How to Spot Potential Threats Using SAR for Change Detection

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WITHIN NATO, Intelligence, Surveillance and Reconnaissance (ISR) is a prime user of Space-based capabilities. ISR systems provide the ability to acquire information regarding activities and resources of an adversary and to extract data concerning the geographic characteristics of a particular area of interest, including denied areas where little or no data can be obtained from other sources without putting at risk personnel and means.

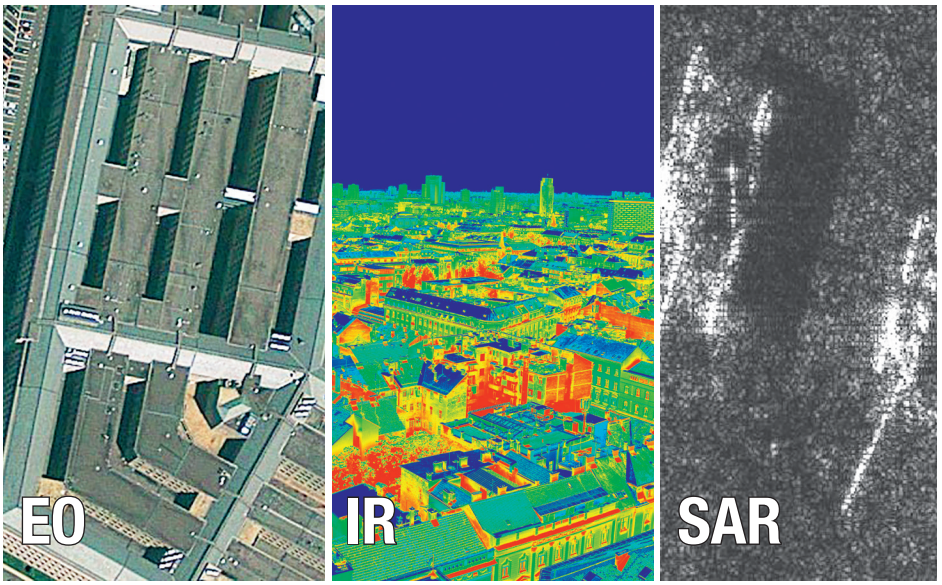
Indeed, due to various UN Space treaties[1], all Space assets can transit any territory on Earth without prior authorization. This allows for Space-based ISR assets to take images and gather Intelligence without requesting border crossing authority, thus reducing the vulnerability of Earth-bound ISR assets (Maritime, Air and Land) to adversary actions. These are not the only advantages that Space-based imagery offers as compared to airborne imagery. Indeed, the latter cannot be acquired during degraded weather conditions and planes cannot assure the overflight of an area of interest along the exact same path over time. Additionally, even though terrestrial assets are more flexible in their deployment, they usually require a considerable amount of time to reach the area of interest.

However, some Space-based ISR systems are impacted by terrestrial weather conditions as well, which may result in a poor image collection. This is not the case of Synthetic Aperture Radar (SAR) satellites, whose imagery has been used in the study described in this article. Indeed, a radar signal is able to penetrate clouds, vegetation, and, in specific conditions, even the ground, thus allowing the detection of underground objects. Additionally, SAR works in all light conditions.

A single satellite in a polar orbit[2] will overfly all locations on the Earth's surface. However, the revisit time cannot be adjusted and cannot be less than one day. In order to revisit a target more frequently, a constellation of satellites is needed. Additionally, for planning purposes, it is important to note that a product with a higher resolution[3] usually coincides with a smaller footprint[4] and a higher revisit time. Vice versa, a lower resolution usually is associated with a larger area of coverage and shorter revisit time. Finally, unlike aircrafts, satellites assure the passage along the same path every orbit.

Among the several NATO uses and effects of ISR capabilities, Change Detection (CD) is one of the most useful for targeting, Intelligence and to counter Improvised Explosive Devices (IEDs). CD is intended to automatically or semi-automatically detect changes

over time in an area of interest. Depending on the image resolution, CD allows to spot objects of very small dimensions (*i.e.* less than 50 centimetres) or disturbed dirt and even tyre tracks on grass fields. If a change happens in an area of interest in the timeframe between two observations, it can be detected by imagery processing. Both natural and man-made changes are detectable; usually, natural changes are on large scale, while man-made ones are limited to small portions of the images. This article describes the ability of different techniques to spot small changes in SAR images, whether natural or man-made.



ABOVE: Examples of the most common ISR capability products. From Left: Electro-optical (EO) imagery, infrared (IR) imagery and Synthetic Aperture Radar (SAR) imagery. EO sensors provide photography-like imagery, IR sensors provide imagery by exploiting the temperature of bodies, and SAR sensors use microwaves to get the image. The main advantage of EO and IR products is the simplicity of reading the image, so the information can be extracted immediately. On the other hand, they are affected by terrestrial weather. SAR imagery is an all-day, all-weather product, but it necessitates significant processing time and analysts. All these capabilities are fundamental for Space support in NATO operations.

SAR Imagery

A SAR is a radar mounted on a moving platform (*i.e.* a satellite). It uses the motion of the platform over a target region to provide better resolution than conventional beam-scanning radars. The distance the SAR travels over a target in the time taken for the radar pulses to return to the antenna creates the large "synthetic" antenna aperture. In other words, the *size* of the antenna is given as the *sum* of positions that the antenna takes while "illuminating" the same area of interest. As a rule of thumb, the larger the aperture, the higher the image resolution will be, regardless of whether the aperture is physical (a large antenna) or synthetic (a moving antenna). This allows SAR to create high resolution images with relatively small physical antennas, which is a particularly important factor for Space-based assets because it implies a reduction of weight and consequently of costs of putting such device in orbit.

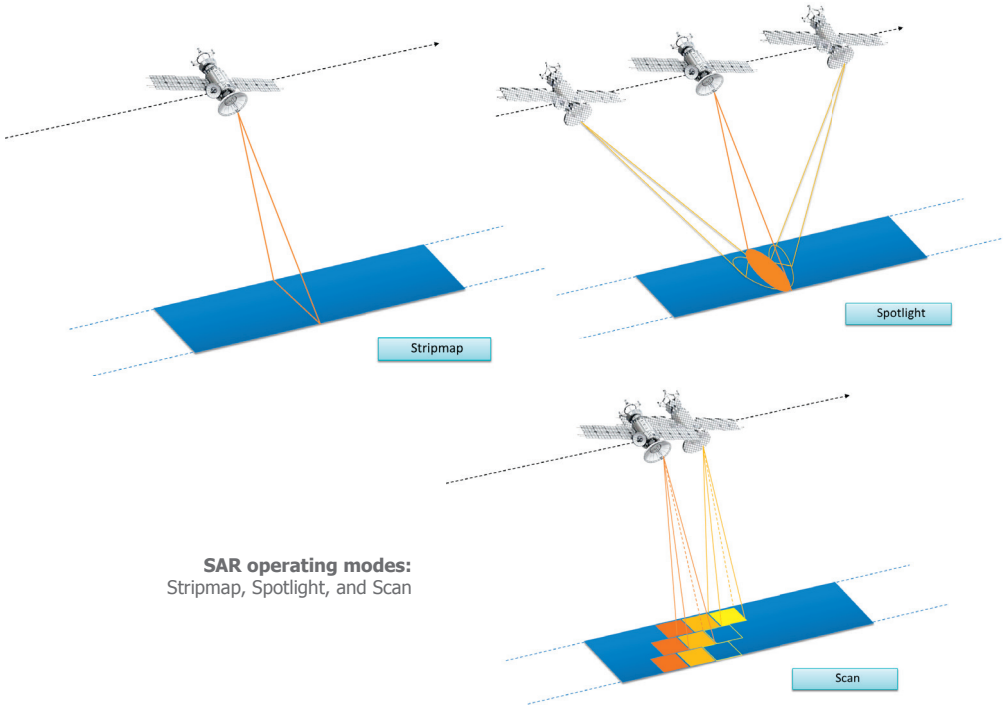
SAR imagery is obtained by exploiting the interaction of a microwave signal (X-band: frequency = 8 to 12 GHz, wavelength = 2.5–3.75 cm) with terrain and objects on Earth. To create a SAR image, successive pulses of waves are transmitted to "illuminate" a target scene, and the echo of each pulse is received and recorded: (1) The radar on board of the satellite (the payload[5]) emits electromagnetic signals, (2) The waves propagate through the atmosphere (clouds included), (3) The pulse is backscattered by objects on the Earth's surface, (4) The echo reaches back to the sensor, which creates the SAR imagery.

Significant computational resources are required to process the observations. However, the new technologies with higher computing speed allow such processing to be done in near-real time on board a satellite. The result is a map of radar reflectivity[6], including both amplitude and phase. The amplitude information, when shown in a map-like display, gives information about ground cover in much the same way that a black-and-white photo does. Unfortunately, the phase differences between adjacent image picture elements ("pixels") also produce random interference effects called speckle, which is a sort of graininess with dimensions of the order of the resolution.

NATO Global Hawk unmanned surveillance aircraft. Photo by © Northrop Grumman

The SAR imagery has wide applications in remote sensing and mapping of the surfaces. Some of the other important applications of SAR are as follows:

- **Topography:** If the two samples are obtained simultaneously (perhaps by placing two antennas on the same satellite, some distance apart), then it is possible to extract terrain



SAR operating modes:
Stripmap, Spotlight, and Scan

altitude as well as radar reflectivity, producing a Digital Elevation Model (DEM).

- **Geology:** SAR polarimetry is a technique used for deriving qualitative and quantitative physical information for land, snow and ice, ocean and urban applications. Radar waves have a polarization. Different materials reflect radar waves with different intensities, but anisotropic materials such as grass or sand often reflect different polarizations with different intensities. Polarimetry uses the changes in the random polarization returns of some surfaces and between two images of the same location at different times to determine where changes not visible to optical systems occurred. Also, polarimetry allows terrain classification and subsurface imaging. Examples include subterranean tunneling or IED hidden underground.
- **Volcano and earthquake monitoring (interferometry):** If the two samples are separated in time, perhaps from two passes over the same terrain, it is possible to detect and quantify terrain shifts between observations. This is a powerful tool in geology, glaciology and geography, and can be used for mapping land deformations due to earthquakes or to forecast volcanic eruptions and assess their consequences.
- **Environment monitoring:** Such as forestry, which includes forest height, biomass, deforestation; oceanography; oil spills; flooding; urban growth; global change.
- **Military surveillance:** Includes strategic policy and tactical assessment.
- **3D imagery of moving targets (inverse SAR):** By observing a moving target over a substantial time period with a stationary antenna.

Objects in motion within a SAR scene alter the Doppler frequencies of the returns. Such objects therefore appear in the image at wrong locations. Generically speaking, the higher their speed is, the further they will be from their actual position. For example, trains appear away from their tracks, and road vehicles may be depicted off the roadway and therefore not recognized as road traffic items.

SAR mainly operates in three modes:

- **Stripmap mode:** The antenna stays in a fixed position. When the antenna aperture travels along the orbital path, a signal is transmitted and the backscatter of each of these signals is commutatively added on a pixel-by-pixel basis.
- **Spotlight mode:** In this mode, the radar beam is steered continually as the spacecraft moves, so that it "illuminates" the same patch over a longer period of time, thus giving better resolution for a smaller ground patch.
- **Scan mode:** The antenna beam sweeps periodically and thus covers much larger area than stripmap and spotlight modes.

The radar signal can be written as sum of two terms: one term represents the power of the signal itself, and one its phase. By analysing both these terms, it is possible to extract from the image a huge amount of information (*i.e.* the speed of objects on Earth, the presence of camouflaged means, etc). Techniques that exploit both these terms are known as coherent techniques, and allow also the detection of "microscopic" changes (up to the dimension of the resolution cell of the image). If only the term that describes the power is analysed, we talk about incoherent techniques; these are not able to distinguish small changes at the same degree as coherent ones.

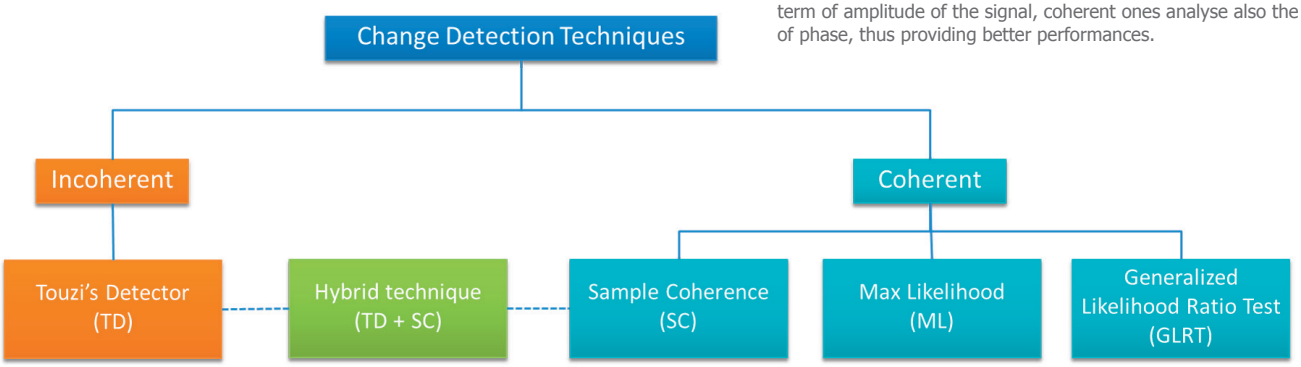
Typically, "useful" signals are mixed with disturbances (*i.e.* thermal noise, interferences, clutter, etc). The echoes coming from the same targets are definitely correlated (they are similar) one to each other because they are deriving from the same object. On the contrary, the noise (N), by its nature, is composed by samples that are statistically independent. In fact, by taking into account all the phases coming from the same target, it is possible to significantly increase the performance of the Signal-to-Noise Ratio (SNR), which for the case of this study is most properly called Clutter-to-Noise Ratio (CNR).

Change Detection Fundamentals

It is necessary to introduce some fundamental concepts of CD. False Alarm (FA) refers to the case in which a change is detected whilst it did not take place in reality. Generically speaking, a false positive error is a result that indicates a given condition has been fulfilled when it has not. The opposite situation, known as misdetection, occurs when a change happened, but it is not detected. This situation is also known as false negative, and indicates that a test condition failed, while it was successful. Any change test must make a trade-off between these two common metrics.

In order to assess the performance of different techniques, this study has been conducted with a probabilistic approach. With respect to the concepts of FA and misdetection,

BELOW: An overview of the Change Detection techniques used. Incoherent techniques exploit only the information contained in the term of amplitude of the signal, coherent ones analyse also the term of phase, thus providing better performances.



we will call them Probability of False Alarm (P_{FA}) and Probability of Misdetection (P_M), indicating the probability that these events happen. P_{FA} represents the proportion of all negatives that still yield positive test outcomes. P_M is the proportion of positives, which yield negative test outcomes.

The probability complementary to P_M is called Probability of Detection (P_D), and represents the probability of detecting a change that actually occurred. It is the key performance indicator in CD analysis. Probabilities range between 0 and 1.

The decision about the presence of an useful signal among disturbances (*i.e.* thermal noise, interferences, clutter, etc) is based on the overcoming of a threshold (T). Since the P_{FA} depends only on T and noise (N), once N is known it is possible to find the value of T for a fixed value of P_{FA} ($P_{FA}=10^{-3}$ has been considered acceptable for the purposes of this study). Generally speaking, the lower the desired P_{FA}, the higher the T, but at the same time the higher the P_M and consequently the lower the P_D.

BELOW: A transmission system radio maintainer mounts a helical antenna to an AM-1 to send and retrieve information via satellite. Photo by Airman 1st Class Zachary Hada, U.S. Air Force.

For this study, SAR images have been created by modifying one image with different levels of CNR (from 0 dB [decibel] to 40 dB) and different values of the coefficient of decorrelation R (from 0 to 1), which describes the similarity between two images (the higher the value of R is, the more similar the images are). In other words, we create different images starting from one single image, just by varying both the terms of amplitude (CNR) and phase (P) of the signal in accordance with a Gaussian-like probability. Parameters as CNR and R will have subscripts 1 and 2 for the two images compared, respectively.

Readers need not understand the math behind the methodologies, but should be aware that the Monte-Carlo Method (MCM) has been chosen in order to calculate the aforementioned parameters with a probabilistic approach. In particular, according to the Neyman-Pearson Criterion, P_{FA} is taken constant (Constant False Alarm Rate condition $P_{FA}=10^{-3}$) and so that P_M is minimized, thus maximising P_D.

In Bayesian statistics, the Monte-Carlo method is one of the most known and robust methods used in modelling problems that require integration over hundreds or even thousands of unknown parameters. This study is focused on coherent techniques, but includes an incoherent method as well in order to estimate the difference in performance between these two approaches. A "hybrid" incoherent-coherent technique has also been assessed.

The process used to assess the performances of all the techniques includes two different phases:

1. **P_{FA} analysis:** Provides the value of T in correspondence to $P_{FA}=10^{-3}$ when CNR and R vary.
2. **P_D analysis:** With the values of T computed in the P_{FA} analysis, the trend of P_D is calculated for the correspondent combinations of CNR and R of the second image, which are called respectively CNR_2 and R_2.

Touzi's Detector (TD)

The first technique, TD, is incoherent, which means that the decision about the presence of a change is based on the variations of the average backscattering power of the scene. This particular technique considers the ratio between the intensity of signals of the two images. This ratio is then compared with the threshold T, and the hypothesis of change is verified or not, depending on the overcoming of T. As expected, the values of T in correspondence of $P_{FA}=10^{-3}$ are higher for higher values of CNR and R.

Indeed, in these cases the noise has a smaller role than the clutter, and the two images are strongly correlated (more similar); hence it is more likely to detect a change that actually is not a change (FA).

As foreseen, values of P_D are quite low when values of P_{FA} are high, and vice versa. Also, it is normal that the performance decreases for lower values of P, since in this case images are less correlated one to each other and it will be more difficult to detect changes. Likewise, P_D

decreases when CNR decreases, because clutter will be "covered" by noise. The negative peak of performance is placed in correspondence of CNR_1=CNR_2. Therefore, TD is sensitive to the variations of power, while it is not to the variations of coherence. This means that it fits more with man-made changes, which usually imply huge variations of the power in the areas of the image where changes actually happen.

Sample Coherence Detector (SC)

This coherent technique uses the cross-correlation coefficient as the main parameter to assess the performances. It quantifies the level of resemblance of two images by describing the correlation between scenes observed at different moments in time. It is also known as "coherence", and ranges between 0 (total changes) and 1 (no changes at all). Disturbances like tyre tracks on a grass field can potentially cause the complete loss of coherence without any change in the average backscattering power of the image. For this reason, coherent techniques are more performant than incoherent ones.

Performances of SC depend on the ability in distinguishing decorrelation due to man-made disturbances and decorrelation due to other natural factors (*e.g.* rain, wind, etc). CD is strongly dependent on the level of contrast between man-made changes and other sources of decorrelation. The coherence depends on the number of pixels considered in the estimation window. The more they are, the more likely is a high contrast between man-made changes and other disturbances. While man-made changes usually cause a total decorrelation localized within few pixels of the observed scene, natural phenomena bring a high level of decorrelations spread over the whole picture.

This is particularly true when the second image refers to a moment very far in time from the first one (*e.g.* a different season of the year). As a consequence, SC is subject to high level of P_{FA}, while the amplitude of the signal is less affected by environmental phenomena. The poor performance in terms of P_{FA} can be mitigated by doing a vast operation of averaging. However, this operation decreases image resolution. In the same resolution cell there might be pixels that have been changed and others that have not; therefore, this procedure leads to a degradation of performance in terms of P_D.

Areas with no changes will be characterized by a level of coherence between 0.2 and 0.7. It will never reach the theoretical level of 1 because of the speckle, which makes every picture different from the other ones also if no change happens. Therefore, the bigger the estimation window, the lower is the P_{FA}.

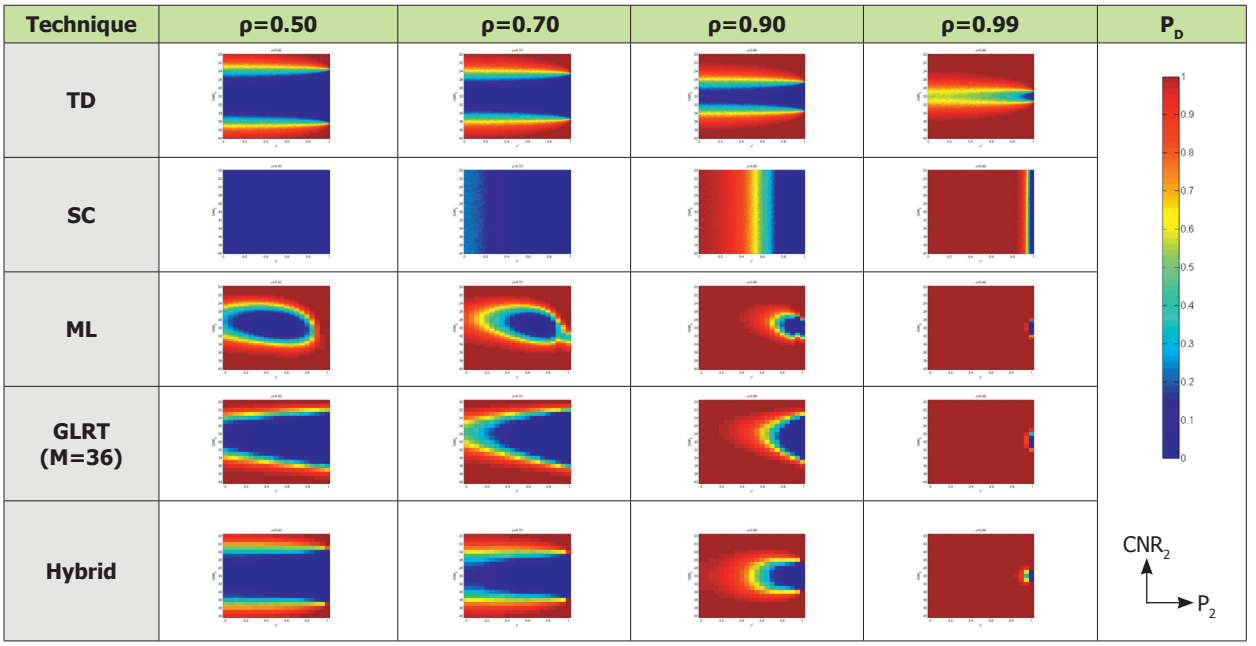
From the P_{FA} analysis, the level of T is generically higher than it was with Touzi's Detector, so for high values of P we expect a higher level of P_D. Hence, the SC detector is not sensitive to variations of power while it is to variations of coherence.

Max Likelihood Detector (ML)

This method is based on a different approach to the problem. In fact, in order to separate man-made changes from non-man-made ones, we hypothesize that some of the characteristics of the image are known. This is a strong hypothesis, so that this detector is also knows as the clairvoyant detector, and is considered the ideal/optimal method.

The P_{FA} is sensitive to the variations of the coherence, more rapidly when R and CNR have higher values. For this technique the cancellation notch is similar to a circle, and it is located in correspondence of CNR_1=CNR_2 and P_1=R_2 because for that condition the two images are more similar to each other. Performance increases as CNR and P_D increase. This method offers great performances but it assumes the knowledge a priori of some characteristics of the image, which most of the times is an unre-

BELOW: An overview of P_D performances for the different techniques. TD is sensitive to CNR variations, SC to coherence variations, while ML, GLRT and the Hybrid technique are all sensitive both to CNR and coherence variations.



alistic hypothesis, unless in-situ measurements come along with the satellite image.

Generalized Likelihood Ratio Test (GLRT)

This coherent technique can be considered an adaptive version on ML, since the parameters that were (unrealistically) considered known in ML, for this technique are computed by extracting some information directly from the images. More specifically, these values stem from the pixels around the so-called Cell-Under-Test (CUT), a section of the image which slides along the image every step, in order to estimate these parametres considering data from the entire image.

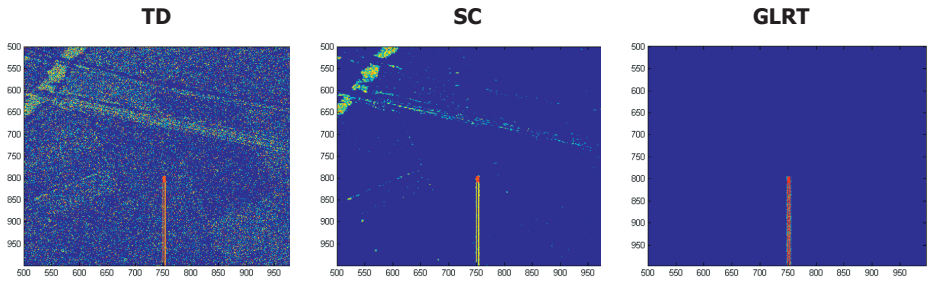
The performance of this detector changes depending on the number (M) of pixels composing the ring around the CUT. This technique has similar performance to ML: it is sensitive to both power and coherence variations, and the main losses (compared to ML) are in the area where R is bigger than P_2, an area of little interest since it is difficult to think of a change that makes the two images more correlated one to each other.

It is important to notice that the performance of GLRT asymptotically gets closer to the performances of ML as the number of pixels of the evaluation ring increases. If this number is equal to the number of the image's pixels, GLRT's performance coincides with that of ML.

Hybrid Detector (HD)

By observing the outcome in terms of PD obtained with the previous techniques, it is worth noticing that we can obtain a good performance by combining TD and SC. Even more advantageous than simply merging the best results stemming from these two techniques, is to combine them through the operation know as logical-or. In other words, the probability is calculated when the condition of TD or the condition of SC is verified. Since two different techniques contribute at the same time, for each technique should be considered $P_{FA}=0.5\cdot10^{-3}$ (half of the P_{FA} used up to now for the other techniques).

For low values of R the hybrid technique presents huge losses compared to GLRT and to ML. However, it has good performances (comparable with the ones from the other two techniques) when R assumes high values, which is actually the most interesting circumstance. In this situation, the loss in terms of performance is negligible, while the advantages are huge with respect to simplicity of coding the technique; robustness, and computational cost. Additionally, no knowledge of image's characteristics or a priori assumptions are needed.



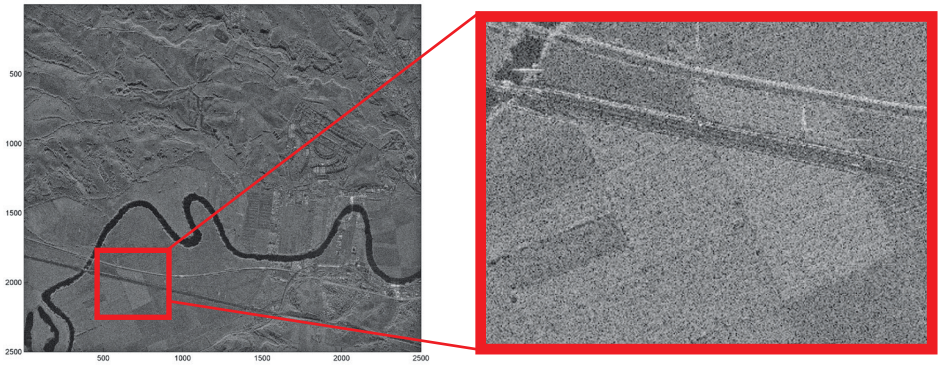
P_D tractor	P_D tyre tracks
0.7827	0.7210

P_D tractor	P_D tyre tracks
0.8025	0.5215

P_D tractor	P_D tyre tracks
0.9013	0.8203

ABOVE: Performances of TD, SC and GLRT detectors.

BELOW: Cosmo-SkyMed image with the changes introduced (tractor and tyres' tracks on the grass field).



Real Case

After this theoretical/probabilistic analysis, the more promising techniques have been applied to SAR images obtained by Italy's Cosmo-SkyMed. For this article we took into consideration a X-band (Frequency=9.6·109 Hz) image, captured by the satellite at an altitude of 627 km, having a resolution of 1 metre in one direction, 1.2 metre in the other direction. This resolution is bigger than any kind of tyre, but the techniques are equally valid if imagery with a better resolution is used. The covered area is 7,503 metres x 8,470 metres.

As we did in the previous analysis, we take the image and decorrelate it using a decorrelation coefficient (P). For this analysis we considered P=0.9 and CNR=20 dB. We consider a patch of the image, which has been taken so that it includes most of the characteristics of the entire image (*e.g.* grass fields, motorway, railway, water, etc). From the P_{FA} analysis it results that the performance is comparable to the one obtained with the simulated images. For GLRT we consider an estimation ring composed by 40 pixels, placed around the CUT and sliding along the image.

In the patch two changes have been added: an agricultural mean (*i.e.* a tractor), which is completely decorrelated with respect to the first image (R=0), and its tyre tracks on the grass field, which have a decorrelation factor of about 0.2. In the remaining parts of the image, the decorrelation is about R=0.9. Also, the value of power has decreased by 5 dB for the vehicle and by 3 dB for the tyre tracks. All these values have been taken from in situ measurements.

With TD it is possible to distinguish the changes in the image with a good P_D, even though it is an incoherent technique. The number of false alarms is negligible; also, since they

are very sparse within the image, they do not create any ambiguity. With SC the level of false alarms is lowered with respect to TD. Also, they are mostly placed in correspondence to the river, where CNR has low values. However, that area can be easily distinguished from the others, and the presence of false alarms does not compromise the general performance of the technique. The GLRT detector allows to completely remove all the false alarms. The areas close to the changes are an exception, but the value of P_D is still low (around 0.2). From this point of view, the GLTR technique offers the best performance, with average values over 0.9 for the mean and around 0.82 for the tyre tracks, 90% and 82% of probability to detect the change respectively.

In conclusion, no technique can be considered the absolute best. However, the choice depends on different factors: the nature of the target to detect (man-made or natural), the CPU available, which is a non-negligible aspect since often images have dimensions of several GB. More, all the techniques can be applied both over air- and Space-borne images.

How the NATO Joint Force Commander Benefits From the ISR Capability

While Nations are not likely to allocate a satellite to a NATO mission or exercise, they can provide a set or allocation of imagery and data in response to a request for information. NATO's primary source of ISR is the USA National Geospatial-Intelligence Agency (NGA), which uses commercial data from the DigitalGlobe satellites. NATO receives data from the NGA to the NATO Intelligence Fusion Centre (NIFC) located in the United Kingdom. With the exception of optical data provided by the USA via the NGA, NATO does not have any standing agreements related to Space-based ISR neither with governmental entities nor with commercial providers.

Within NATO member countries, the main ISR assets are reported in the table below. Italy's Cosmo-SkyMed, Germany's SAR Lupe, Canada's Radarsat II, the EU's Copernicus, and USA's national means are the most important SAR assets. CD techniques could be very useful in support of NATO operations because they can automatically or semi-automatically provide information about the movement of enemy forces, otherwise impossible to detect.

The same techniques applied in the case of tyre tracks over a grass field are equally applicable to the case of a convoy driving through a sandy zone, or even to detect the movement of groups of people on smooth surfaces (*i.e.* gravel roads, snowy fields, deserts, etc). Change Detection is only one of the many applications that can be taken as example to show how essential ISR capability is in supporting NATO operations. Through this capability, the Joint Force Commander is able to gather a wide range of information, useful for very different purposes, from military operations to humanitarian or disaster relief operations. More, by its nature, Space is the ultimate high ground. This implies that information can be collected anywhere in the world and immediately received somewhere else, thus allowing decision makers to effectively assess the situation in battlefields, natural catastrophe scenarios, and for peacekeeping as well.


Photo by HQ MARCOM

END NOTES:

1 Mainly the United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, commonly known as the UN Outer Space Treaty.

2 An orbit in which a satellite passes above or nearly above both poles of the body being orbited on each revolution, in this case the Earth.

3 This higher resolution provides the ability of distinguishing two objects in the image.

4 Area of the Earth covered with a single sight from the satellite.

5 The payload houses the mission components consisting of instruments and also the tools designed for the specific mission.

6 In general, a measure of the efficiency of a radar target in intercepting and returning radio energy. It depends upon the size, shape, aspect, and dielectric properties of the target.

7 Several additional launches are scheduled. Besides, numerous contributing missions provide complementary data.

BELOW: NATO member countries' main ISR assets.

ISR asset	Constellation	Sensor	Resolution	Data provided to NATO
SAR Lupe (DEU)	5	SAR	0.5 m	Special request
Cosmo-SkyMed (ITA)	4	SAR	<1 m	Special request
Helios (FRA, ITA, BEL, ESP, GRC)	2	EO & IR	0.4 m	Special request
Pleiades (FRA)	2	EO	0.5 m	Special request
Radarsat II (CAN)	1	SAR	0.8 m	Special request
National Means (USA)	Several	EO, IR, SAR	<1 m	Special request
Copernicus (EU/ESA)	3[7]	EO, IR, SAR	<1 m	Free / Special request