Gas pipeline monitoring in Europe by satellite SAR

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Abstract

At present, gas pipeline networks in Europe are routinely monitored by vehicle and air patrols to protect them against damage by soil movement and third part interference. Because of the expenses, pipeline operators are investigating the possibilities to replace these traditional monitoring methods by remote sensing from space. A preliminary analysis shows that considerable savings can be achieved by deploying a user network of ground stations to receive the Synthetic Aperture Radar (SAR) data of the ENVISAT, RADARSAT-2, ALOS and TerraSAR satellites.

Keywords: SAR, PRESENSE, satellite, remote sensing, pipeline monitoring.

1 Introduction

European gas pipeline operators routinely monitor their pipeline networks to protect them against damage caused by soil movement, third party interference and gas leakage. At present, monitoring is done by vehicle and air patrols along the pipeline routes, regardless of the terrain and weather conditions, which is expensive and can be hazardous. The Pipeline REmote SENsing for Safety and the Environment project (PRESENSE) 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 soil movement and third party interference. This requires a resolution of $3 - 100$ m and an interval of two weeks or less, where a resolution of 3 m likely represents the limit of commercial SAR imagery for the near future. One of the priorities is to assess how these requirements can be met without having to build a new satellite constellation. In this paper it is proposed to deploy a user network of ground stations to receive the data from recently-launched and future SAR satellites. In this regard, four satellites are being considered, *i.e.*, ENVISAT operated by the European Space Agency (ESA), RADARSAT-2 which is operated by the Canadian Space Agency (CSA), ALOS operated by the National Space Development Agency of Japan (NASDA) and the UK/German satellite pair TerraSAR operated by InfoTerra/Astrium. Preliminary results indicate that with a constellation of the above satellites, soil movement throughout Europe can be monitored with an interval of about two weeks and a resolution of $20 - 30$ m without having to deploy corner reflectors, whereas third part interference can be monitored with an interval of $6 - 10$ days and $3 - 10$ m resolution.

2 Ground surveillance with satellite SAR

Over the past decades, several methods have been developed to monitor the earth's surface with satellite SAR. Although each of these methods has its own specific applications, they all have in common that regular

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observations have to be obtained of a point on the ground. Hence, the satellite orbit is designed such that the ground track repeats itself after a period on *nd* days, the satellite repeat period. Depending on the number of ground tracks on which the location can be imaged, the interval between subsequent observations equals a fraction of the repeat period. In this section it is discussed which SAR methods can be used for pipeline monitoring and how the above-mentioned interval can be computed for each of these methods.

2.1 SAR monitoring methods

Table 1 shows some typical values of the resolution and monitoring interval that are required for protecting pipeline networks against soil movement and third party interference. Soil movement such as land slides and ground subsidence are typically monitored once every six months with a resolution of better than 100 m. Urgent situations, however, may require a status update within two weeks after request. In case of interference by third parties, most of the pipeline damage is caused by heavy industrial equipment such as farm tractors, excavators and trucks. During excavation or logging activities, damage by this equipment can be done by striking or driving over the buried pipelines. Terrain signatures of excavation and logging are monitored typically once every two weeks with a resolution of better than 30 m, whereas to detect the presense of objects like farm tractors, the resolution has to be better than 10 m. Obviously, with 10 m resolution, the number of false alarms can be relatively high. While this is certainly true in urban areas, the great majority of pipelines run through rural areas, where the number of false alarms is much less.

Table 1: Pipeline monitoring requirements and possible SAR monitoring methods.

	Soil movement	Third party interference	
		Terrain	Objects
Resolution (m)	< 100	< 30	< 10
Interval (weeks)	26 (2 at request)	2	2
Method	Repeat-track interferometry[1]	Change detection[2]	CFAR detection[3]
	Multiple-track interferometry[2]		Change detection[2]

(1) Same track, (2) northgoing and southgoing track pairs, (3) northgoing and southgoing tracks.

Measuring soil movement with SAR is done with a method called interferometry, *e.g.*, [Henderson and Lewis, 1998]. With this method, two images of the same area taken from an identical or almost identical perspective, are combined into an interferogram. For each pixel in the interferogram, the phase difference is a measure for the height change that has occurred on the ground during the time between the images, as well as for the local height itself if the images are obtained with slightly different incidence angles. The local height can be eliminated with an elevation model of the area. As shown in the left plot in figure 1, in case of repeat-track interferometry, the two images are collected from the same northgoing ground track (solid arrows with the times T_1 and T_2) or the same southgoing ground track (dashed arrows). This means that the images will have the same incidence angle which facilitates their interferometric correlation. With multiple-track interferometry, the images are collected from neighboring northgoing or neighboring southgoing ground tracks, *i.e.*, the solid and dashed arrows, respectively, with the times T_1 and T_2 in the middle plot of figure 1. The obvious advantage over repeat-track interferometry is that more tracks can be used for imaging. This results in a shorter interval between the images of the interferogram, as well as in a shorter interval between subsequent interferograms. A disadvantage is that for a cross-track distance of more than a kilometer, the images cannot be interferometrically correlated. However, this problem can be mitigated by installing a few low-cost corner reflectors along the pipeline routes in areas where soil movement has to be monitored. Soil movement in the area is then monitored from the phase differences at the corner reflectors.

Object detection can be done by directly comparing each pixel in the image against its background, which is known as CFAR (Constant False Alarm Rate) detection, *e.g.*, [Goldstein, 1973]. If the pixel value significantly stands out above the background, the pixel may be declared suspicious. More likely, however,

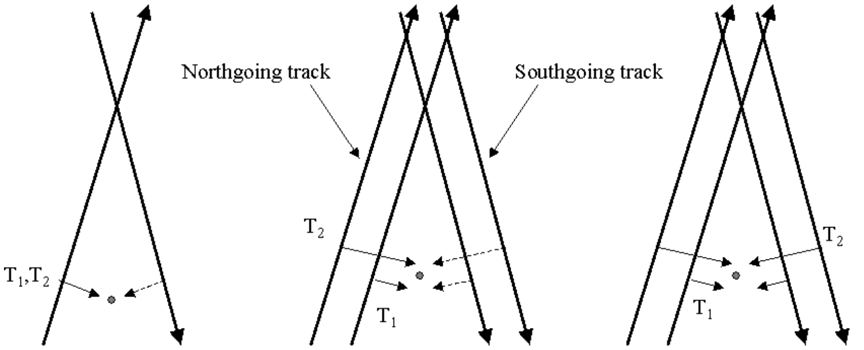

Figure 1: Ground track geometry for repeat-track interferometry (left), multiple-track interferometry and change detection (middle) and CFAR detection (right). Denoted by T_1 and T_2 are successive times that the location can be imaged.

object detection, as well as terrain mapping, will be done by comparing two co-registered images and look for changes indicating logging, excavation or vehicle activity. To reduce the number of false alarms and to ascertain third party interference, the locations of suspicious pixels as obtained from this change detection procedure may be enhanced with other information, *e.g.*, GIS (Geographic Information System), imagery from other sensors, or even the SAR image itself. Note that CFAR detection can be done from northgoing and southgoing tracks (solid arrows with the times T_1 and T_2 in the right plot in figure 1), but that change detection can only be done from neighboring tracks (similar to multiple-track interferometry), provided that the incidence angles of subsequent images do not differ too much. With a swath of about 50 km for high resolution (< 10 m) and 100 km for medium resolution (≈ 30 m), the difference in incidence angle is about 3° and 8°, respectively. Change detection of objects with 3° incidence difference is quite feasible but mapping terrain changes with 8° incidence difference is not because of a significantly different terrain backscatter [Ulaby and Dobson, 1989]. However, this can be solved by doing a landuse classification on the images and comparing the classification results instead of the images themselves.

Figure 2 and figure 3 give examples of change detection and landuse classification based on SAR imagery from PHARUS, a Dutch airborne SAR operating in C-band. In the change detection experiment, images are taken one day apart. The detected changes in the center and top-right corner of the image correspond with military vehicles. The landuse classification result has been enhanced with the SAR image itself to restore the details such as roads and parcel boundaries that are often removed by a classification procedure.

Figure 2: SAR image of military vehicles at a test range in Amersfoort, Netherlands (left and middle), and detected changes (right) in white. The images are taken one day apart with the PHARUS airborne SAR and have 3 m resolution.

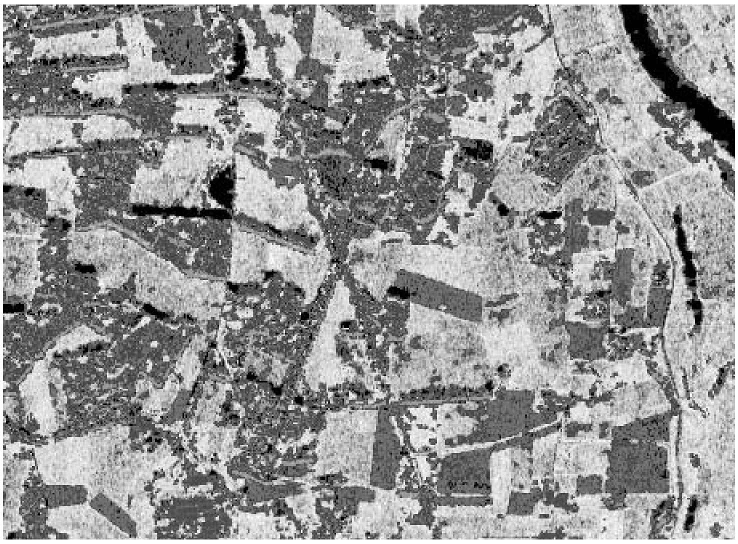

Figure 3: Landuse classification of a rural area in Heerde, Netherlands, based on a SAR image obtained with the PHARUS airborne SAR. The classification result has been enhanced with the SAR image of 3 m resolution. Black indicates water, whereas light and dark gray indicate short vegetation and forest, respectively.

2.2 Monitoring interval

For each method in table 1, the monitoring interval is defined as the time between two successive observations made with that method. In case of CFAR detection, an observation corresponds with a SAR image of the area so that the monitoring interval is the time between subsequent images. With change detection and interferometry, however, an observation consists of an image pair. Consequently, in case of these methods, the monitoring interval is the time between subsequent image pairs.

Because the time interval between ground tracks on which the location can be imaged is not constant, neither is the monitoring interval. For this reason, it is convenient to define the monitoring interval as the average of all monitoring intervals computed over a long enough period. According to this definition, the monitoring interval ΔT for a constellation of ns satellites in case of repeat-track interferometry is the reciprocal of the total number of tracks per day on which the location can be imaged, *i.e.*:

$$\Delta T = \frac{1}{2\sum\limits_{i=1}^{ns} \frac{1}{nd_i}} \tag{1}$$

In the above equation, nd_i is the repeat period of one of the satellites in the constellation. The factor two arises because interferograms can be obtained on northgoing and southgoing tracks. Note that because interferograms are obtained on exactly the same track, the monitoring interval is the same for all latitudes. In case of multiple-track interferometry, and CFAR and change detection, the monitoring interval as defined above equals the ratio of the earth's circumference at latitude ϕ and the total swath covered per day by all satellites in the constellation:

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

where nr_i and $swath_i$ are the number of orbital revolutions in a repeat period and the swath, respectively, of one of the satellites. Note that because the swath is constant whereas the earth's circumference decreases with latitude, the monitoring interval decreases accordingly. The factor two again results from imaging on northgoing and southgoing tracks. The ratio $\frac{nr}{nd}$ is called the ground track parameter and equals approximately 14 for SAR satellites at typical altitudes of $600 - 1000$ km.

3 Possible scenarios for pipeline monitoring

Assuming that gas pipelines are inspected once every two weeks by traditional surveillance methods, the costs associated with these surveillance activities for the whole of Europe (longitude λ between $-10°$ and $30°$, latitude ϕ between $40°$ and $60°$) are estimated at about \$15 million per year. If the pipeline network is to be monitored from space by SAR with a resolution of $3 - 100$ m, figure 4 shows the number of satellites that are required to achieve a monitoring interval (1) and (2) of two weeks or less. For a resolution of 100 m and 30 m, one satellite is required for a monitoring interval of two weeks. For the same monitoring interval but a higher resolution of 10 m and 3 m, respectively, two and three satellites are needed. The costs for the design, building, launch and five years of operations of a small dedicated SAR satellite are estimated at approximately \$100 million, *i.e.*, \$20 million per year. Hence, to monitor transmission pipelines throughout Europe by a newly-built SAR satellite system with an observation interval of two weeks will cost between $\$20 - 60$ million per year, depending on the required resolution.

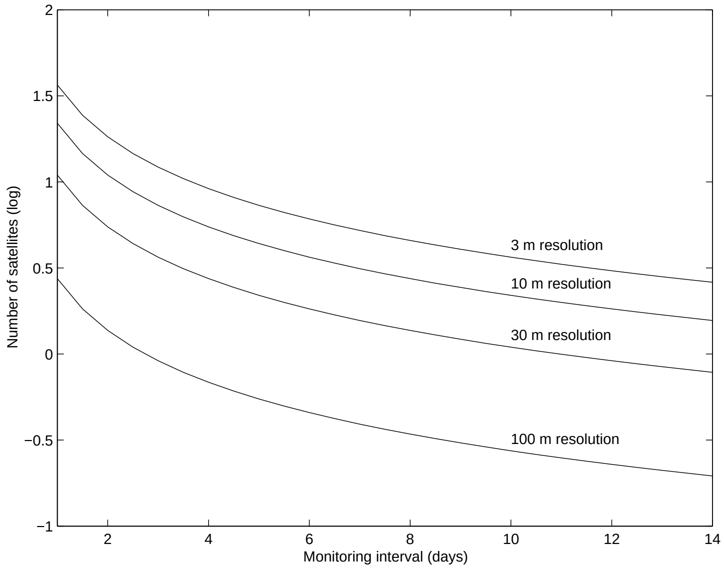

Figure 4: Number of satellites to achieve a required monitoring interval over Europe for different resolutions. It is assumed that a resolution of 3, 10, 30 and 100 m corresponds with a swath of 30, 50, 100 and 400 km, respectively, and that imaging is done on northgoing and southgoing tracks. Note that the number of satellites is given on a log scale.

An interesting alternative for building a satellite system will be offered in the near future by the simultaneous operation of the ENVISAT, RADARSAT-2, ALOS and TerraSAR satellites. The SAR imagery of these satellites will be made available either by direct order of the images from the responsible distributor or by receiving the raw satellite SAR data with a user network of ground stations.

According to the exploitation policies for ENVISAT and RADARSAT-2 [Kohlhammer, 2001], the commercial price for a SAR image of 30 × 30 km (3 m resolution) or 100 × 100 km (30 m resolution) is about $\$1500 - 3000$. The area of Europe that has to be covered measures approximately 6,000,000 km^2, which requires 600 images of 30 m resolution or 6600 images of 3 m resolution. Assuming an average price of \$2000 per image and a monitoring interval of two weeks, the costs for imaging Europe with 30 m and 3 m resolution are, respectively, about \$30 million and \$340 million per year, which by far exceeds the costs of traditional surveillance methods.

On the other hand, by receiving the SAR data with a user network of ground station, about eight stations are required to monitor Europe, assuming each station has a coverage area of 1000 km in diameter. A typical ground station with SAR processing capability costs about \$0.5 million. With a lifetime of $5 - 10$ years, the costs of the ground station network are perhaps $\$2 - 3$ million per year, including operations. Additional costs are associated with licenses with the responsible space agencies and for programming the satellite. In case of ENVISAT, a fee of about \$15 per image has to be paid. Assuming this price is representative for future satellites, the total fee for imaging Europe with 3 m resolution and a two week interval is about \$2.5 million per year. Hence, the overall costs of the ground station scenario can be estimated at $\$5 - 6$ million per year.

From the above discussion it seems that if traditional surveillance methods are to be replaced by satellite SAR, cost savings can only be achieved by deploying a ground station network to receive and process the raw SAR data. In the next section, therefore, several constellations will be discussed of satellites of which the data can be received by user ground stations.

4 Suitable satellite constellations

In this section, the possibilities of several satellites for pipeline monitoring are investigated, either in a single-satellite or in a multi-satellite constellation. For each SAR mode, the monitoring interval is computed for interferometry and for CFAR and change detection. Whether these monitoring intervals can be attained depends on the data agreements that can be negotiated with the space agencies that operate the satellites. Likely, not all satellite passes over Europe will be assigned to monitoring of the pipeline networks. However, provided these data gaps are sparse, they can be filled by other sensors, *e.g.*, by the traditional air patrols.

4.1 Investigated satellites

In table 2, the most important orbit and SAR characteristics are listed of the satellites investigated in this paper. All satellites in table 2 are commercial and have been or will be launched between 2002 and 2005. With expected lifetimes of $5 - 10$ years, this means that the full satellite constellation will be operational in the second half of this decade. 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. Note that table 2 only lists the SAR modes with a resolution of 100 m or better and a large enough swath to provide complete coverage over Europe, either in a single-satellite or multi-satellite scenario. Also note that in case of the medium (≈ 30 m) and high-resolution (< 10 m) modes, the satellites can position their beams within a total swath of about $400 - 500$ km and $15^\circ - 50^\circ$ incidence angle. Details about the satellites can be found on various sites on the internet (*e.g.*, http://god.tksc.nasda.go.jp, http://envisat.esa.it,http://www.space.gc.ca and http://www.infoterra-global.com).

4.2 Satellite constellations

In case of repeat-track interferometry, the monitoring interval of each SAR mode in table 2 equals half the repeat period as can be easily seen from (1). For multiple-track interferometry and CFAR and change detection, figure 5 shows the monitoring interval as computed with (2) as a function of latitude for all the SAR modes in table 2. Note that in case of TerraSAR, the monitoring interval applies to each one satellite of the tandem pair. Regarding the low-resolution modes (ENVISAT Wide Swath, RADARSAT-2 ScanSAR Wide and ALOS ScanSAR), figure 5 shows that a monitoring interval can be obtained over Europe of $2 - 3$ days at mid-latitudes and $1 - 2$ days at higher latitudes. In case of the medium-resolution modes (ENVISAT Image, RADARSAT-2 Standard and TerraSAR ScanSAR), the swath of the TerraSAR ScanSAR mode being twice as large as that of the other two SAR modes results in a monitoring interval twice as small. Hence, a monitoring interval is found of about 5 days at mid-latitudes and 3 days at higher latitudes for TerraSAR

Table 2: Orbit and SAR characteristics of the investigated satellites.

SAR mode	Ground track parameter	Frequency band	Nominal resolution (m)	Swath (km)
ENVISAT	501/35	C		
Wide Swath			100	400
Image			20	100
RADARSAT-2	343/24	C		
ScanSAR Wide			100	500
Standard			30	100
Fine			10	50
Ultra-Fine			3	30
ALOS	671/46	L		
ScanSAR			100	350
Fine			10	70
TerraSAR	265/18	L, X		
ScanSAR			30	200
Stripmap			3	40

ScanSAR. For the other two modes, these monitoring intervals are 10 days and 7 days, respectively. With the high-resolution modes (RADARSAT-2 Fine/Ultra Fine, ALOS Fine and TerraSAR Stripmap), figure 5 shows that only ALOS' Fine mode can provide complete coverage over Europe because of its relatively large swath and small ground track spacing. With RADARSAT-2 Fine/Ultra-Fine and TerraSAR Stripmap, the dashed lines in the plots of figure 5 correspond with half the repeat periods of these satellites. As can be easily shown, the ratio of the repeat period and the monitoring interval at latitude ϕ computed for imaging on neighboring tracks, *i.e.*, all tracks are either northgoing or southgoing, gives the coverage (as a percentage) at that latitude. Because figure 5 is computed for imaging on northgoing and southgoing tracks, latitudes in this figure at which the monitoring interval is larger than half the repeat period suffer from incomplete coverage. In case of RADARSAT-2 Fine/Ultra-Fine and TerraSAR Stripmap this means that nowhere over Europe complete coverage can be obtained

Table 3 gives a summary of the ability of each of the SAR modes for monitoring soil movement, and for terrain mapping and object detection. Whether a SAR mode is suited depends on the required resolution and monitoring interval (table 1) and whether or not complete coverage can be obtained over Europe. If all these three requirements are fulfilled, a " + " is entered in table 3. If not, a " − " is entered, as well as the reason why, *i.e.*, a monitoring interval that exceeds two weeks or an incomplete coverage. In case of no entry, the resolution of the SAR mode is insufficient according to table 1.

With repeat-track interferometry, only the repeat periods of RADARSAT-2 and TerraSAR are small enough to provide interferograms with an interval of 2 weeks or less, while their ScanSAR and Standard modes provide complete coverage with the required resolution.

In case of multiple-track interferometry, as well as with CFAR and change detection, most SAR modes of sufficient resolution have a monitoring interval of two weeks or less, except for RADARSAT-2 Fine/Ultra-Fine and TerraSAR Stripmap. Moreover, with these SAR modes, the coverage over Europe is incomplete.

Table 3 shows that ALOS' Fine mode is the only SAR mode that can provide terrain mapping, object detection and interferometry with a monitoring interval of less than two weeks on a single satellite (see also figure 5). However, monitoring gas pipelines by ALOS' Fine mode requires that corner reflectors are deployed. There are several possibilities to mitigate this problem as well as to improve ALOS' monitoring interval by combining satellites into a multi-satellite constellation. With these constellations, the SAR modes

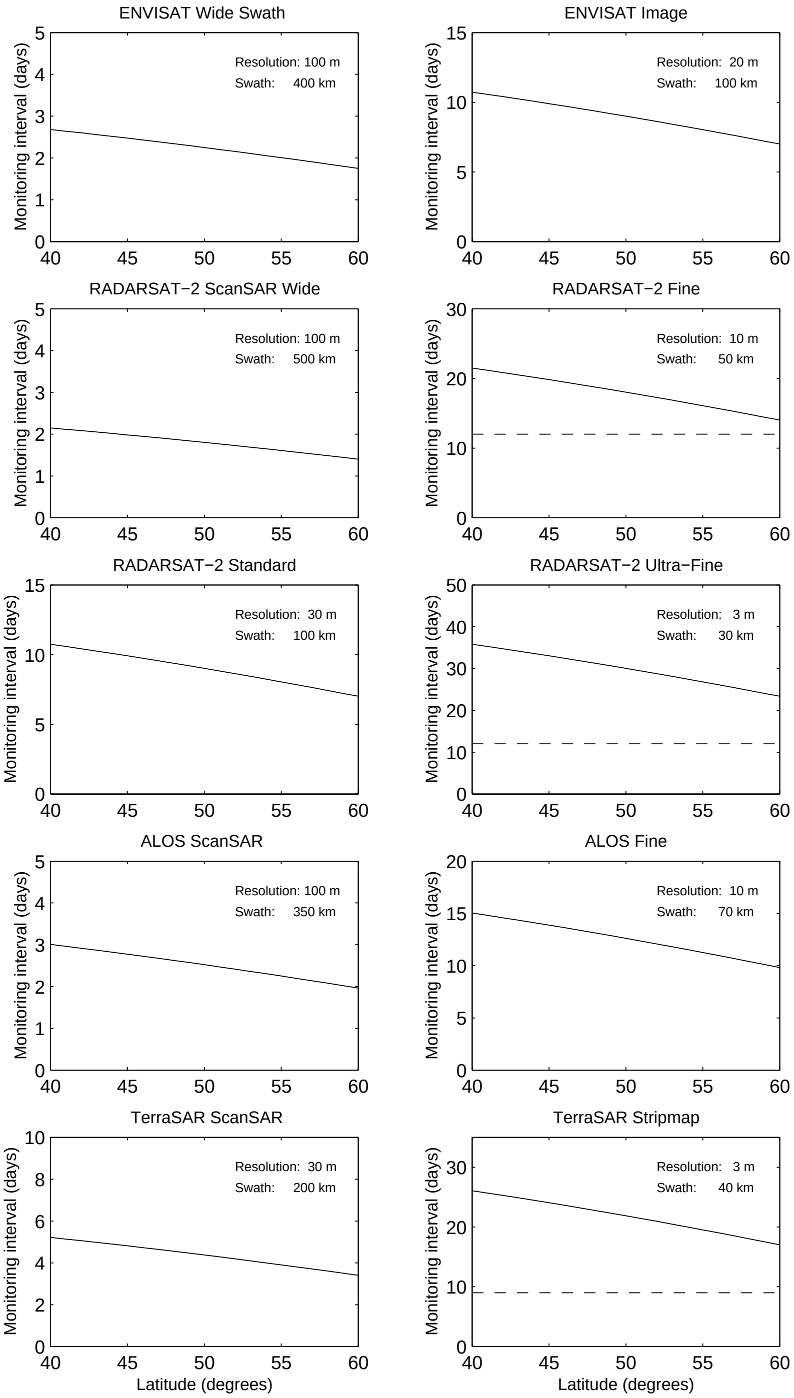

Figure 5: Single-satellite monitoring intervals over Europe. The dashed lines in the plots for RADARSAT-2 Fine/Ultra-Fine and TerraSAR Stripmap mode correspond with half the repeat periods of these satellites.

Table 3: Ability of the selected SAR modes for monitoring soil movement by interferometry, terrain by change detection and objects by CFAR and change detection.

SAR mode	Soil movement		Terrain	Objects
	Repeat-track int.	Multiple-track int.	Change det.	CFAR/change det.
ENVISAT				
Wide Swath	$-^{1}$	$+$		
Image	$-^{1}$	$+$	$+$	
RADARSAT-2				
ScanSAR Wide	$+$	$+$		
Standard	$+$	$+$	$+$	
Fine	$-^{2}$	$-^{2}$	$-^{2}$	$-^{2}$
Ultra-Fine	$-^{2}$	$-^{2}$	$-^{2}$	$-^{2}$
ALOS				
ScanSAR	$-^{1}$	$+$		
Fine	$-^{1}$	$+$	$+$	$+$
TerraSAR				
ScanSAR	$+$	$+$	$+$	
Stripmap	$-^{2}$	$-^{2}$	$-^{2}$	$-^{2}$

(1) Monitoring interval exceeds 2 weeks, (2) incomplete coverage.

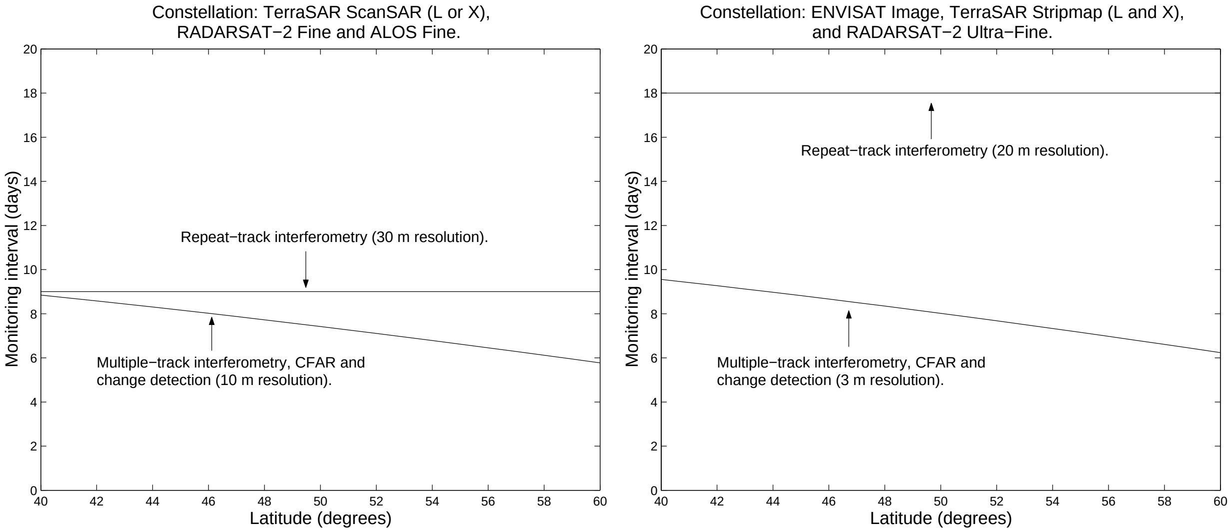

Figure 6: Multi-satellite monitoring interval over Europe for two satellite constellations that can be used for pipeline monitoring.

that can be combined are mainly dictated by the detection of objects with the change detection procedure, which requires that both images must have the same resolution. With regard to the frequency band, it should be possible to perform change detection on hard targets from a mixture of, *e.g.*, L band and C or X band images. However,whether the number of false alarms due to the differences in terrain backscatter for different bands remains acceptable requires further study.

For instance, with a constellation of one of the TerraSAR satellites in ScanSAR mode together with RADARSAT-2 and ALOS in Fine mode, the left plot in figure 6 shows that it is possible to do repeat-track interferometry with a monitoring interval of 9 days and a resolution of 30 m (TerraSAR), and to perform CFAR and change detection with an interval of $6 - 9$ days and 10 m resolution (RADARSAT-2 and ALOS). If the monitoring interval for repeat-track interferometry of two weeks could be slightly eased to 18 days, another feasible constellation would consist of ENVISAT's Image mode, the two TerraSAR satellites in Stripmap mode and RADARSAT-2 in Ultra-Fine mode. With this constellation, ENVISAT would be used for repeat-track interferometry with 20 m resolution, whereas the other modes will enable CFAR and change detection with 3 m resolution and a monitoring interval of $6 - 10$ days (figure 6). Note, however, that because the TerraSAR satellites move over exactly the same ground track, the coverage of this constellation at mid-latitudes may not be complete. What part of Europe can be covered depends on the phasing of the TerraSAR and RADARSAT-2 ground tracks over Europe, which will have to follow from a ground track simulation and coverage analysis.

5 Conclusions

From a preliminary cost comparison it seems that considerable saving can be achieved if traditional methods for monitoring gas pipelines are replaced by satellite SAR. With a user network of about eight ground stations, the raw satellite SAR data of the recently-launched or future satellites ENVISAT, RADARSAT-2, ALOS and TerraSAR can be received throughout the whole of Europe.

Two constellations of these satellites seem promising for monitoring soil movement, and for terrain mapping and object detection. The first constellation consists of one TerraSAR satellite in medium-resolution mode (30 m), and RADARSAT-2 and ALOS in high-resolution mode (10 m). With this constellation it is possible to obtain interferograms on repeated passes with an observation interval of 9 days and 30 m resolution and to map terrain changes and perform object detection with an interval of $6 - 9$ days and 10 m resolution. In a second constellation, both TerraSAR satellites are used together with RADARSAT-2 in their high-resolution modes (3 m), augmented with the medium-resolution mode (20 m) of ENVISAT. With this constellation, repeat-track interferometry can be done with an interval of 18 days whereas terrain mapping and object detection can be performed with $6 - 10$ days. However, because the TerraSAR satellites move over the same ground track, this constellation may probably not provide complete coverage at mid-latitudes. As the coverage depends on the phasing of the satellite ground tracks over Europe, a coverage analysis is required to assess the performance of this constellation.

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