SAR Satellite Concept for Observation of Gas Transmission Pipelines

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Abstract

Gas pipeline networks are routinely monitored to protect them against damage caused by third party interference. Because of the expenses, pipeline operators in Europe are investigating the possibilities to replace traditional air and ground surveys by remote sensing from space. A preliminary analysis shows that by deploying a user network of ground stations to receive the Synthetic Aperture Radar (SAR) data of the RADARSAT-2, ALOS and TerraSAR satellites, the interval with which the pipelines are monitored and the probability to detect heavy industrial vehicles along the pipeline routes can both be improved.

1 Introduction

The great majority of pipeline faults are caused by third party interference due to, *e.g.*, cable laying, construction, or drainage activities [Mather et al., 2001]. For this reason, gas pipeline operators in Europe routinely monitor their pipeline networks to protect them against damage caused by the industrial vehicles used during these activities. At present, monitoring is done mainly by air and ground patrols along the pipeline routes [Hopkins et al., 1999, Mather et al., 2001, Zirnig et al., 2001], which is expensive and can be hazardous. The Pipeline REmote SENsing for Safety and the Environment project (PRESENSE), led by Advantica Technologies Ltd., brings together the expertise of several of the major European gas pipeline operators and space research organizations to investigate techniques and methods in order to improve safety and reduce survey costs by satellite remote sensing. Because of its capability to operate at day and night and in all weather conditions, Synthetic Aperture Radar (SAR) has been selected as one of the techniques to monitor third party interference [Zirnig et al., 2001].

According to literature, pipeline networks are monitored by traditional surveys with an interval or revisit time of typically two weeks and a detection probability of about $60 - 70\%$ [Hopkins et al., 1999, Mather et al., 2001]. One of the aims of PRESENSE is to investigate how satellite SAR can meet these requirements within a cost-effective scenario. In this paper it is proposed to deploy a user network of ground stations to receive and process the data from SAR satellites that will be launched in the near future (before 2005), *i.e.*, RADARSAT-2, ALOS and TerraSAR. The revisit times of these satellites over Europe are computed and SAR data are simulated to assess the detection probabilities that can be obtained with the various SAR modes. The analysis so far, of which results are presented in this paper, has focused on heavy industrial vehicles, *i.e.*, with a typical size of $5 - 10$ m, which form a substantial threat to the pipelines [Mather et al., 2001]. Detection of smaller vehicles is done within the current research work of PRESENSE. Preliminary results indicate that with a constellation of the above satellites, considerable cost savings can be achieved and that pipelines throughout Europe can be monitored with an interval of 5.5 days or better and a detection probability of about 80% for heavy industrial vehicles or, alternatively, with an interval of better than 10 days and a detection probability of about 95%.

2 Data simulation

To detect heavy industrial vehicles requires a SAR resolution of better than about 10 m. Table 1 lists some important orbit and SAR characteristics of future commercial satellites that can provide this resolution, *i.e.*, RADARSAT-2 in its Fine and Ultra-Fine mode, ALOS in Fine mode and TerraSAR in Stripmap mode. The ground track parameter in the second column expresses the ratio of the number of orbital revolutions nr

Table 1: Orbit and SAR characteristics of the RADARSAT-2, ALOS and TerraSAR satellites.

SAR mode	Ground track parameter nr/nd	Frequency band	Nominal resolution (m)	Swath (km)
RADARSAT-2	343/24	C		
Fine			10	50
Ultra-Fine			3	30
ALOS Fine	671/46	L	10	70
TerraSAR Stripmap	265/18	L, X	3	40

that the satellite performs before returning over the same place on earth after a satellite period of nd days. The resolutions in the fourth column are with regard to a single-look image. Note that a resolution of 3 m apparently represents the limit of commercial SAR imagery for the near future. With TerraSAR, the system consists of two satellites, one operating at X band and the other at L band. Both satellites move over the same ground track, the trailing satellite lagging the leading satellite by three days.

To assess the detection and false alarm probabilities of the SAR satellite concept, SAR images with the frequency and resolution characteristics of table 1 have to be simulated. Unfortunately, only data in X-band were available of a rural scene and of vehicles with the same backscatter characteristics as those of the heavy industrial type. Still, as a rough approximation, the backscatter σ_0 of vehicles as well as that of the background scene may be considered proportional with the square of the radar frequency [Bachman, 1982, Long, 1975, Ulaby and Dobson, 1989]. Because the aim of this paper is not to perform detailed simulations but to assess the detection statistics of the satellite concept, images in C and L band were simply derived from the simulated X-band image by a frequency scaling of the linear backscatter values.

Single-look X-band SAR images with vehicles were simulated for resolutions of 3 m and 10 m, as well as for an intermediate resolution of 5 m. The image background was created from an X-band SAR scene of 0.5 km size and 0.5 m resolution for about 10 looks (VV polarization, 60° incidence). Because of the large number of looks, this scene may be considered free of speckle so that single-look images can be created from it by pixel averaging to the required resolution and next multiplying the backscatter values in the resulting pixels by an exponential probability density function to add speckle. Vehicles were created by pixel averaging X-band images of a military armored vehicle at different aspect angles and 0.1 m resolution. The armored vehicle has a size of about 6 × 8 m, typical of heavy industrial vehicles. Ten such artificial vehicles were inserted in the background. As an example, figure 1 shows the resulting simulated X-band SAR image at a full resolution of 0.5 m, where the vehicles are labeled 1 to 10. The inlay in the top-right corner shows a magnification of the vehicle labeled 1.

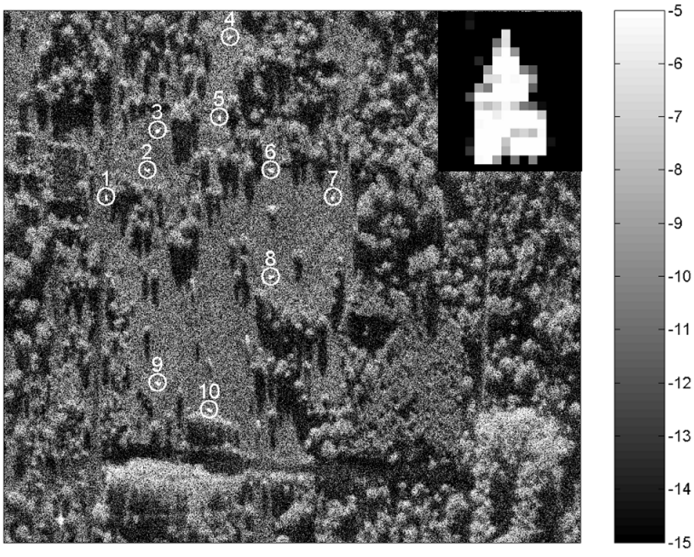

Figure 1: Simulated X-band SAR scene of 0.5 m resolution. Displayed is the backscatter σ_0 in units of decibel (dB).

3 Vehicle detection

The detection and false alarm probabilities that can be obtained with each of the SAR modes in table 1 were determined by applying a standard Constant False Alarm Rate (CFAR) detection to the simulated SAR images. With CFAR detection, the backscatter in a pixel is compared with the backscatter statistics of the surrounding background. The pixel is declared a detection if its backscatter σ_0 relative to the mean of the background's backscatter, μ_{σ_0}, exceeds a threshold of a number of times the root mean square of the background's backscatter, rms_{σ_0}:

$$\frac{\sigma_0 - \mu_{\sigma_0}}{rms_{\sigma_0}} > K \quad (1)$$

where K is the so-called CFAR constant. Background pixels that exceed the CFAR threshold will erroneously be detected as vehicles resulting in false alarms.

CFAR detection was performed on the simulated X-band SAR images of 3 m, 5 m and 10 m resolution. Because the C and L-band images were derived by a frequency scaling of the X-band images, the detection results of these images will be the same as that of the X-band image of the same resolution. Different values of the CFAR constant were specified in equation (1) and the number of vehicle pixel detections as well as the number of false alarms were counted. Dividing these numbers by the total number of vehicle and background pixels in the image, the detection probability P_D and the false alarm probability P_{FA}, respectively, are obtained. For each of the three resolutions, figure 2 shows the relation between P_D and P_{FA}, *i.e.*, the Receiver Operating Curve (ROC). Note from these curves that the smaller the CFAR constant is chosen, the more vehicles are detected but that the number of false alarms increases as well. Also note that the detection result becomes slightly worse with decreasing resolution for the larger values of the CFAR constant. This is because of the averaging of the backscatter values over the vehicle pixels, which reduces the larger backscatter values. However, the important conclusion from figure 2 is that for SAR modes with a resolution between 3 m and 10 m, a detection probability of about 80% can be obtained for heavy industrial vehicles against a false alarm probability of a few percent. This is moderately better than the detection probability of about $60 - 70\%$ of the traditional air and ground patrols.

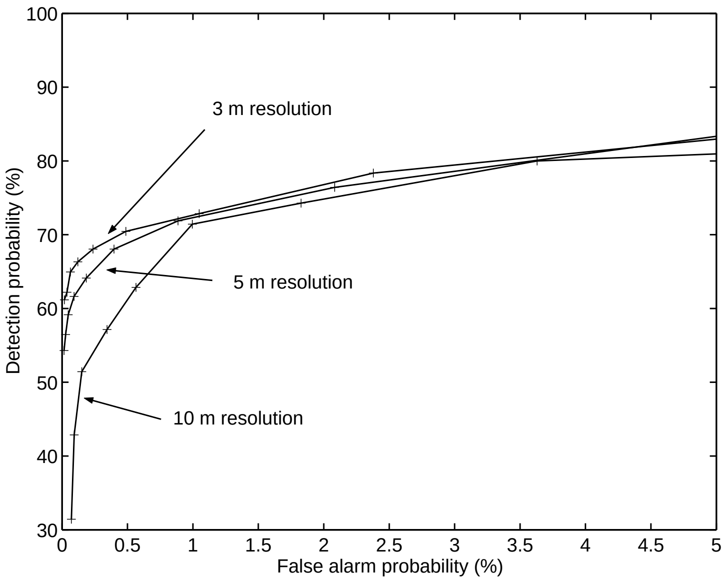

Figure 2: Receiver Operating Curves (ROCs) of CFAR algorithm for X, C, and L-band SAR images of 3 m, 5 m and 10 m resolution.

4 Satellite revisit times

It may be shown that the time interval between ground tracks on which a location on the earth's surface can be imaged is not constant. For this reason, the satellite revisit time is defined as the average of all time intervals between successive imagings computed over a long enough period. According to this definition, the satellite revisit time ΔT for a constellation of ns satellites equals the ratio of the earth's circumference at latitude ϕ and the total swath covered per day by all satellites in the constellation:

$$\Delta T(\phi) = \frac{40,000 \cos \phi}{2 \sum_{i=1}^{ns} \frac{nr_i \times swath_i}{nd_i}} \tag{2}$$

where $swath_i$ is the swath of one of the satellites. The factor two in the denominator results from imaging on northgoing and southgoing tracks. Note that because the swath is constant whereas the earth's circumference decreases with latitude, the satellite revisit time decreases accordingly.

Figure 3 shows the revisit times for three satellite constellations, *i.e.*, a constellation consisting of 10 m resolution SAR modes (RADARSAT-2 Fine and ALOS Fine), of 3 m resolution SAR modes (RADARSAT-2 Ultra-Fine and TerraSAR Stripmap), and a combination hereof (RADARSAT-2 Fine, ALOS Fine and TerraSAR Stripmap). Note that with the constellation of combined resolutions, the Fine mode of RADARSAT-2 is included. It may be shown, however, that including the Ultra-Fine mode instead gives very similar results. The conclusion from figure 3 is that the constellations of 3 m resolution and 10 m resolution modes can provide a revisit time over Europe of less than 10 days, which is competitive with the interval of about two weeks of traditional surveys. In case a constellation is formed of combined SAR modes of 3 m and 10 m resolution, the total swath is approximately twice as large as that of the other two constellations so that twice as many images are collected. As a result, a revisit time of less than 5.5 days can be obtained, which is a significant improvement over traditional survey methods. Note that such a constellation of combined SAR modes requires a more sophisticated CFAR algorithm than the pixel-based scheme used in section 3. However, modifications to the algorithm are easily made and, for instance, may consist of clustering the detected pixels and next combining the images of different resolutions for the purpose of comparison.

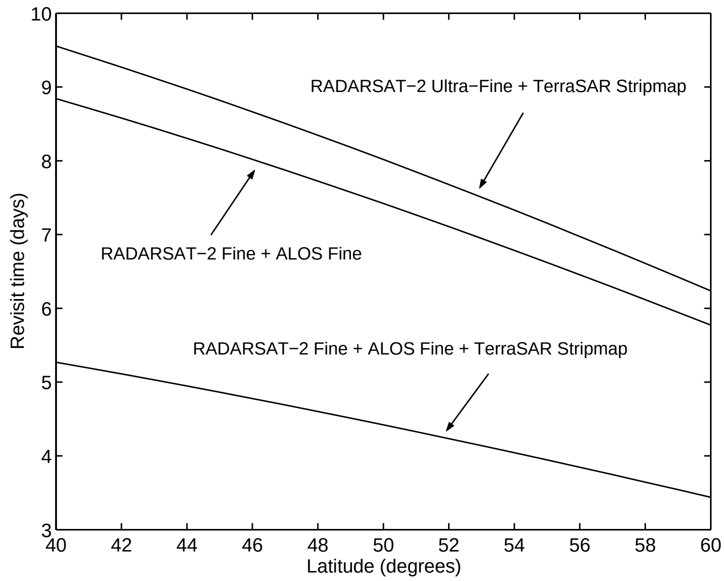

Figure 3: Satellite revisit times over Europe for a constellation of 3 m resolution modes (RADARSAT-2 Ultra-Fine + TerraSAR Stripmap), a constellation of 10 m resolution modes (RADARSAT-2 Fine + ALOS Fine) and a constellation of combined 3 m and 10 m resolution modes (RADARSAT-2 Fine + ALOS Fine + TerraSAR Stripmap).

5 Comparison of possible satellite constellations

In table 2, the three satellite constellations mentioned in section 4 are compared, *i.e.*, a constellation consisting of 3 m resolution modes, of 10 m resolution modes, and of a combination of 3 m and 10 m resolution modes. The comparison is in terms of the general pipeline monitoring requirements, revisit time and detection probability P_D. The detection probability in table 2 applies to a false alarm probability P_{FA} of a few percent, which is a typical value that can be obtained with air and ground patrols. From figure 2 and

Table 2: Revisit time and detection probability P_D of three possible satellite constellations to monitor third party interference.

	Resolution		
	3 m	10 m	3 m and 10 m
Revisit time (days)	< 9.5	< 9	< 5.5
$P_D(\%)$	80	80	80

figure 3, it can be seen that in case of the 3 m resolution constellation, the detection probability is about 80% at a false alarm probability of a few percent if pipelines are inspected once every $6 - 9.5$ days between $40° - 60°$ latitude. The same applies to the 10 m resolution constellation for one inspection every $6 - 9$ days and hence also to the combined resolution constellation for one inspection every $3.5 - 5.5$ days. Hence, the revisit time of the combined resolution constellation is about twice as small as that of the other two constellations for the same detection probability.

It is worth noting that if it is decided by the pipeline operators that a revisit time of approximately ten days is sufficient, the fact that the combined resolution constellation delivers twice as many images can be used to increase the detection probability. A pixel is declared a vehicle if it is detected either in the first image, or in the second image, or in both images. Because the ROC curves in figure 2 of 3 m resolution and 10 m resolution are the same for a false alarm probability of a few percent, the detection probability when collecting two images over ten days, $P_D^{(1,2)}$, is:

$$P_D^{(1,2)} = 2P_D - P_D^2 \tag{3}$$

Hence, with a detection probability of one image, P_D, of about 80%, the detection probability when using two images every ten days, $P_D^{(1,2)}$, is about 95%.

6 Conclusions

Compared to gas pipeline surveys with traditional air and ground patrols, constellations of the future satellites RADARSAT-2, ALOS, and TerraSAR, can shorten the revisit time and improve the detection probability of heavy industrial vehicles.

With a constellation of RADARSAT-2 and ALOS in their Fine modes, pipelines can be monitored with 10 m resolution once every $6 - 9$ days with a detection probability of about 80% at a false alarm probability of a few percent in case of heavy industrial vehicles. Combining the Ultra-Fine mode of RADARSAT-2 and the Stripmap mode of TerraSAR, the same revisit time and detection probability can be obtained but for 3 m resolution.

Most promising seems a constellation of RADARSAT-2 and ALOS in their Fine modes and TerraSAR in Stripmap mode. With this constellation, either the revisit time can be reduced by a factor two or the detection probability can be improved to about 95%.

The above results indicate that if smaller vehicles can also be detected, the SAR satellite concept may possibly provide a cost-effective alternative to replace the traditional patrols. However, this requires further research, as is currently being done within the PRESENSE project.

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