

SPACE STUDY

STUDY AND ANALYSIS OF ISR IN THE HIGH NORTH

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By **Lieutenant Colonel José María Cifuentes Rivera**,
NATO Space COE Staff Officer,
Concept Development and Experimentation Division,
Spanish Air Force

1 • INTRODUCTION

1 • Scope of the Study

It is not possible to find a unanimous definition of the term High North. Within NATO itself, some documents describe it as 'an elastic term used in various European states to describe the area of Northern Europe below the Arctic Circle, as well as the North Atlantic, Nordic, and Baltic approaches. In this sense, the European Arctic encompasses both the marine Arctic and the Arctic landmass stretching from Greenland in the West to the Norway/Russia border in the Barents Sea in the East, and it includes areas of strategic importance such as the Greenland-Iceland-United Kingdom (GIUK) gap and Svalbard'[1].

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However, in other publications NATO commonly uses the term High North to refer to the Arctic region, which includes the territories of eight Arctic nations: Canada; Greenland (Denmark); Iceland; Norway; Sweden; Finland; Russia; and the United States[2].

In any case, it is widely recognised that this region holds significant strategic importance for the Alliance and remains a key focus area for ensuring collective defence, promoting cooperation, and tackling emerging challenges in the Arctic.

In this context, the use of ISR capabilities can provide very valuable information that offers decision-makers and action-takers improved situational awareness of the conditions on the ground.

ISR is the acronym used to refer to Intelligence, Surveillance, and Reconnaissance. The NATO Allied Joint Doctrine for Joint Intelligence, Surveillance and Reconnaissance (AJP-2.7) defines JISR¹ as 'an integrated intelligence and operations set of capabilities, which synchronises and integrates the planning and operations of all collection

capabilities with the processing, exploitation and dissemination of the resulting information in direct support of the planning, preparation, and execution of operations'[3].

The same Allied doctrinal publication states that the term intelligence encompasses all aspects of intelligence collection and involves various methods and systems used to observe, sense, record, or convey information. Among the various intelligence collection disciplines, Imagery Intelligence (IMINT) stands out; it derives its results from imagery obtained via sensors located on the ground, at sea, or aboard aerial or space platforms.

Surveillance involves methodical observation of various domains, locations, individuals, or objects using visual, electronic, photographic, or other techniques. In contrast, reconnaissance refers to missions aimed at gathering information through visual observation or other detection methods, observing the activities and resources of an adversary or collecting data on the meteorological, hydrographical, or geographic characteristics of a particular area.

The challenge of using ISR capabilities in the High North relates directly to the environmental conditions of the region. Therefore, ISR systems must be able to cope with extreme cold weather conditions and electromagnetic disturbances caused by solar interference, and deal with resolution quality issues due to snowfall, cloud coverage, wind, and precipitation[4].

Taking into account the unique and challenging characteristics of the region, the purpose of this study is to analyse which type of sensor might be the most suitable for carrying out imagery intelligence collection tasks in the High North, so that the products obtained through such intelligence activities can support military operations.

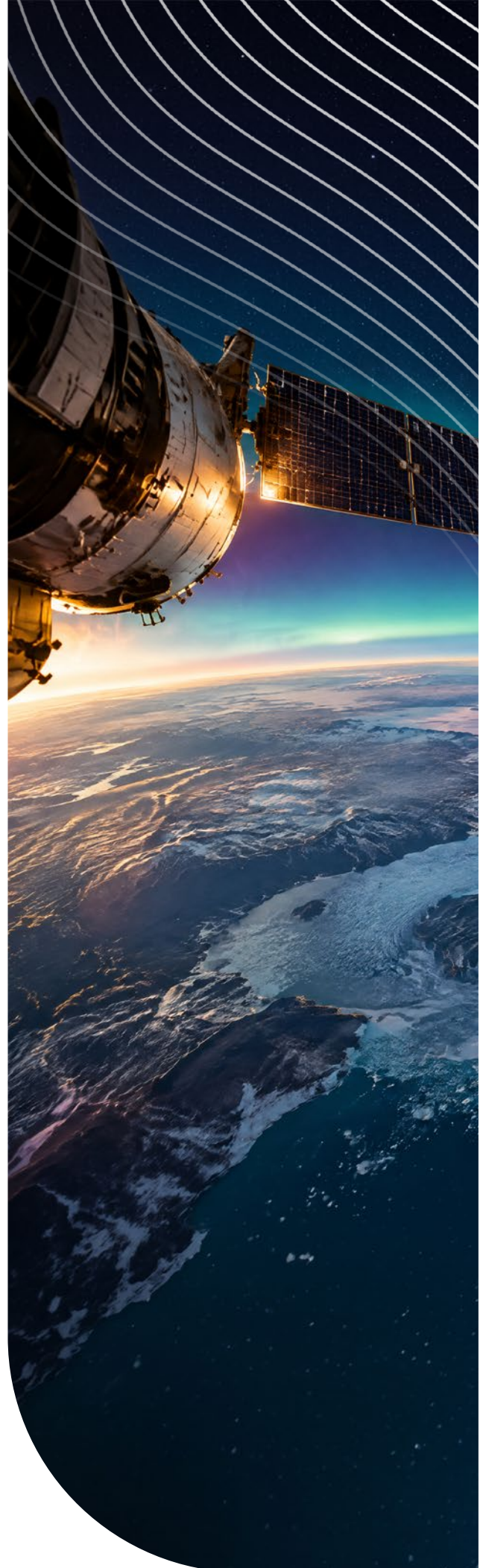
1. JISR refers to Joint ISR. The term joint refers to the activities, operations and organisations in which elements of at least two services participate (NATO AJP-2.7).



2 • Definition of remote sensing

The concept of remote sensing has numerous definitions. Notably, Campbell and Wynne (2011) define it as: 'the practice of deriving information about the Earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth's surface'[5].

From the definition itself, some of the fundamental elements of this concept can be extracted. On the one hand, images obtained from a distance will provide valuable information about the observed object, implying that the sensors that will collect these images can be carried on different platforms. On the other hand, the use of electromagnetic energy from different regions of the electromagnetic spectrum to carry this valuable information means that objects will provide different responses depending on the type of electromagnetic energy they interact with. Finally, as the remote sensing sensor is located at a distance from the observed object, the electromagnetic energy coming from the object will be influenced by the atmospheric conditions present at the moment of image acquisition, as all energy reaching the sensor must pass through a portion of the Earth's atmosphere.





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3 • Key concepts of remote sensing

One of the fundamental concepts within remote sensing is image resolution. Estes and Simonett (1975) define resolution as 'the ability of an imaging system to record fine detail in a distinguishable manner'[6].

The level of detail that can be acquired through remote sensing depends directly on the resolution of the imaging system. However, there are other influencing factors, such as the characteristics and surroundings of the observed object, atmospheric conditions, and the operating conditions of the sensing systems, such as their altitude and ground speed.

When analysing the resolution of a system, it is important to distinguish between spatial, spectral, radiometric, and temporal resolution. Spatial resolution refers to the size of the smallest unit area on the ground that a sensor can distinguish and record². It defines the smallest level of detail that a sensor can capture.

The spatial resolution of an image is primarily determined by the sensor aperture and the altitude of the platform upon which it is hosted. A smaller sensor aperture results in higher spatial resolution, while a higher platform altitude leads to lower image resolution[7].

Spectral resolution refers to the capability of a sensor to separate spectral features and bands into their individual components within the electromagnetic spectrum. It also indicates its ability to differentiate between wavelength intervals. Images with higher spectral resolution offer more detailed information compared to those with lower spectral resolution. Multispectral imagery offers a greater ability to distinguish between individual targets when compared with single-band images.

A key advantage of detecting different spectral bands separately is the ability to then combine them in various ways to enhance the visual information in the image. Higher-resolution data allows for better differentiation of the features of the Earth's surface using different band combinations.

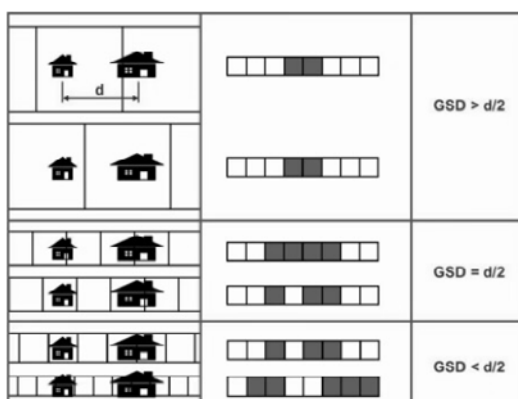
2. This is sometimes expressed as the Instantaneous Field of View (IFOV) of the sensor, the Ground Sample/Sampling Distance (GSD) or Ground Resolved Distance (GRD), where GSD is the distance on the ground represented by each pixel expressed in ground units.

Radiometric resolution is defined as follows[8]: ‘The sensitivity of a sensor to small fluctuations in the amount of energy in the electromagnetic spectrum’. In this sense, the finer the radiometric resolution of a sensor, the more sensitive it is in detecting small differences in reflected or emitted energy.

Finally, temporal resolution in remote sensing refers to the ability to obtain images of the same location or object on the Earth’s surface during different periods of time. Temporal resolution plays a crucial role in detecting changes and monitoring the environment. As it pertains to space-based sensors, it refers to the time it takes for a space-based platform to complete an orbit and revisit the same observation area. In this case, temporal resolution depends on the orbital parameters, the characteristics of the sensor, and the swath width.

From the point of view of the image analyst, the term image resolution refers to the ability to distinguish between objects, as depicted in Figure 1. Theoretically, for individual distinction, adjacent objects must be separated from each other by at least one Ground Sample/ Sampling Distance (GSD)[9]. However, a general rule is to have an image with a GSD approximately 2.5 times smaller than the distance separating the two objects[10].

Fig. 1. The ability to distinguish between adjacent objects on an image[10]



The left-hand column of Figure 1 shows the positions of two neighbouring objects on the Earth's surface, separated by a distance denoted by 'd'. The squares in the background illustrate the GSD footprint of the image. The middle column displays the relevant (grey) pixels impacted by the reflectance of the actual objects, as they appear in the image. The right-hand column illustrates the connection between the GSD of the image and the distance separating the real objects[10].

From this illustration, it can be inferred that if the GSD is greater than half the distance between the objects, those objects will always appear in the image as a single object. If the GSD is equal to half the distance between the objects, only in the case that the GSD footprint fits in the gap between, the objects will they be represented separately in the image. Finally, if the GSD is less than half the distance between the objects, the objects will always be represented separately in the image.

In this context, it is worth noting that according to the Allied Intelligence Publication NATO Imagery Intelligence (IMINT) Tactics, Techniques and Procedures (AIntP-21), imagery interpretation is 'the extraction of information from photographs or other recorded images. The process of location, recognition, identification, and description of objects, activities, and terrain represented on imagery'[11].

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From this definition, the following concepts can be extracted[10]:

- **Detection [location]** is the ability to discover the existence of an object based on its configuration and on other contextual information without object recognition.
- **Recognition** is the ability to classify a feature or an object on an image as belonging to a specific group (e.g. tank, single-lane bridge).
- **Identification** is the ability to identify the precise type of a feature or an object on an image (e.g. T-72 tank, MiG-21).
- **Technical analysis [description]** is the ability to describe precisely a feature, an object, or a component of an object.

With the previous concepts in mind, it is possible to approximately determine a required spatial resolution, based on the type of object observed.

Fig. 2. Minimum resolved object sizes in metres[10]

TYPE OF TARGET	DETECTION	RECOGNITION	IDENTIFICATION	TECHNICAL ANALYSIS
Urban Areas	60.0	15.0	3.0	0.75
Surface Ships	15.0	4.5	0.15	0.04
Airfield Facilities	6.0	4.5	3.0	0.15
Aircraft	4.5	1.5	0.15	0.04
Missile Sites	3.0	1.5	0.15	0.04
Vehicles	1.5	0.5	0.15	0.04
Rockets & Artillery	1.0	0.5	0.15	0.04

2 • THE ELECTROMAGNETIC SPECTRUM

1 • Overview of the Electromagnetic Spectrum

The electromagnetic (EM) spectrum can be defined as 'the range of frequencies of electromagnetic radiation and their respective wavelengths and photon energies. [...] This frequency range is divided into bands characterised by their frequency properties and sensor capabilities, starting with short wave to longer wavelengths, gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, and radio waves. The estimated limit of short wavelengths is the Planck length; there is no known limit for long wavelengths'[8].

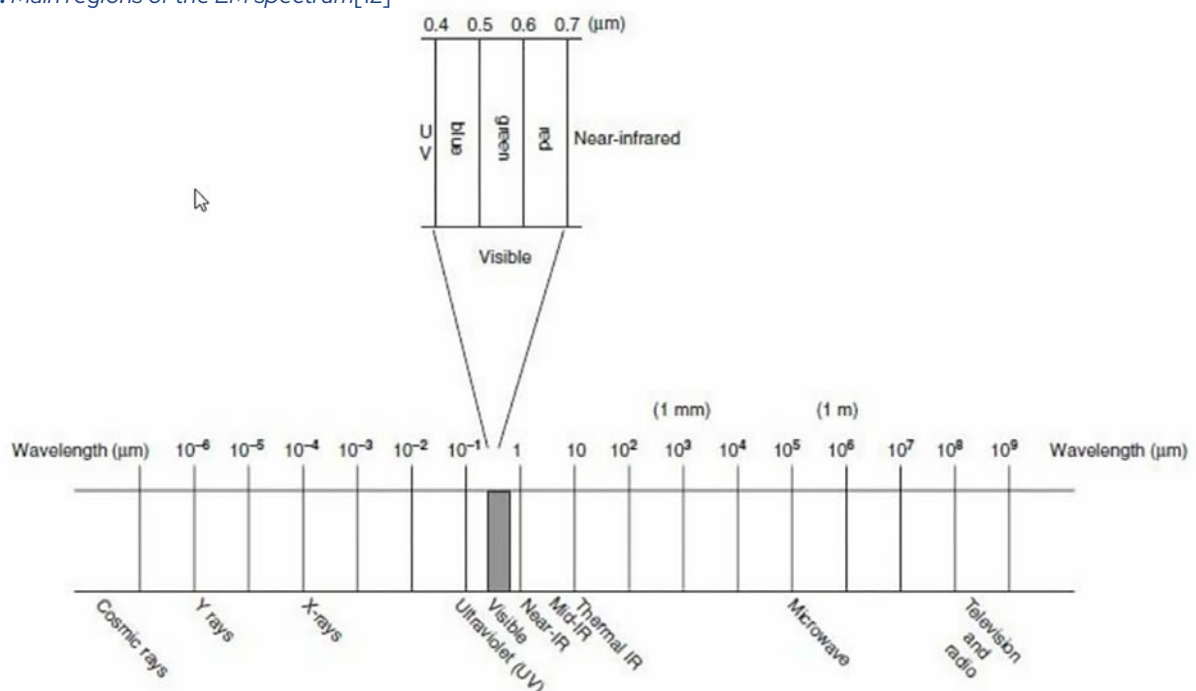
Electromagnetic energy can be produced through various means. The sun generates a broad spectrum of EM radiation that travels through space.

As this radiation approaches the Earth, it passes through the atmosphere before reaching the surface. Part of it is reflected back up from the Earth's surface, while some of it is absorbed and subsequently re-emitted. Both the reflected and emitted energy that sensors capture can be utilised to create remotely sensed imagery. Finally, man-made radiation, such as that generated by imaging radars, can be also used for remote sensing.

2 • Main regions of the Electromagnetic Spectrum

The main regions of the EM spectrum used for remote sensing are indicated in Figure 3. However, it should be noted that within a full spectrum of solar energy, there are no pronounced discontinuities between bands, as depicted in Figure 3.

Fig. 3. Main regions of the EM spectrum[12]



The three major bands used for remote sensing are the visible radiation band, the infrared band, and the radar band. The first two facilitate the acquisition of images from solar energy, requiring passive sensors that collect this energy once it has been reflected or absorbed by objects.

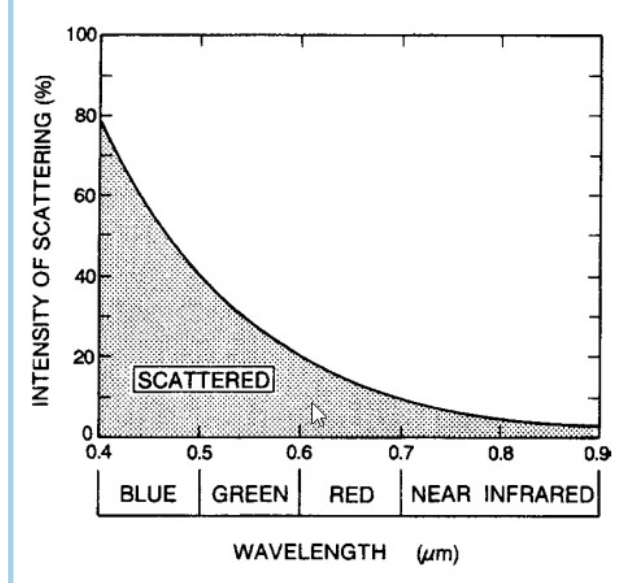
On the other hand, radar band imagery is based on the principle that most materials reflect a portion of the electromagnetic radiation transmitted by the sensor toward the object, and that the distance from the antenna to the object can be measured based on the time it takes for the signal to travel to, and return from, the object. In the case of radar radiation, it is necessary to have an active sensor that first generates and then collects this radiation.

3 • Energy interactions

As all the radiation used for remote sensing must pass through the Earth's atmosphere, some conditions present within it may have a substantial impact on the quality of the images and data produced by the sensors. In these circumstances, solar energy passing through the atmosphere is subject to possible modifications due to various physical processes. The most common are scattering, absorption, and refraction.

In some cases, EM energy can be redirected by particles suspended in the atmosphere, or by large molecules of atmospheric gases. This process is called scattering. The extent of scattering is influenced by the size and abundance of the particles, the wavelength of the radiation, and the depth of the atmosphere that the energy travels through. Scattering redirects radiation, causing part of the incoming solar beam to be sent back into space and the other part to reach the Earth's surface, degrading the quality of the recorded image[5].



Fig. 4. Increased scattering at shorter wavelengths[5]

Refraction occurs in the atmosphere when light moves through layers with different levels of clarity, humidity, and temperature. These variations cause light rays to bend as they transition from one layer to another.

Absorption of certain EM wavelength radiation is caused by some of the gases that make up the atmosphere. The radiation that is not absorbed is transmitted to the Earth's surface, although it can also be affected by scattering. The gases primarily responsible for absorption are ozone, carbon dioxide and water vapour. Water vapour is significantly more efficient at absorbing radiation than all other atmospheric gases combined. The regions of the spectrum within which absorption does not occur are called atmospheric windows.

Fig. 5. Major atmospheric windows[5]

ULTRAVIOLET AND VISIBLE	0.30-0.75 μm 0.77-0.91 μm
NEAR INFRARED	1.55-1.75 μm 2.05-2.4 μm
THERMAL INFRARED	8.0-9.2 μm 10.2-12.4 μm
MICROWAVE	7.5-11.5 μm 20.0 +mm

When electromagnetic energy reaches the Earth's surface, it undergoes reflection, absorption, or transmission. The extent to which each process occurs depends on the surface characteristics, the wavelength of the energy, and the angle of illumination.

Reflection happens when electromagnetic radiation encounters a surface and part of its energy is redirected away from it, instead of being transmitted or absorbed. The characteristics of reflection are influenced by the roughness or smoothness of the surface, relative to the wavelength of the radiation. Specular reflection directs nearly all incoming radiation in a specific and predictable direction while, if the surface is rough, relative to the wavelength, EM energy is scattered more or less equally in all directions (diffuse reflection).

Transmission of radiation occurs when radiation passes through a substance without significant attenuation. According to Campbell and Wynne (2011), 'from a given thickness, or depth, of a substance, the ability of a medium to transmit energy is measured as the transmittance³. [...]The transmittance of many materials varies greatly with wavelengths [...]. For example, plant leaves are generally opaque to visible radiation but transmit significant amounts of radiation in the infrared'[5].

Taking all the above into consideration, Parker and Wolff (1965) express the following idea: 'Everything in nature has its own unique distribution of reflected, emitted and absorbed radiation. These spectral characteristics can [...] be used to distinguish one thing from another or to obtain information about shape, size, and other physical and chemical properties'[13].

3. In imagery, the ratio of light that is passed through a medium divided by the amount of light that is incident on that medium. Value ranges between 0 and 1. ESRI GIS Dictionary. Available on <https://support.esri.com/en-us/gis-dictionary/transmittance> [Accessed 22 July 2025].



3 • REMOTE SENSING SYSTEMS

1 • Remote sensing sensors and platforms

All images in remote sensing are produced through the use of sensors that capture EM radiation. Depending on the source of EM energy they use, sensors can be classified as passive or active.

Passive sensors are defined as such because they do not emit any type of radiation; they only capture information from solar radiation reflected by the Earth or emitted by terrestrial objects themselves. On the other hand, active sensors are so-called because they emit their own electromagnetic radiation, which is reflected off objects, and then measure the energy that is reflected back to them. Among passive sensors are those that generate electro-optical images, while active sensors are best represented by imaging radar and Light Detection and Ranging (LiDAR).

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Remote sensing sensors are mounted on platforms. These platforms are usually classified into three categories: ground-based; airborne; and spaceborne. Given their frequent use, and the fact that most remote sensing systems rely directly or indirectly on the relative motion between the sensor and the target, this study will focus on analysing airborne and spaceborne platforms.

Airborne platforms carry sensors that can be mounted on aircraft (fixed wing or rotary wing), Unmanned Aerial Vehicles (UAVs) or even balloons. Aircraft have been used extensively as remote sensing platforms because they are capable of operating over a wide range of altitudes. The chosen altitude will, naturally, impact the scale, spatial coverage and spatial resolution of the data collected⁴[14].



The disadvantages of remote sensing from aircraft include: the instability of the platform; limited geographic coverage (due to the relatively low operational altitude); high cost; and dependence upon weather conditions. The non-permissive environment of the Arctic further complicates the level of difficulty of operating a remote sensing aircraft in this region.

The use of UAVs for remote sensing has many advantages. These systems are generally less expensive than crewed aircraft and can be deployed for very long missions without being limited by the endurance of human crews. Additionally, they can operate without putting their operators at risk. However, while there has been a notable surge in the use of UAVs for remote sensing in general, and for ISR

4. Aircraft can fly at relatively low altitudes allowing for sub-meter sensor spatial resolution.



in particular, the increased dependence on uncrewed systems has also introduced new challenges. These challenges are linked to their susceptibility to cyberattack, vulnerability to adversarial counter-UAVs air defences, and operational limitations in GPS-denied environments[15].

Spaceborne remote sensing involves the use of sensors mounted on satellites. The effectiveness of these sensors for monitoring is largely influenced by the orbital parameters of the satellite. Remote sensing relies on several orbital characteristics: altitude; inclination angle; period; and repeat cycle.

Altitude is the distance from the satellite to the mean surface level of the Earth. That distance influences, to a large extent, which area is viewed and to what level of detail. The inclination is the angle between the orbital plane and the equator and determines, together with the field of view of the sensor, the latitudes that can be observed. Period is the time

taken to complete one full orbit, while the repeat cycle is the time that passes between two successive identical orbits[16].

Space-based platforms can be placed in several types of orbits around Earth. Low Earth Orbit (LEO)⁵ is commonly used for ISR platforms, which can follow several orbital tracks around the planet. Polar-orbiting platforms, for example, are inclined by nearly 90 degrees to the equatorial plane and travel from pole to pole as the Earth rotates. This enables instruments aboard these platforms to rapidly acquire data for the entire globe, including the polar regions. Many polar-orbiting platforms are also Sun-Synchronous, meaning that the platform follows a nearly polar orbit that passes the equator at the same local solar time on every pass. This is useful for image-taking satellites because shadows will be approximately the same on every pass, allowing for the comparison of two images taken over the same area.

Fig. 6. Overview of the main characteristics of LEO, MEO and GEO[17]

	LEO Low Earth Orbit	MEO Medium Earth Orbit	GEO Geostationary Earth Orbit
ALTITUDE	100 - 2,000 km	5,000 - 24,000 km	35,786 km
ORBITAL PERIOD	90 - 120 minutes	≈ 12 hours	24 hours
ORBITAL VELOCITY	≈ 80 km/s	≈ 5 km/s	≈ 3 km/s
INCLINATION	0°-100°	0°-180°	0° (equatorial)
TIME IN VIEW OF A GROUND STATION	< 15 minutes	2 - 4 hours	24 hours
ORBITAL LIFESPAN	Short (5 years)	Medium (5-15 years)	Long (15 - 25 years)
SATELLITES FOR WORLDWIDE COVERAGE WITHOUT GAPS	40 - 80 satellites	8-24 satellites	3-4 satellites
LAUNCHER NEEDED	Medium-lift launch vehicle	Heavy-lift launch vehicle	Heavy-lift launch vehicle
CAPABILITIES IN THIS ORBIT	SATCOM, ISR, SSA, METOC	PNT	SATCOM, ISR, SSA, SEW

5. LEO is an orbit situated between 200km and 2,000km of altitude. ISR satellites in LEO usually circle the earth at an altitude of between 250 and 800km. The selected altitude determines the size limitations of the observation equipment, while its decrease usually means a reduction in the lifetime of the satellite.



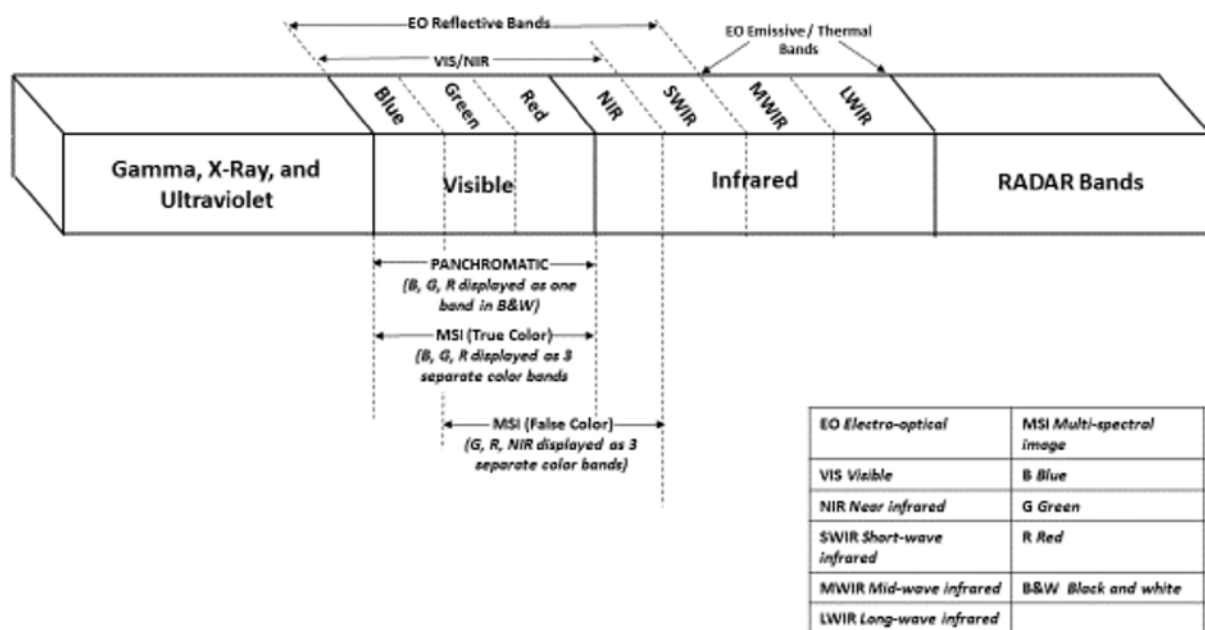
2 • Electro-optical remote sensing

Electro-optical imaging refers to the technology that combines optics and electronics to capture and process visual information from the electromagnetic spectrum. According to the NATO AIntP-07 NATO Imagery Interpretability Rating Scale (NIIRS), Electro-optical (EO) imagery refers to the collection of electromagnetic energy from the visual, near-infrared and/or thermal infrared parts of the electromagnetic spectrum. EO sensors are passive,

only collecting electromagnetic energy emitted by or reflected off the object itself.

EO reflective imagery includes: panchromatic imagery⁶; multispectral imagery⁷; hyperspectral imagery⁸; day-time near-infrared (NIR) imagery; day-time short-wavelength infrared (SWIR) imagery; and day-time mid-wavelength infrared (MWIR) imagery. EO emissive imagery refers to the self-emitted illumination (spatial and thermal signature) of an object and includes night-time MWIR imagery and night-time long-wavelength infrared (LWIR)⁹ imagery[18].

Fig. 7. EO reflective and emissive/thermal bands[11]



6. Panchromatic imagery is acquired with a sensor that is sensitive to all or most of the visible spectrum and generally has a higher resolution than infrared. Panchromatic imagery is collected by sampling a broad range of the visible and near-infrared EO spectrum in a single band[11].

7. Multispectral/hyperspectral imagery is collected by sensors sensitive to a series of specific wavelengths, usually grouped in bands. By collecting multiple bands, processing software can build composite images highlighting the desired spectral signatures. Multispectral imagery comprises between two and tens of spectral bands, whereas hyperspectral imagery consists of hundreds of bands[11].

8. For each pixel in an image, a hyperspectral camera acquires the light intensity (radiance) across a large number of contiguous spectral bands, typically from a few tens to several hundred. Every pixel in the image thus contains a continuous spectrum (in radiance or reflectance) and can be used to characterise the objects in the scene with great precision and detail[11].

9. LWIR refers to the thermal imaging region in which sensors can obtain a completely passive image based on thermal emissions only, requiring no external light or thermal source, such as the Sun, Moon, or infrared illuminator[11].

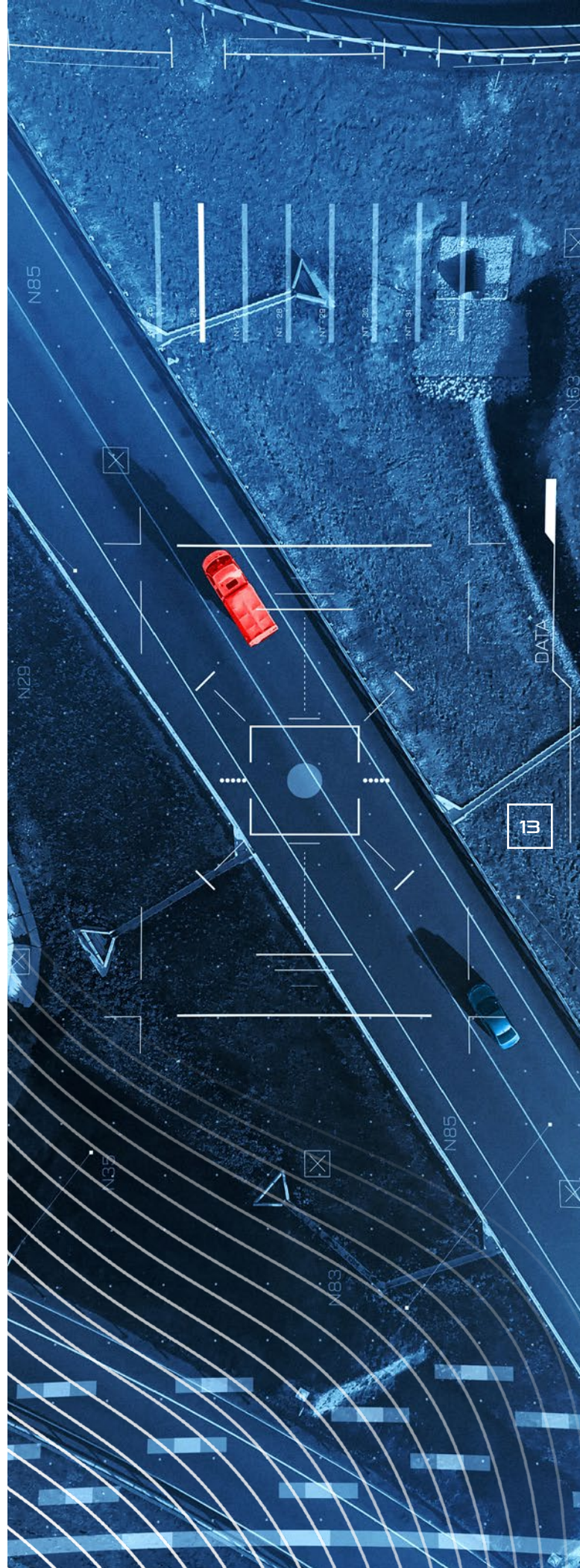
Other than visible light and near-infrared EO systems, all other EO systems generally operate day and night and in most weather conditions. When used together, EO systems are generally effective at detecting concealed elements within the environment. Being passive, EO systems are very difficult to jam or disrupt. Thermal infrared is less effective for the identification of targets during day-to-night transition periods and when backgrounds and targets have only a small difference in temperature[19].

3 • Radar remote sensing

Radar is an active collection system that can penetrate almost all atmospheric conditions, depending on the power and frequency of the transmitter. The primary limitation of radar imagery lies in the capabilities of the platforms performing the collection mission. Radar works on the principle that all materials will reflect some of the electromagnetic radiation directed at them, and the distance to the target can be measured by the time it takes for a signal to travel to the target and return. There are two types of radar imagery: synthetic aperture radar and moving target indicator imagery[19].

Synthetic aperture radar is a type of radar that uses the relative motion between the transmitting and receiving antennas. This technology typically provides better standoff resolution than other imagery systems. Operating at high altitudes and oblique angles, synthetic aperture radar can cover large areas and provides excellent standoff ranges, allowing platforms to operate over friendly territories while imaging denied areas. It can cover several hundred thousand square kilometres in a single mission, although this comes at the cost of scale, ground resolution, and the ability to identify individual equipment items.

Data interpretation can be almost real-time with a data downlink. When compared with previous synthetic aperture radar coverage using techniques like interferometry, radar stereoscopy, or polarimetry, it can provide greater intelligence about target status and activity.



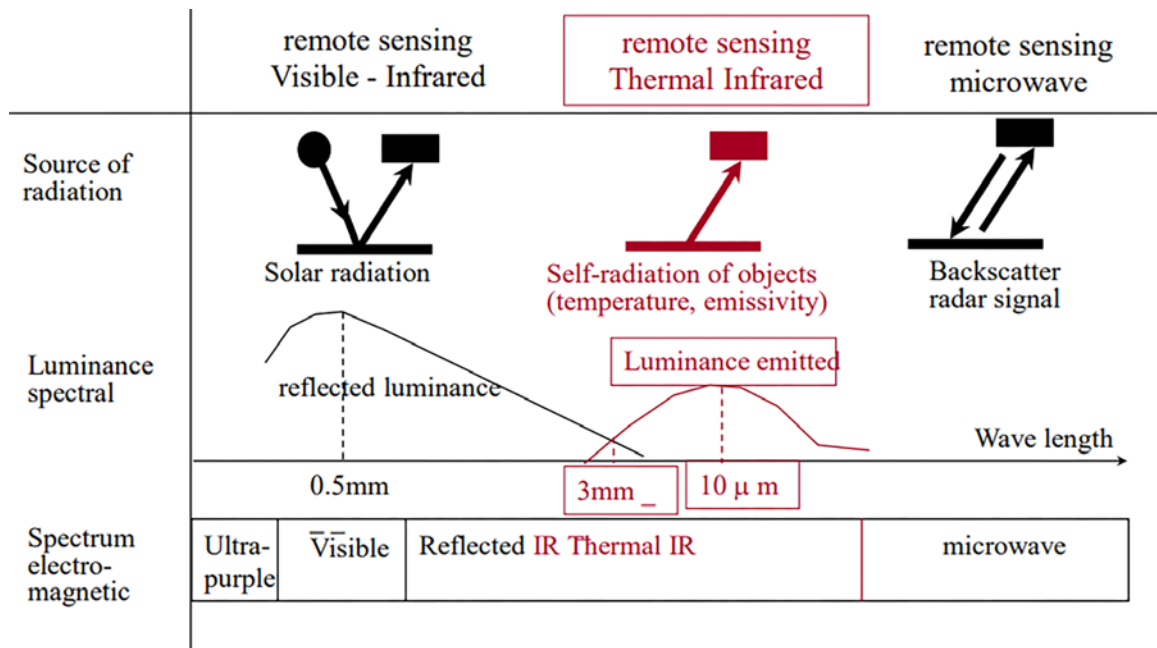
Moving target indicator imagery comes from radar technology that uses the Doppler shift principle to exclude stationary objects. The imagery is created by plotting multiple radar sweeps, which display movement paths and enable speed calculation. The number of targets trackable by a moving target indicator system is only constrained by its software and computing power. This makes moving target indicator the most effective sensor type for detecting ongoing movement.

As for the advantages of using a radar sensor, these systems can penetrate fog, haze, clouds and smoke, but can be limited by severe precipitation, terrain elevation and sand storms. Additionally, space

weather can interfere with radar signals, causing false returns or false targeting. Radar systems provide extensive area coverage and can operate day and night, providing good standoff capability[19].

However, radar systems also have limitations. Analysis of synthetic aperture radar imagery is not intuitive and better results are possible when analysts are adequately educated, well trained, familiar with the target type, and have access to previous visual or infrared images of the area. Additionally, synthetic aperture radar is also an active system that transmits energy, which can be detected and is susceptible to jamming and deception.

Fig. 8. Sensors and radiation sources[20]

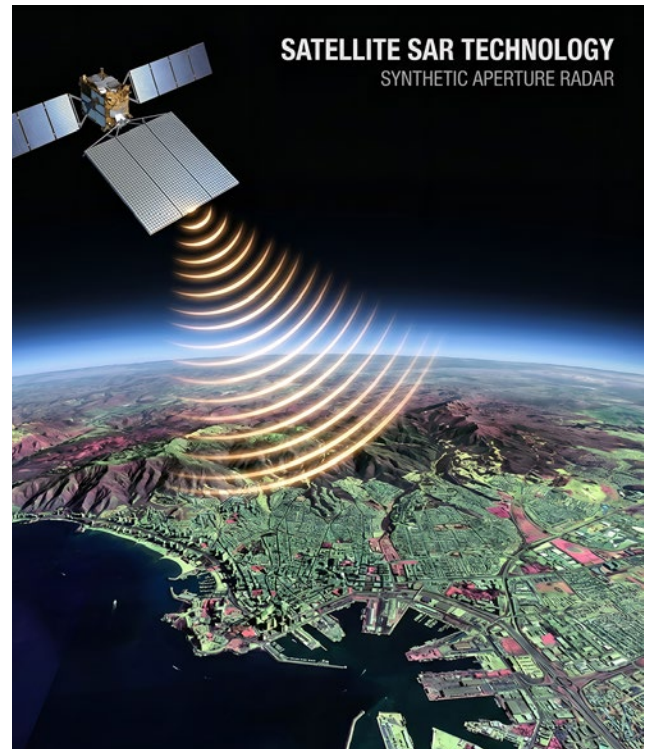


4 • SYNTHETIC APERTURE RADAR

1 • SAR sensors

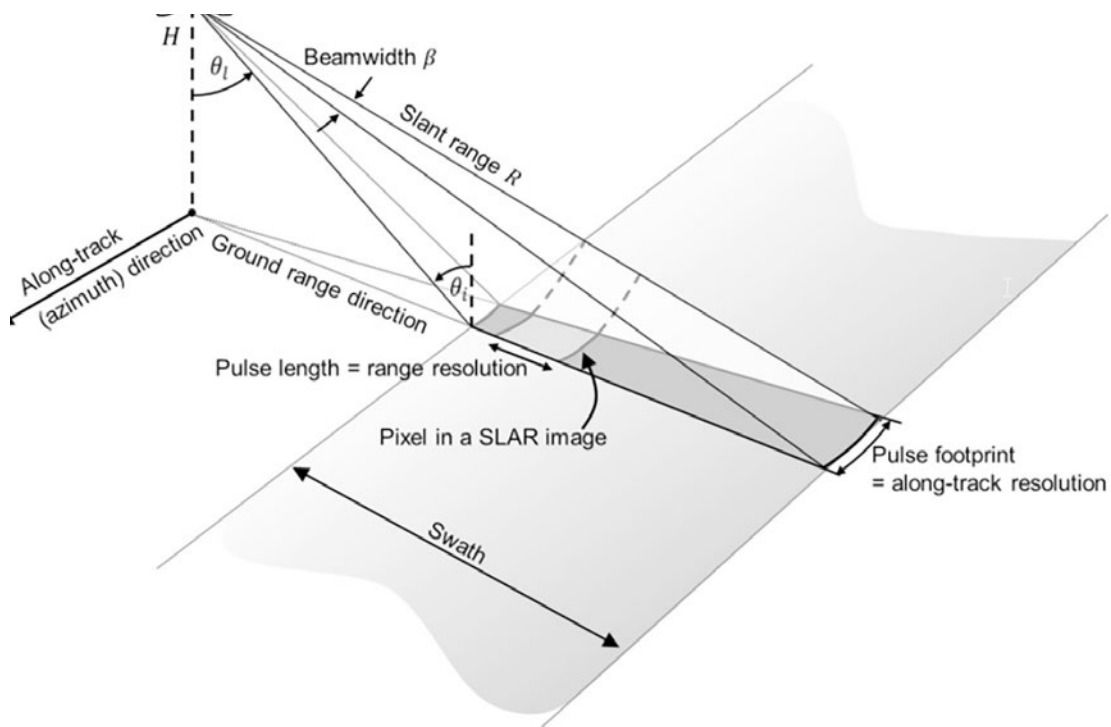
Synthetic aperture radar (SAR) is a type of imaging radar that receives wide-band echoes from different positions due to the relative movement between the platform and the target. During a specific accumulation period, SAR processes these echoes coherently to create a two-dimensional image of the target, allowing for high-resolution observation of its true image.

The resolution of the image is typically defined in terms of range resolution and azimuth resolution. Range resolution is normally defined as the minimum distance between two points that can be distinguished. High range resolution can be achieved by employing a pulse compression technique to obtain a very narrow pulse width[21].



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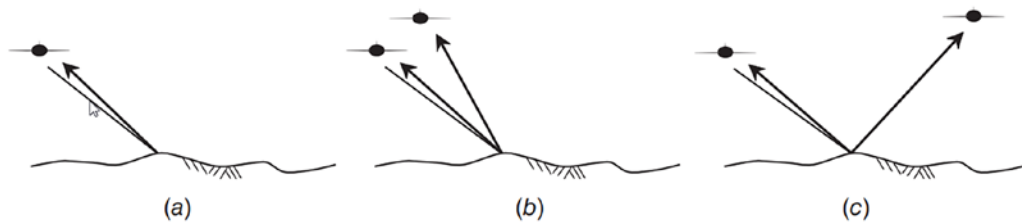
Fig. 9. Geometry of a SAR sensor[22]



In the azimuth direction, a radar sensor moving uniformly in a straight line transmits and receives pulse signals at interval positions with a specified pulse repetition frequency. High azimuth resolution is achieved by coherently processing the received echoes. To obtain high resolution, a synthetic aperture – equivalent to a large albeit impractical array aperture – is created, based on the relative movement of the radar relative to the target[21].

SAR systems can work in a monostatic configuration, in which a single physical antenna acts as both transmitter and receiver, but it is also possible to operate two radar antennas in a bistatic configuration. In this case, one antenna transmits, while both antennas receive signals reflected by the surface.

Fig. 10. Monostatic (a) versus bistatic (b) and bistatic forward-scattering radar configurations[23]



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The bistatic configuration shown in Figure 10 (b), is useful for SAR interferometry, a technique in which radar images are obtained over a given area, from two slightly different angles.

The transmission characteristics of signals from any radar system are mainly determined by two key factors: the wavelength and the polarisation of the energy pulse employed. Figure 11 lists the common wavelength bands used in SAR remote sensing.

Fig. 11. Microwave bands used in SAR remote sensing[24]

MICROWAVE BAND	WAVELENGTH	FREQUENCY
K _a -band	0.75 - 1.13 cm	40.0 - 26.5 GHz
K-band	1.13 - 1.67 cm	26.5 - 18.0 GHz
K _u -band	1.67 - 2.40 cm	18.0 - 12.5 GHz
X-band	2.40 - 3.75 cm	12.5 - 08.0 GHz
C-band	3.75 - 7.50 cm	08.0 - 04.0 GHz
S-band	7.50 - 15.0 cm	04.0 - 02.0 GHz
L-band	15.0 - 30.0 cm	02.0 - 01.0 GHz
P-band	30.0 - 100 cm	01.0 - 0.30 GHz

The wavelength of a radar signal determines the extent to which radiation is affected by atmospheric conditions. Generally, severe atmospheric effects on radar signals are restricted to shorter wavelengths (below approximately 4 cm). However, in most operational conditions, even these wavelengths experience only minimal atmospheric attenuation, despite variations in the influence of clouds and rain. In this sense, clouds have minimal impact on radar signals, but heavy precipitation can result in significant echoes[23].

No matter the wavelength, radar signals can be sent and/or picked up in various polarisation modes. The polarisation of an electromagnetic wave refers to the geometric plane in which its electric field oscillates. In 'multipolarisation' radar systems, the signal can be filtered so that its electric field oscillations are confined to a single plane, perpendicular to the direction of wave propagation. SAR systems can receive up to four different polarimetric combinations simultaneously, based on their horizontal and vertical transmission and reception modes: horizontal transmit and horizontal receive (HH); horizontal transmit and vertical receive

(HV); vertical transmit and horizontal receive (VH); and vertical transmit and vertical receive (VV).

Any system that measures multiple polarisations, such as HH and HV, is called a polarisation diversity or multipolarisation radar. A system that captures all four orthogonal polarisation states (HH, HV, VH, and VV) is known as fully polarimetric or quadrature polarised.

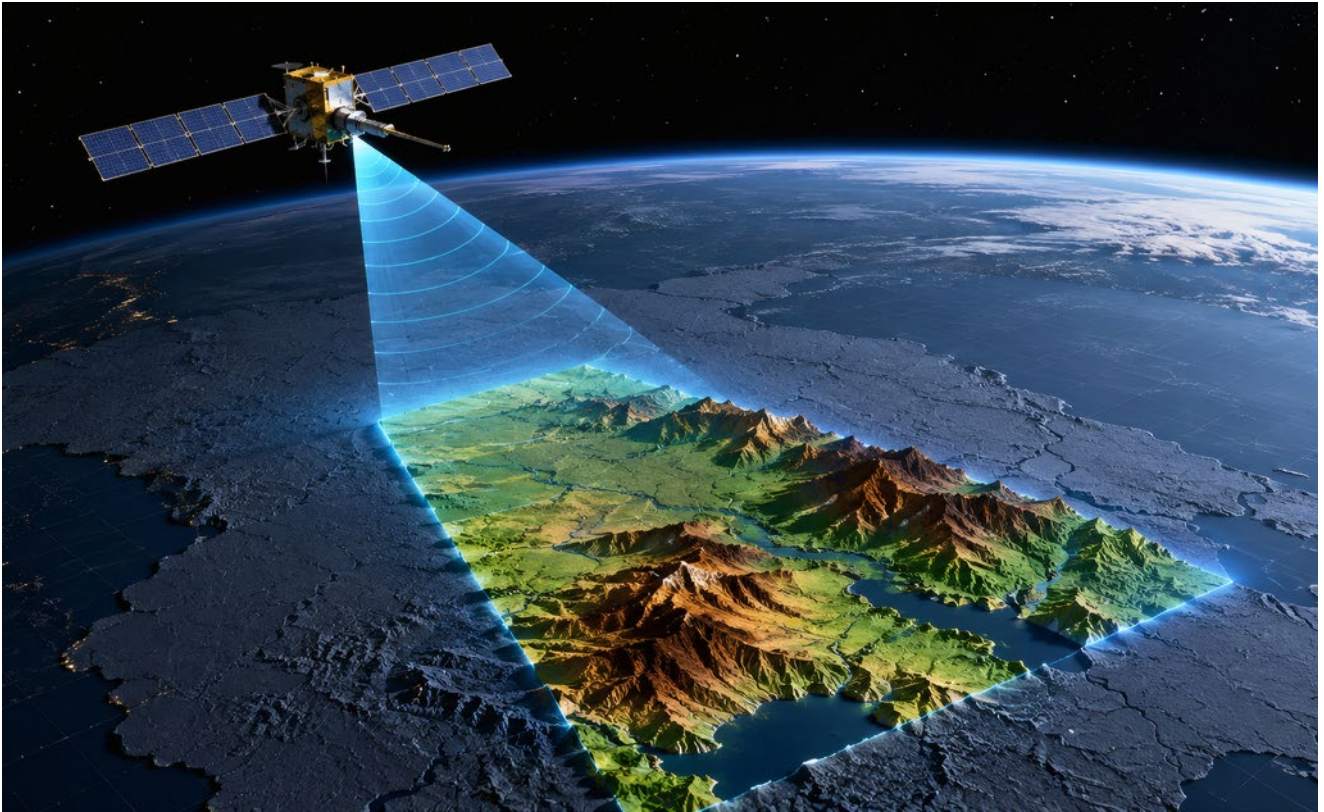
Since different objects alter the polarisation of the energy they reflect to different extents, the type of signal polarisation will affect the appearance of these objects in the resulting images.

SAR systems can be operated in different modes. The most frequently operated ones are described in Figure 12. The highest spatial resolution is obtained with spotlight mode, while the largest coverage is provided by scanning mode at the expense of azimuth resolution. In spotlight mode, the SAR antenna is continuously aimed at the target area as the airborne or spaceborne SAR system moves past it. This extended illumination of the target area allows for a longer effective synthetic aperture length.

Fig. 12. Comparison of SAR operation modes[21]

NO.	OPERATION MODE	ANTENNA REQUIREMENTS	CONTINUOUS IMAGING CAPABILITY	FEATURES
1	Strip-map	No scanning	Yes	Traditional imaging mode, mature in technology
2	Scanning	Range scanning	Yes	Wide and large imaging can be generated; generally used in large-scale survey but with low-azimuth resolution, strong scalloping effect, and difficult radiation correction
3	Spotlight	Azimuth scanning	No	Fine and high-resolution imaging can be generated but imaging area is small; generally used in fixed-point surveillance
4	Sliding spotlight	Azimuth scanning	No	High-resolution imaging can be generated, and imaging area is between strip-map and spotlight
5	Mosaic mode	Range-azimuth 2D scanning	No	High-resolution and wide-swath imaging can be generated, at the cost of increasing the antenna scanning scope
6	TOPS mode	Range-azimuth 2D scanning	Yes	Wide-swath imaging can be generated at the expense of azimuth resolution, and the scalloping effect is eliminated by azimuth antenna scanning





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Regarding radar images, there are two factors that can affect their appearance: radar image speckle and radar image brightness variation. Speckle is characterised by a seemingly random arrangement of bright and dark pixels within the image, resulting in a distinctively grainy texture. It can be partially reduced using image processing techniques, although the best results are achieved when using multiple-look processing techniques. This procedure involves averaging several independent images of the same area, produced using different parts of the synthetic aperture, to create a smoother image. The number of statistically independent images averaged together is referred to as the number of looks.

As for radar image brightness variation, SAR images frequently exhibit differences in brightness along the range direction, resulting in them becoming progressively darker as the range increases. This effect is usually more pronounced in airborne radar systems than spaceborne systems because their lower altitude provides a broader range of look angles.

Depending on the characteristics of the monitored object and its surroundings, the intensity of the radar signal return to the sensor can vary.

Thus, the greatest returns are obtained from objects located on slopes facing the radiation, as well as those with high moisture content, metallic objects, or those in urban areas, as their geometric shapes often act as perfect reflectors of radar energy. Highly polished surfaces or those acting as specular reflectors result in very low radar radiation returns to the sensor, with no return from objects located in radar shadow areas.

Spaceborne radar sensors offer several advantages. Considering that radar is an active sensor that allows image acquisition both day and night, and in almost any weather conditions, this capability can be well exploited by using the entire orbit of the host satellite, both in the ascending and descending nodes, for image acquisition.

Due to the fact that the energy emitted from a radar sensor undergoes only small variations in its incident angle relative to the Earth's surface, it is easy to distinguish returns caused by angle variations from those produced by the shape, structure, and composition of the objects located on the surface. This is not always true with airborne sensors, due to the changes in the incident angle across the image swath.

2 • Radar Interferometry

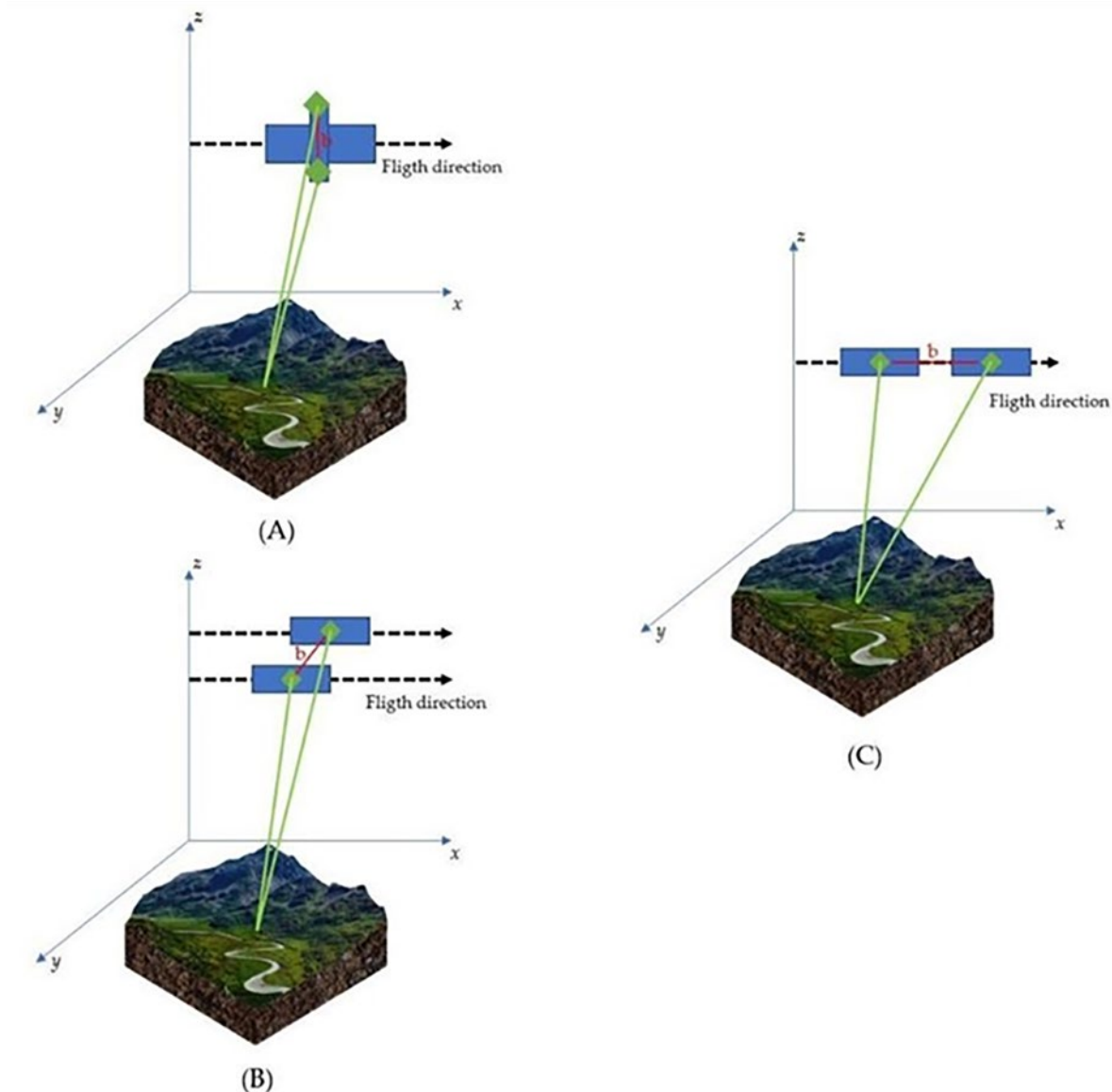
Radar interferometry techniques, often referred to as Interferometric Synthetic Aperture Radar (InSAR), offer a method of processing SAR images by comparing the differences between two radar signals, specifically the phase differences of the energy returning to the sensor, in the same monitored geographic area. The resulting product is called an interferogram.

Across-track interferometry uses one or more radar antennas positioned across the flight direction for image acquisition. Depending on the configuration,

the system can collect data either from slightly different locations at different times (single-antenna repeat-pass interferometry), or simultaneously from two separate across-track positions (two-antenna single-pass interferometry).

Along-track interferometry employs two antennas placed one behind the other along the direction of motion of the platform. Each antenna records a SAR image of the same area, taken under identical geometries and separated only by a very short time interval, determined by the distance between the antennas[25].

Fig. 13. InSAR configurations: (A) single-pass across-track, (B) repeat-pass across-track and (C) along-track[25]



Radar interferometry is a useful tool that can be employed to measure both ground displacements and the movement of structures built upon it. As such, data obtained via this technique can be used to identify and assess damage to infrastructure, both on a small scale (e.g., a railway line) and in detailed cases (e.g., a bridge)[26].

However, this radar data processing technique also has a series of limitations when using spaceborne sensors. Due to the near-polar paths of satellite orbits, the line of sight focuses on capturing ground deformations in the east-west direction. Nevertheless, ground movement aligned north-south (or south-north) does not produce motion toward or away from the satellite, rendering InSAR unable to detect such a deformation¹⁰.

There are also several limitations tied to the properties of the sensors and the applied processing techniques. These include: shadow and layover effects in steep terrain; temporal decorrelation in areas with vegetation or snow cover; and difficulties detecting small, fast-changing areas due to spatial resolution constraints and phase ambiguity[27].

Layover occurs when the radar signal first strikes the top of an object before reaching the ground. As a result, the echo reflected from the top of the building reaches the sensor before the one from its base, causing the structures in the resulting image to appear tilted toward the sensor. Radar shadow in SAR images refers to areas from which no return signal is received due to the observation geometry. This phenomenon occurs when an object or topographic feature blocks the radar signal from reaching certain areas.

Fig. 14. Advantages and limitations of InSAR[27]

ADVANTAGES		LIMITATIONS	
MAIN ELEMENT	DESCRIPTION	MAIN ELEMENT	DESCRIPTION
Remote sensing	No need of access to the monitored area	Relative measurement	Measurement relative to a calibration/reference point
Active sensors	Acquisitions independent to illumination by the sun	Uncontinuous monitoring	At this moment, revisit time usually > 10 days. No InSAR information in between
Microwave sensors	Acquisitions independent to weather conditions	Phase ambiguity	Velocity has to be $< \lambda/2$ between 2 acquisitions and 2 points
Large coverage	Specially suitable for movement detection at regional scale	Geometrical distortions	Layover, shadow effects limit the real coverage
		Variable spatial resolution	Spatial resolution can be too low to be able to detect small moving areas
Good accuracy	Ability to detect mm/yr displacement rates	1-dimensional measurement	Measurement along the line-of-sight (LOS). No sensitivity in N-S plane (near polar orbits)
Sensors development	Constant improvement of coverage, revisit times, resolutions, etc.	Coherence variability	Reduced capability on vegetated area, snow, etc. limits the real coverage
InSAR technology development	Significant research field: constant improvement of the processing chain	Unwrapping procedure	Due to the potential discontinuous movement patterns and decorrelation
Constant datasets enlargement	Availability of data from the 90's. Large datasets allow overcoming part of processing limitations	Removing of atmospheric & topographic effects	Due to the high variability of the atmospheric delay & uneven quality of the DEM used to remove the topographic component

3 • High-resolution SAR imaging

As previously mentioned, the term resolution encompasses different concepts (spatial, spectral, radiometric, and temporal). However, when the objective is to distinguish the smallest object on Earth's surface that can be resolved from its surroundings in an image, the relevant concept is spatial resolution, as it directly determines the level of observable detail.

Based on spatial resolution, images captured by an airborne sensor can be categorised as low-, medium-, or high- resolution. However, this categorisation is merely a reference, as continuing technological advancements can result in resolutions that were once classified as high-resolution now being considered low.

Considering that spatial resolution can be simplistically associated with GSD (the distance on the ground represented by each pixel in the image, as expressed in ground units), we can refer to low resolution when the pixel size is 20 m or greater, medium resolution within the range of 2.0–20 m, high resolution between 0.5 and 2.0 m, and very high resolution when the pixel size is less than 0.5 m GSD[28].

In the case of SAR sensors, the level of detail in an image is directly linked to the wavelength of the radiated signal. As a general rule, shorter wavelengths correspond with higher resolution. Considering the distribution of radar bands described in Figure 11, the X band would be classified as high resolution, the C band as moderate to high resolution, the S and L bands as medium resolution, and finally, the P band as low resolution.

10. Interferometric SAR measures displacement only along the satellite's line-of-sight (LOS). Because most radar satellites fly in near polar orbits and look sideways (east or west), the LOS direction has a strong east-west component but almost no north-south component, as it hardly changes the distance between the satellite and the ground.



It should be noted that the way in which radar energy interacts with objects on the Earth's surface also depends on the wavelength of the emitted signal. In this regard, when the wavelength value is similar to that of terrain height variations (roughness level), a large portion of that energy is returned to the sensor, and the observed surface appears brighter in the image. If the wavelength of the radiation is greater than the amplitude of terrain height variations, no energy will return to the sensor, and the surfaces will appear darker and therefore smooth in the image.

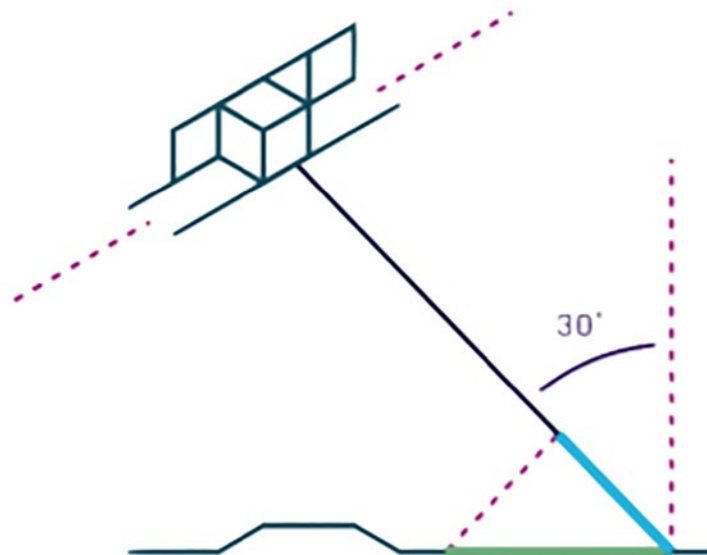
Similarly, the greater the wavelength, the higher the level of penetration of the radiated energy. For example, to detect an object located on the surface beneath a vegetation cover, it would be more effective to use bands such as the L band, which is characterised by a high wavelength value.

Modern SAR systems enable the acquisition of high-resolution images, facilitating the detection

and identification of objects located on the Earth's surface. These include small structures such as: buildings, roads, and bridges; vehicles like cars or boats; infrastructure elements such as power lines, pipelines, and communication towers; and urban features like rooftops, parking lots, and streets.

Although spatial resolution is initially not affected by the altitude of the platform hosting the sensor, certain image characteristics are influenced by this altitude. For instance, to achieve a relatively wide swath (50–70 km), the radiation emitted by an airborne sensor must reach the Earth's surface at a high incidence angle, leading to undesirable imaging variations across the swath due to viewing geometry. Spaceborne sensors mitigate these variations by operating at higher altitudes and achieving a narrower range of incidence angles[29]. However, ground resolution improves as the incidence angle increases.

Fig. 15. Incidence angle and ground range resolution[30]



	INCIDENCE ANGLE 30°	INCIDENCE ANGLE 60°
Slant Range	0.50m	0.50m
Ground Range	1.00m	0.55m



Below are some examples of very high-resolution SAR images obtained from spaceborne and airborne sensors.

Image 1. Very-high-resolution SAR image (spaceborne sensor)[31]



Image 2. Very-high-resolution SAR image (airborne sensor)[31]



Besides aircraft and satellites, it is also necessary to consider the possibility of using UAVs as a platform to obtain high- (or even very high-) resolution SAR images. UAVs are affordable, widely available, and can be quickly deployed. They can navigate paths and reach areas that are challenging for traditional aircraft or spacecraft. However, they are normally limited to carrying small, lightweight payloads, and the power they can make available to radar sensors is somewhat restricted. Consequently, UAV-based SAR imaging is more effective at shorter distances. Additionally, UAVs are susceptible to flight instability due to wind and turbulence, which, along with the inaccuracies of onboard inertial navigation systems (INS) or global positioning systems (GPS), can affect their performance[32].

Image 3. UAV SAR image taken by 1 GHz radar[33][34]



5 • CASE STUDY

1 • Situation analysis

The Arctic region is a distinctive physical environment with its own set of challenges. Both maritime and terrestrial areas within it exhibit conditions that are absent in other parts of the world. The climate is extreme, featuring long, dark, cold winters and short, cool summers with continuous daylight. The severe weather and vast distances in the Arctic hinder the ability to maintain constant surveillance, while the sparse population and lack of infrastructure complicate the collection of real-time intelligence. Given these conditions, remote sensing is impacted by prolonged winter darkness, leading to reduced intelligence quality compared to that gathered during operations in lower latitudes [35].

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It is for these reasons that it is essential to choose the best type of platform and sensor to be used for obtaining images of a target on the ground. Space assets can be very valuable for obtaining information about targets located on the Earth's

surface. It is for this reason that the number of Earth observation satellites being put into orbit has progressively increased, mostly in the so-called Low Earth Orbit (LEO)¹¹ regime that enables the collection of high-resolution imagery.

Spaceborne sensors can also play a significant role in the targeting cycle, providing precise information for the analysis of targets and identifying optimal impact points, as well as information on the structural and functional state of the targets within the Battle Damage Assessment process.

Regarding sensors, satellites can be equipped with both passive (electro-optical) and active (SAR) sensors, with the resolution of the obtained images varying according to the type of sensor used. This resolution will depend on the altitude of the orbit relative to the ground. In this sense, the higher the orbit, the lower the resolution generally obtained while, on the other hand, the higher the ground coverage achieved.

Fig. 16. Comparison between different spaceborne sensors. SSO refers to Sun-Synchronous Orbit [17]

	EO	IR	SAR
RESOLUTION	< 1 meter	≈ 20 meters	< 1 meter
OPERATIONAL TIME	Only during daylight	Day and night	Day and night
WEATHER CONDITIONS	Only clear sky	Only clear sky	All weather
IMAGE PROCESSING	Easy	Easy	Difficult (it requires time and expertise)
ORBIT	Mainly LEO polar	Mainly LEO polar	Mainly LEO polar (SSO)

As indicated in Figure 16, the choice of one type of sensor over another will depend on the level of detail desired in the images and the atmospheric conditions present at the time of image acquisition.

Images obtained within the visible spectrum provide a higher level of detail while facilitating their analysis and interpretation due to their simplicity. However, their acquisition is only possible during the day and

¹¹ LEO is an orbit situated at an altitude of between 100 km and 2,000 km. LEO satellites are constantly in motion with a period of approximately 100 minutes [17].



in the absence of any atmospheric element that may disturb this acquisition, such as clouds.

Thermal sensors that capture infrared energy emitted by objects on the Earth's surface are the only passive sensors that allow image acquisition both day and night, although some atmospheric conditions present at the time of acquisition can affect this process.

SAR sensors allow image acquisition both day and night and are generally not affected by the weather conditions present at the time of acquisition. However, both the processing and subsequent analysis of the acquired images require more time and analyst specialisation due to the complexity of operating with this type of sensor.

2 • Challenges and limitations

The challenges and limitations of ISR missions for targets in the Arctic region are determined by its geographical situation and the atmospheric and climatic conditions present there during much of the year. As such, it is important to consider that the use of an aircraft as a remote sensing platform will be affected by the changing atmospheric conditions present in the area. Aircraft safe operating minima will often mean that image acquisition can only be conducted during brief time intervals.

The Arctic region experiences significant electromagnetic interference in the atmosphere, which can severely impact wireless communications. This interference is often due to atmospheric ducting, where electromagnetic waves are trapped and guided by the atmospheric layers, leading to extended signal propagation and increased interference.

Additionally, the harsh and variable atmospheric conditions in the Arctic can degrade the performance of position, navigation, and timing (PNT) satellites, making reliable communication and navigation more challenging¹².

UAVs have the advantage that flight missions can be deployed at a more flexible time frame and that certain atmospheric effects which affect image acquisition are more easily avoidable compared to using aircraft or satellites. However, a common drawback of long-endurance UAVs is their difficulty in operating at extreme northern and southern latitudes. Links based on geostationary satellites tend to become less reliable in those latitudes¹³. Additionally, the very low temperatures that can be reached in these areas can also affect the efficiency of some elements of the UAV systems, such as batteries.

Regarding satellites, there are also challenges and limitations related to the orbits within which they operate. As such, and due to the curvature of the Earth, LEO orbits, which are typically used for remote sensing sensors, are suitable for reconnaissance tasks, but at the expense of being able to observe a wider area on the ground. LEO orbits also have the shortest orbital period, leading to the fastest overflight of the target area (brief observation windows introduce a need for constellations or repeated passes to ensure coverage) [36].

Modern spaceborne sensors can adjust their field of view, but this involves a trade-off between the area covered and the resolution achieved. Thus, obtaining lower resolution images for wide-area coverage, with adjacent images combined, enables the ground to be covered in fewer swaths. This can be crucial when the satellite path results in a long delay between successive passes over the target area [36]. Satellites in polar orbits can repeatedly and consistently observe high-latitude regions, making them ideal for tracking environmental changes, creating maps, and conducting surveillance in the High North.

Earth observation satellites also require ground support infrastructure that can provide telemetry, data reception, and an initial level of processing. Most of these satellites are in polar LEO orbits, meaning that they pass over the poles (or very nearly) with

12. Factor marked by ionospheric irregularities, frequent geomagnetic storms, low satellite elevation angles, and rapidly changing weather patterns contribute to increased signal delays, reduced satellite visibility, and intermittent loss of reception, all of which undermine the accuracy and stability of GPS and other satellite-based services.

13. Geostationary satellites, used by many datalink systems, are stationed above the equator, so as UAVs travel toward higher latitudes, these satellites are located very low on the horizon. This results in weaker and less stable connections, as well as longer and more attenuated signal paths through the atmosphere.



each revolution around the Earth. Therefore, the positioning of a ground station in polar/sub-polar regions can be far more advantageous than in other latitudes.

3 • Comparative analysis of results obtained from different sensors

Electro-optical sensors are referred to as passive since they rely on natural radiation from the Sun or Earth such as visible and near-infrared wavelengths, as they operate in regions of the electromagnetic spectrum where this natural radiation is strongest. Amongst these sensors are those that capture energy within the visible spectrum in the form of a single band (panchromatic) and those that can collect it in three separate bands¹⁴, obtaining a 'true colour' image. The latter typically capture not only visible energy but also near-infrared and even short-wave infrared radiation¹⁵.

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Bands outside the visible spectrum naturally exhibit colours that do not correspond to those that the human eye can perceive. To represent their intensity,

colours are artificially assigned to what is known as band combinations. For instance, when the near-infrared (NIR) band is shown in red, the red band in green, and the green band in blue, the resulting image is called a false-colour combination.

Panchromatic images appear in greyscale, where the brightness level represents the data value, and generally provide higher spatial resolution than those formed from separate bands. This is because detectors in panchromatic cameras gather energy from the entire spectral range so the total intensity of solar radiation is much higher in every pixel. Moreover, in common colour sensors, each pixel is assigned to a colour according to a filter matrix; hence, no single sensor pixel corresponds directly to a pixel in the final picture, but instead contributes only partial colour information.

It is possible to enhance the spatial resolution of a multispectral image by integrating a panchromatic band. This technique is known as panchromatic sharpening and consists of combining a panchromatic image with a low-resolution multispectral image to achieve a higher spatial resolution while preserving spectral attributes^[37].

Images 4 & 5. Fukushima nuclear plant before (left) and after (right) the 2009 tsunami^[38]



14. Red, Green and Blue (RGB).

15. These sensors are referred to as multispectral sensors.

Images 4 and 5 show examples of the level of detail that can be achieved with a spaceborne sensor. The images were obtained by the GeoEye-1 satellite, which features a line scan imaging system capable of capturing radiation from the visible spectrum in both panchromatic and multispectral modes. In multispectral mode, the sensor is sensitive to visible spectrum bands as well as near-infrared radiation. The maximum spatial resolution achieved in panchromatic mode is 0.41 m, whereas in multispectral mode, it reaches 1.64 m. By combining a panchromatic image with a multispectral one, a true-colour final product is obtained with a resolution of 0.5 m¹⁶[39].

The main advantage of true-colour images is that they depict scenes in the natural colours perceived by the human eye, making analysis and interpretation easier. Images obtained in the visible spectrum possess high spatial resolution, making them an excellent choice for studies requiring intricate details. Their main limitation lies in the fact that they are restricted by the day/night cycle as well as the prevailing weather conditions at the time the image is captured. For instance, visibility of the target of interest may be obstructed by cloud cover.

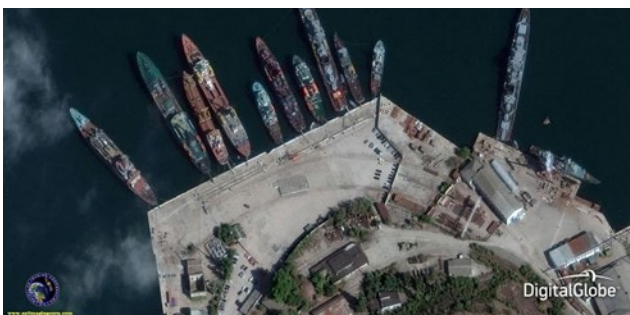
Images 6 & 7. A military research and development centre before (left) and after (right) a missile attack [40]



Images 6 and 7 show a military research and development centre, before and after a missile strike. The images were obtained by the WorldView-2 satellite, which provides 0.46 m of spatial resolution in panchromatic mode and 1.8 m in multispectral (8 bands), and the WorldView-3 satellite with a 0.31 m resolution in panchromatic mode and 1.24 m in multispectral. Image 8 shows another example of an image taken by WorldView-3 – a 0.30 m resolution true-colour product.

Another type of passive sensor used for remote sensing is one that captures emitted infrared energy, also known as thermal-infrared. All objects with a temperature above absolute zero (0 K or -273°C) emit electromagnetic radiation. The specific wavelength at which this emission is most intense depends upon the temperature of the object. For Earth, which has an average temperature of approximately 300 K, its peak emission occurs in the thermal infrared range.

Image 8. Crimea Sevastopol Naval Base[40]



The advantage of thermal infrared is that it can be obtained independently of the Sun, meaning that it can be acquired during the day and night. However, thermal images have lower resolution compared to those obtained from reflected energy (optical bands) and are subject to atmospheric disturbances related to the distance between the observed target and the sensor. As a consequence, thermal images

16. According to the European Space Agency, <https://earth.esa.int/eogateway/missions/geoeye-1#instruments-section>. [Accessed 22 July 2025].

obtained from satellites have a spatial resolution that is still far from that achieved with visible sensors.

Image 9. Thermal image of a Nuclear Scientific Research Centre, October 2023[41]

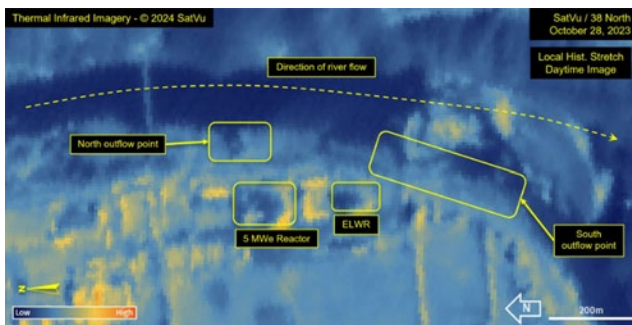
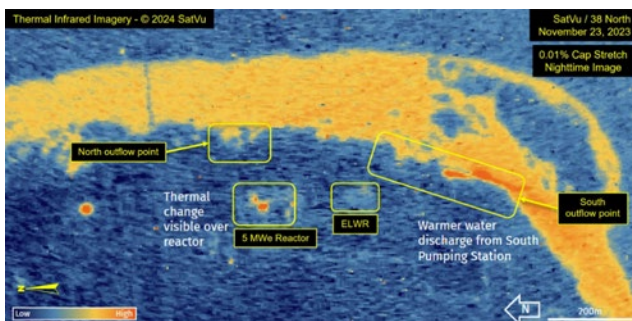


Image 10. Thermal image of a Nuclear Scientific Research Centre, November 2023[41]



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Images 9 and 10 are examples of the products that can be obtained using a spaceborne thermal sensor. Both images are of a nuclear power plant and, by comparing the results obtained on different dates, it is possible to observe evident indications of an increase in the activity levels at the aforementioned plant.

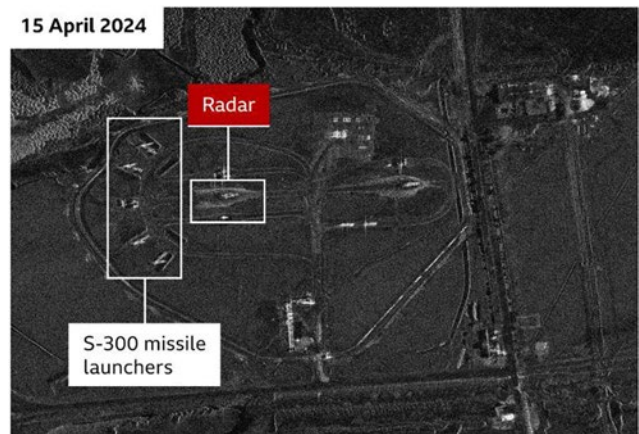
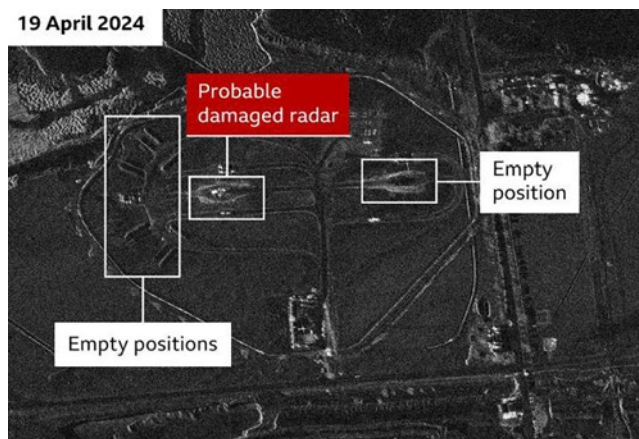
These images were obtained by the HotSat-1 satellite, located in a sun-synchronous orbit¹⁷ and featuring a sensor capable of providing up to 3.5 m resolution¹⁸[39]. As can be seen, these high-resolution images, while capable of providing valuable information about the activity level of a target, lack the necessary level of detail to allow for a precise interpretation of it.

Once passive sensors have been analysed, it is time to examine active ones. SAR sensors have the advantage of being usable both day and night and in almost any weather conditions. The main

drawbacks of SAR images have traditionally been their lower spatial resolution (compared to images obtained using sensors that operate within the visible spectrum) and the greater complexity involved in working with them, especially when analysing or identifying potential targets.

Regarding resolution, technological advancements have enabled the deployment of commercial satellites equipped with sensors that provide high-resolution images. The following images present the analysis conducted after an attack on an S-300 missile site.

Images 11 & 12. S-300 site before (left) and after (right) an air strike[42]



These images were taken by the synthetic aperture satellite constellation of Umbra, a company that, according to its own data, can provide images with a resolution of up to 16 cm.

17. A nearly-polar orbit passing the equator at the same local solar time on every pass.

18. According to the European Space Agency. Available on <https://earth.esa.int/eogateway/missions/hotsat-1>. [Accessed 22 July 2025].

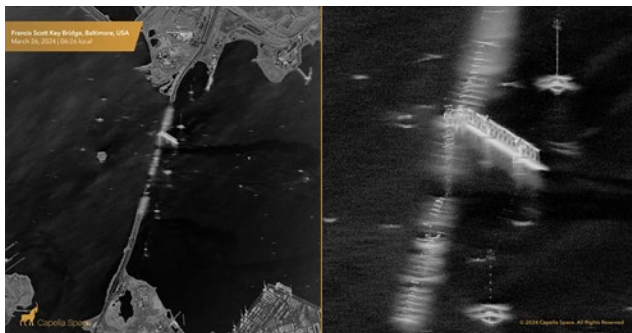


Image 13. Umbra SAR image (16 cm resolution) taken over Honolulu[43]



Image 14 is another example of a satellite SAR image used for infrastructure damage analysis. In this case, it shows the Francis Scott Key Bridge in the United States, after being struck by a cargo ship, which caused its collapse.

Image 14. Francis Scott Key Bridge[44]



When it comes to the complexity of analysing SAR images, it is important to consider that they present a series of challenges that set them apart from those obtained by other types of sensors. These include geometric distortions that sometimes appear in the images, such as: foreshortening, where surface objects appear compressed in the range or cross-track direction; layover, which occurs when the radar beam reaches the top of an object before its base; and shadows, which correspond to areas not illuminated by the radar and therefore lacking information.

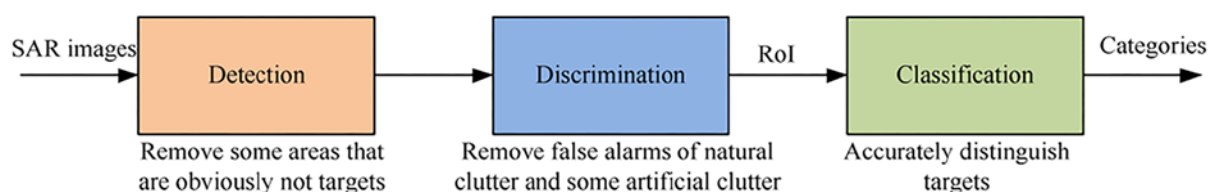
Additionally, SAR images exhibit a speckle noise that gives them a grainy appearance. Although this noise can be reduced using various image processing techniques, completely removing it without affecting image resolution is quite complex.

SAR images also collect radar information that is reflected back from surface objects to the sensor. This information depends on several factors, such as the surface roughness of the object, its dielectric properties, and the angle at which the radar signal reaches the object.

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To address these problems, various algorithms have been tested to assist in automatic target recognition (ATR). Recent technological advances, especially in the field of artificial intelligence, have led to the development of new methods for target recognition and classification, primarily based on machine learning and deep learning, which can significantly aid in analysing SAR images in a more automated way.

Fig. 17. Process of SAR ATR[45]



Some of the algorithms that have been tested have yielded good results in automatically identifying targets, and commercial solutions offering this capability are beginning to emerge. However, certain challenges still need to be overcome. Among these challenges are the difficulty of identifying targets in complex clutter environments and the need to manage large SAR image datasets, given that the radar return of the same target can vary depending on the conditions under which the image was captured, among other factors.

Image 15. Example of SAR ATR[46]

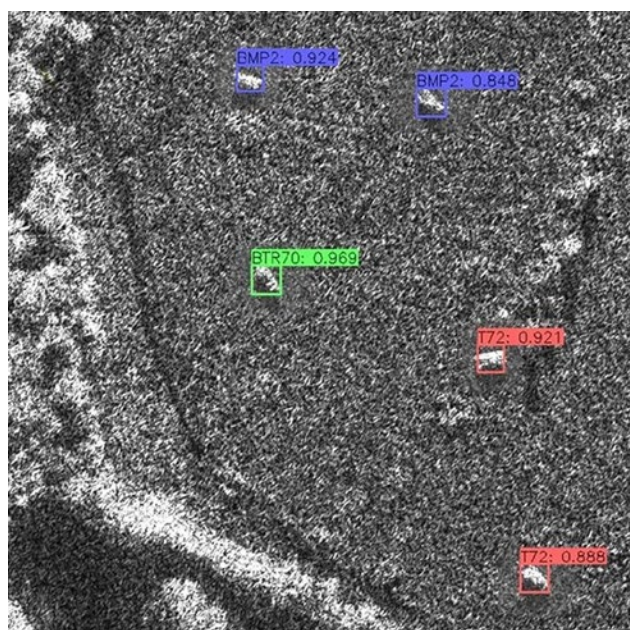


Image 16. Example of SAR ATR[47]



6 • CONCLUSIONS

The High North is a geographical area that has progressively gained strategic importance for the Alliance. In this context, the availability of ISR capabilities for image intelligence acquisition, which provide information that enhances situational awareness of the region and supports decision-making, can prove to be absolutely critical.

The greatest obstacle to successfully conducting ISR missions in this geographical region lies in its unique environmental and atmospheric conditions. In addition to extreme weather, there are electromagnetic disturbances caused by solar activity, as well as many vast snow-covered areas, along with clouds, wind, and precipitation, all of which can significantly impact and degrade the resolution of imagery collected for intelligence purposes.

Given these constraints, the choice of both the type of sensor used to conduct ISR missions and the platform on which the sensor is deployed become critically important. Each option, whether in terms of sensor technology or operational platform, offers distinct advantages and disadvantages that must be carefully assessed to ensure mission effectiveness under the region's challenging environmental conditions.

Regarding platforms, satellites equipped with remote sensing sensors have consistently proven to be a reliable option for conducting ISR missions. The effectiveness of space-based sensors is largely influenced by the orbital parameters of the satellite. Polar orbits are particularly advantageous for acquiring imagery from the High North. Sun-synchronous orbits are especially useful, as they enable the comparison of images of the same target, taken at different times under consistent lighting conditions.

Satellites can be equipped with either passive or active sensors, both capable of acquiring imagery for intelligence purposes. The resolution of the images obtained depends primarily on two factors: the orbital altitude of the satellite, which determines the distance between the sensor and the target on the surface, and the specific type of sensor being used. These variables directly influence the level of detail and accuracy achievable in ISR operations.

Among passive sensors, electro-optical systems include those that capture energy from the visible spectrum, emitted by surface objects. These can operate in a single band, known as panchromatic sensors, or in multiple separated bands, producing what is referred to as a true-colour image.





Generally, panchromatic images offer higher spatial resolution than those obtained through separated spectral bands. However, using techniques such as panchromatic sharpening, it is possible to enhance the resolution of multispectral images by fusing high-resolution panchromatic data with lower-resolution colour bands.

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Although imagery acquired through sensors operating within the visible spectrum typically offers the highest resolution compared to other sensor types, and benefits from being easier to analyse and interpret, its main limitation lies in the dependency of the sensor on daylight and favourable weather conditions. As a result, for the purposes of this study, they may not always be the most suitable option, depending on the environmental circumstances at the time of data acquisition.

Passive sensors also include those capable of capturing thermal energy (thermal infrared) emitted from the Earth's surface, providing highly valuable data for assessing the activity level of a target. These sensors offer the advantage of being operable both day and night. However, under certain environmental conditions, such as cloud cover or heavy precipitation, they may fail to deliver successful results.

In addition to this limitation, the spatial resolution of thermal imagery acquired from satellites remains significantly lower than that achieved by other sensor types, particularly those operating in the

visible spectrum. This reduced resolution can hinder the analysis and identification of smaller targets, making it less effective for detailed intelligence gathering in certain scenarios.

Active sensors are characterised by their ability to capture electromagnetic energy reflected from surface objects, which was previously emitted by the sensor itself. Among these, Synthetic Aperture Radar (SAR) stands out as a key technology for acquiring imagery for intelligence purposes. SAR sensors can operate both day and night and are effective even in the presence of clouds, fog, or smoke, making them virtually the only all-weather imaging solution.

Among the SAR image processing techniques is interferometry, which involves comparing phase differences in the radar returns from two signals over the same geographic area. This can be achieved using a single platform equipped with two spatially separated sensors, a single sensor that revisits the same area multiple times, or by comparing radar signals emitted with different polarisations and received by a single sensor.

In all cases, the resulting imagery provides valuable information about ground movements and the displacement of objects located on the surface, making it a powerful tool for monitoring terrain dynamics and structural changes.

CONCLUSIONS

Although SAR sensors offer robust performance under most weather conditions, they do face limitations in scenarios involving intense rainfall, which can degrade image quality. However, the most significant challenge lies in the complexity of analysing and interpreting SAR imagery. Without highly trained analysts familiar with this type of data, extracting actionable intelligence can be difficult.

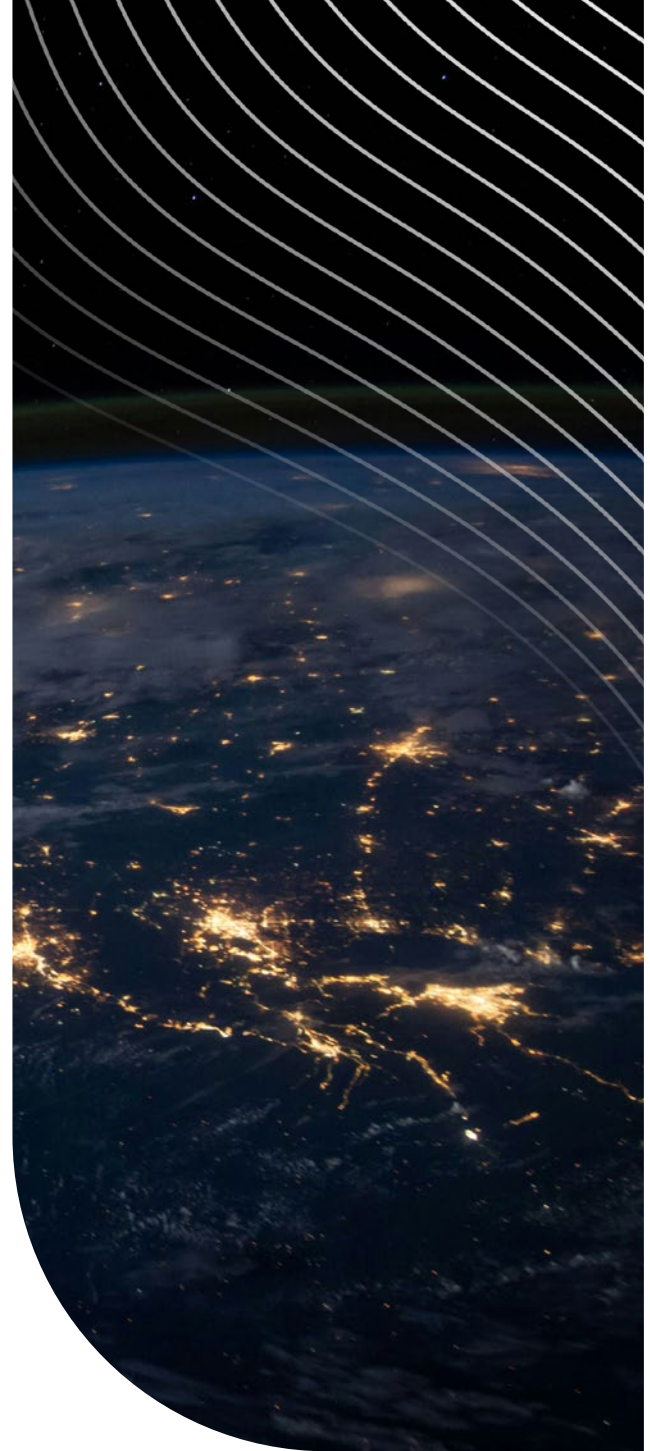
Additionally, as active sensors emit their own signals, they are detectable during operation. This makes them vulnerable to potential interference or jamming, which can compromise mission effectiveness in contested environments.

In terms of resolution, modern SAR systems are capable of acquiring data that allows for the detection and identification of even small objects and structures on the Earth's surface. In this regard, some commercial SAR satellites claim to achieve imagery with resolutions of just a few centimetres, making their performance comparable to that of sensors operating within the visible spectrum.

Technological advances in artificial intelligence have enabled the development of systems capable of detecting and identifying targets almost automatically. This significantly eases the workload of analysts and helps mitigate the limitations associated with the complexity of interpreting certain types of imagery.

These AI advancements are further supported by emerging concepts in remote sensing, such as the deployment of two satellites in the same orbit, one equipped with a SAR sensor and the other with a high-resolution optical sensor. By capturing successive images of the same target, this approach combines the strengths of both sensor types, enhancing the overall quality and reliability of the intelligence gathered.

Considering all the points discussed above, it can be concluded that SAR sensors are the only ones capable of reliably acquiring imagery of targets located in the High North under virtually any environmental and atmospheric conditions present in the region. Nevertheless, it is important to consider the need for high or very high-resolution



imagery in order to conduct detailed analysis of smaller targets. To achieve satisfactory results, it is essential to evaluate the relationship between the target size, intended objective, and required spatial resolution before planning any ISR mission.

It is important to recognise that in the field of remote sensing, no single sensor consistently outperforms all others under every circumstance. Each sensor type has its own strengths and limitations, and the integration of data from multiple sources can significantly enhance the analysis of a target. True strategic advantage lies in having access to the widest possible range of sensors for the execution of ISR missions.



ABOUT THE AUTHOR



Lieutenant Colonel José María Cifuentes Rivera

is a graduate of the Spanish Air and Space Force Academy. He began his career at the Air Force Cartographic and Photographic Centre (Madrid), specializing in imagery analysis for intelligence. After graduating from the Joint Staff Course at the Centre for National Defence Studies (CESEDEN), he was posted to the Spanish Joint Operations Command, serving as a Staff Officer in the J3-Air Division. Since July 2023, he has been assigned to the NATO Space Centre of Excellence as a Staff Officer in the Concept Development and Experimentation (CD&E) Division.

His professional military education includes the Armed Forces Joint Staff Course, the International Imagery Analysis Course (UK-Joint School of Photographic Interpretation), the Spanish Military Photointerpretation Course, the Introduction to Space Support to NATO Operations, and the Space Military Overview Course (France-Space Command). He holds a Law Degree, a Master's Degree in Defence Policy and International Security and a Master's Degree in Operations Research.



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