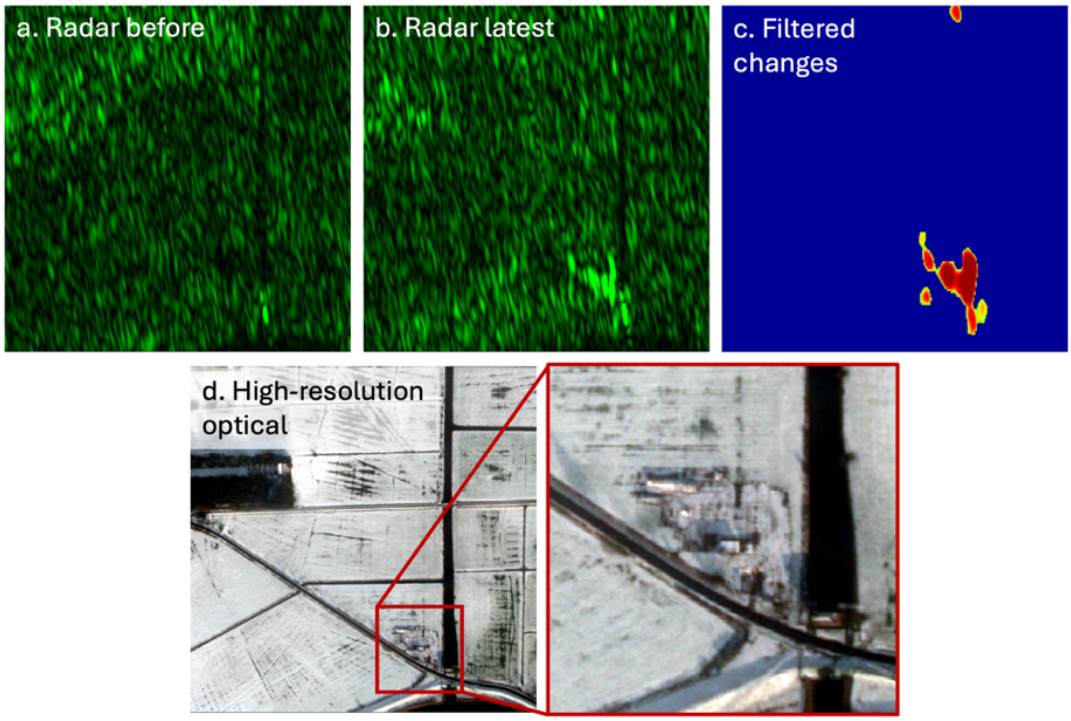
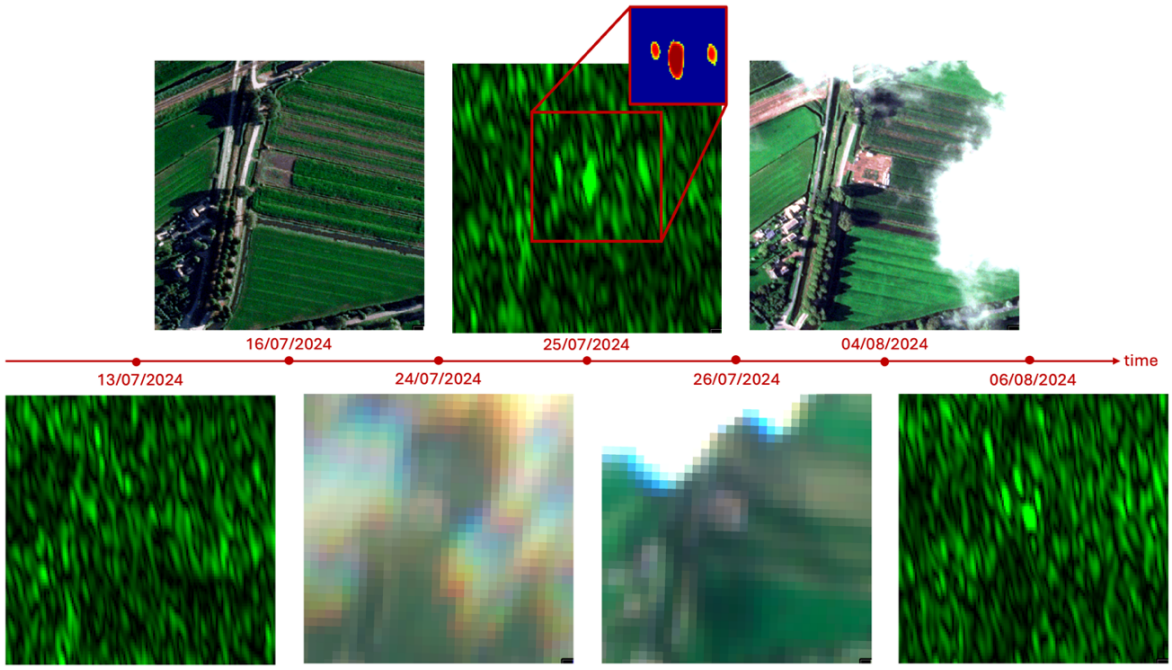


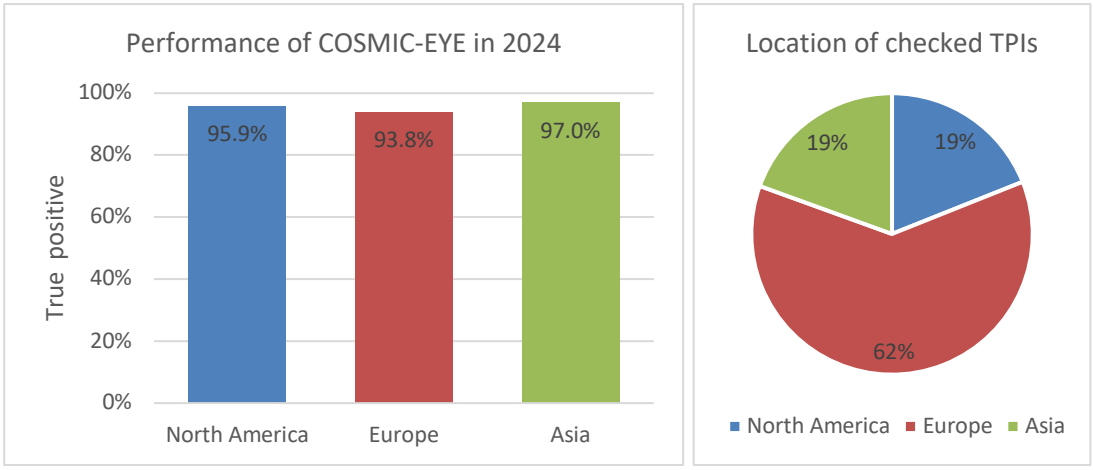
*Figure 8: Example how the combination of radar, multi-spectral and high-resolution optical satellites work together to confirm starting groundworks. On the 13th of July no activity is detected in the radar data. Afterwards no activty is detected based on the high-resolution and multi-spectral data. Only on the 25th of July multiple vehicles are detected by the radar and the activty only takes place in one corner of the field as can be seen in the multi-spectral image one day later. Hence, COSMIC-EYE can already confirm that groundworks are taking place, while a high-resolution optical image was only acquired on the 4th of August to visualise the works. (image acquired from © 2024 Planet Labs PBC, Copernicus Sentinel data (2025))*




3) **Quantified performance**

A study performed in 2024 validated 3,350 unique activities across 21 operators in North America, Europe, and Asia. The true positive rate of 95% across diverse regions highlights COSMIC-EYE's scalability and dependability in addressing operational challenges. These results demonstrate the accuracy at which space-borne sensors can detect TPIs. Figure 9 highlights the operational metrics supporting COSMIC-EYE's effectiveness, reinforcing its role as a reliable monitoring solution.

*Figure 9: Outcomes of a study among 21 operators in North America, Europe and Asia for 3,550 unique activities. On the left the true positive rate per continent is shown and on the right the share of activities in each area.*



# 4 THE NEXT GENERATION OF SATELLITE TECHNOLOGY

In the coming years, satellites with a wide variety of sensors are going to be deployed in orbit. The reduced launch cost of satellites enabled by SpaceX has been a catalyst for the space industry in the past years. Furthermore, advancements in machine learning are going to take the analysis of the satellite data to higher levels. In this section we will explore the impact of future satellite constellations and advancements in machine learning on satellite ROW monitoring. Finally, we conclude with the positive impact satellites can make on sustainability and reduced emissions compared to traditional monitoring methods.

## 4.1 SATELLITE DEVELOPMENTS

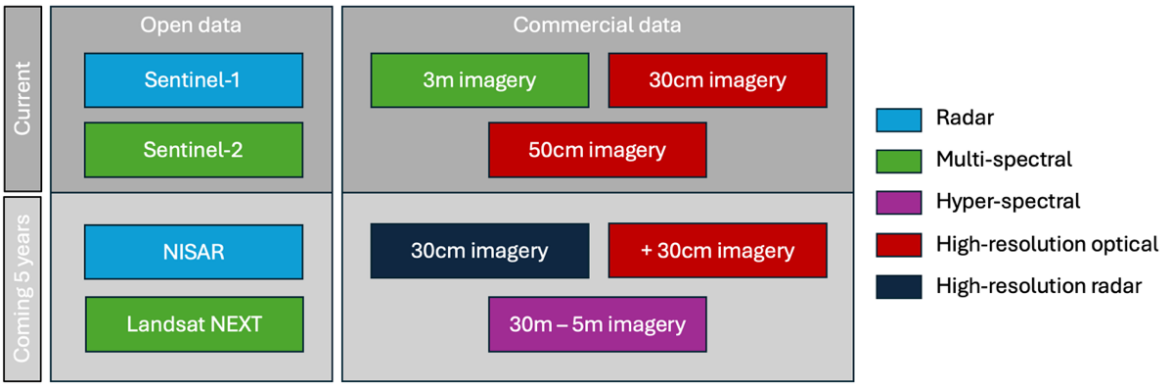
Many new satellites are being developed and launched. Many of the open satellite programs are the backbone of COSMIC-EYE as they highlight where activities are happening before the commercial satellites are actively tasked to zoom in. Figure 10 illustrates how the current satellite constellations are going to double in terms of capabilities in the coming 5 years. An increasing number of satellites and sensors is going to take satellite monitoring to even higher levels.

ESA is continuing their support of the Sentinel constellation and extending the capabilities with additional sensors. The coming years the radar satellites Sentinel-1C and 1D will become operational to continue to legacy of the Sentinel-1 constellation. Also, the multi-spectral Sentinel-2 constellation is continued with Sentinel-2C and 2D. Therefore, the lifetime of these constellations is extended for another 7 years.

Furthermore, NASA is launching their own SAR satellite together with the Indian Space Research Organization. The NISAR satellite will operate at a different wavelength than Sentinel-1, which lowers the disturbance by vegetation and extends the types of activities that can be detected. The amount of radar overpasses is doubling hence increasing the reliability of satellite-based ROW monitoring. The earlier events are detected, the more risk can be mitigated.

Landsat Next is also being developed to be the counter part to the Sentinel-2 constellation. The new generation of satellites will operate at a similar resolution as Sentinel-2. As a result, the open multi-spectral data programs are also doubling their capacity in the years to come.

*Figure 10: Diagram of the current and future satellite constellation categories that contribute to ROW monitoring for linear infrastructure.*




When it comes to high-resolution optical satellites, the main trends show an increase in the number of constellations entering the market. The upcoming defence industry has been one of the main

reasons for an increasing resolution. In the coming years the new standard is going to be 30cm imagery instead of 50cm.

High-resolution radar is also going to enter the monitoring mix which leverages the weather independence capabilities of satellite monitoring further. Currently, many high-resolution radar satellites are not capable to efficiently capture linear infrastructure, or the constellations cannot meet the required revisit times. When the constellations grow in the coming years and acquisition modes improve, there will be an integration of high-resolution radar images for ROW monitoring.

Finally, hyperspectral satellites are being launched that enable the detection of leakages. This technology is not deemed mature yet to monitor linear infrastructure at scale, but in the coming years there will be use cases where it can provide insights. When developed further, the possibilities to monitor more extensive networks might arise as well in the coming years.

## 4.2 Machine Learning developments

Machine learning is advancing every day. Two key highlights are foundation and (Very) Large Language Models (VLLM) that are bound to impact the remote sensing industry. Foundation models have the capability to generalise and optimise many tasks. As they are trained on very large datasets, they can identify key features in different data sources and distil the necessary information for downstream tasks such as ROW monitoring.

On of the key aspects of VLLMs is their ability to interpret and describe the scene depicted on satellite images (see Figure 11). Satellite images are going to be integrated in many workflows in the future, thus forcing less experienced users to interact with them. VVLM can bridge this gap and explain to anyone what's happening in sometimes complex satellite scenes, allowing even more users to integrate satellite into their daily workflow. The technology behind COSMIC-EYE is also advancing based on these latest innovations, making it possible for anybody to turn the satellite data into action.

*Figure 11: Result of a Very Large Language Model describing the scene in a high-resolution optical image. A construction site is detected, and the user is taken by hand to understand what's happening in the scene. (image acquired from © 2022 Planet Labs PBC)*



*Q: Describe the image in the centre?*

*A: "The image in the centre appears to be an aerial view of a construction site. There is a large area of cleared land, possibly for building or development. Surrounding this cleared area are the various buildings and structures, some with red roofs and others with different coloured roofs. There are also roads and vehicles visible in the image."*

## 4.3 Reduced emissions

Sustainability starts to disrupt the ROW monitoring industry and is part of the long-term strategy of most operators. Traditional monitoring methods are already seeing increased costs. Specifically aerial patrol is being affected, and ROW monitoring is an industry where satellites pose a zero-emission

alterative to aerial patrols. COSMIC-EYE's satellite-based monitoring demonstrated a 10% reduction in scope-2 emissions while doubling or tripling monitoring frequency.[2]

In the current energy transition, the number of groundworks is only increasing as the capacity of electricity networks needs to grow, hydrogen networks are developed, and carbon capture/storage projects are taking off. Additional monitoring methods need to be put in place to make sure there is no additional risk of incidents. Satellites can fulfil the increase in monitoring needs at zero additional emissions. This directly supports sustainability efforts and solidifies COSMIC-EYE's role as a modern and efficient monitoring solution.

# 5 CONCLUSION

The past 10 years have seen a very strong growth of satellite and machine learning technology that have enabled the development of a mature alternative to traditional ROW aerial patrols. COSMIC-EYE was developed together with operators all over the world. The system's integration of radar, multi-spectral, and high-resolution optical satellites ensures it can detect a wide range of TPIs in diverse conditions, delivering reliable results for operators globally.

The number of satellites in the foreseeable years keeps increasing, and therefore, the reliability of satellite-based monitoring will also increase further. Conventional aerial patrols are becoming increasingly expensive as costs go up and sustainability disrupts the Right-of-Way monitoring industry. Satellite-based monitoring is a proven alternative in the industry operating on networks over 10,000 kilometres with a true positive rate of 95%. The ability of COSMIC-EYE to operate effectively across networks of varying sizes underscores its transformative potential for ROW monitoring.

Especially, the combination of radar satellites with multi-spectral satellites, the scalability of satellites and application of machine learning algorithms are shown to be a key driver for success. Looking forward, COSMIC-EYE is poised to continue addressing industry challenges by leveraging advancements in technology and sustainability, fulfilling its role as a leading solution in ROW monitoring.

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