SIMULATION AND OPTIMISATION OF AN OF OPTICAL REMOTE SENSING SYSTEM FOR MONITORING THE EUROPEAN GAS PIPELINE NETWORK

M. van Persie, A. van der Kamp, T. Algra

National Aerospace Laboratory NLR, The Netherlands

Theme 20: Application of high resolution data

KEY WORDS: monitoring, pipelines, hazards, high resolution, weather, simulation, performance

ABSTRACT:

In Europe an extensive network of high-pressure gas pipelines exists, which needs to be monitored frequently in order to guarantee the safety. Currently two weekly monitoring takes place by foot, vehicle or helicopter in order to detect third party interference activities like digging. In the PRESENSE project a remote sensing based monitoring system is studied, based on both spaceborne and airborne systems, different types of SAR and optical sensors, automatic processing techniques and a pipeline information management system.

In order to investigate the effectiveness of a high resolution optical satellite configuration as part of the monitoring system simulations have been made with the CLIMAS simulator, especially in relation to the extended linear network, the influence of clouds and season. With this simulator a trade off is studied between platform, orbit, sensor and cloud based satellite tasking variables, given the layout of the pipeline network, and a database of realistic cloud coverage and sunlight conditions.

Results show that a high resolution optical satellite configuration can only fill in a part of the information requirement for monitoring of the European pipeline network. With a constellation of 4 satellites 30% of the monitoring capacity can be covered., From the distribution of the observations network trajectories less suited for satellite observation can be identified. These can be monitored more effectively by other means like aircraft or SAR satellites. Another conclusion is that by using actual cloud information for the satellite scheduling the effectiveness of the optical satellite constellation can be increased by about 100%. In the last part of the study further simulations will be carried out with larger constellations, with combinations with SAR satellites and airborne platforms (manned and UAV's), and with higher monitoring frequencies.

1. EUROPEAN GAS PIPELINE NETWORK

For the transmission of natural gas through Europe an underground network of high-pressure pipelines (15-85bar) with a length of roughly 200.000km exists. In order to guarantee the safety of this network a range of safety monitoring techniques are applied, including regular foot and vehicle patrols along the pipeline route and two-weekly aerial surveillance using helicopters.

The monitoring activities have to be carried out for all kind of areas, at regular intervals throughout the year and largely regardless of weather conditions. These patrols concentrate on the detection of third party interference, ground movements and gas leakage. They prevent developments and events, which could place at risk high-pressure pipelines, the surroundings of pipelines or the security of supplies. Although the conventional methods ensure a high level of safety in pipeline operation, the cost is also very high.

2. PRESENSE FEASIBILITY STUDY

Within the EU 5th Framework project 'Pipeline Remote Sensing for Safety and the Environment' (PRESENSE) a feasibility study is carried out to develop and integrate the elements of a monitoring system that is based on remote sensing data (Pride, 2004). Objective is to improve safety, reduce survey costs and improve transmission efficiency through an increased monitoring frequency. An initial developed system concept has been developed (Persie, 2003) and is shown in figure-1.

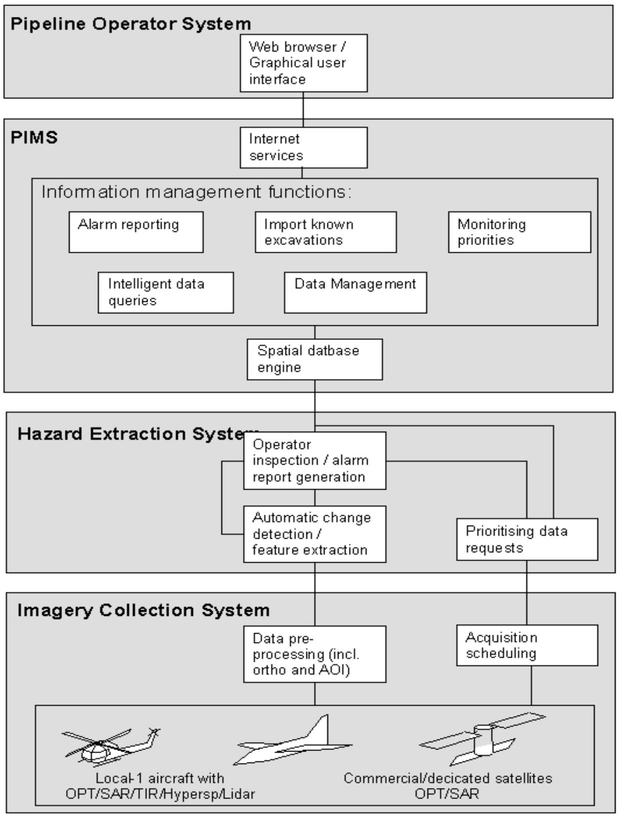


Figure-1: PRESENSE system concept

The pipeline monitoring system is structured into four main system components:

1. The Pipeline Operator System (POS), which is the part of the monitoring system which is used by the pipeline operator for delivery and handling of alarms and for specifying the monitoring characteristics for different parts of the pipeline network.
2. The Pipeline Information Management System (PIMS), which stores all relevant information on the pipeline network, the environment around it, and the integrity monitoring and which provides analyses and scheduling functionalities for the pipeline operator. The PIMS also includes an alarm production system, which decides what hazards should be considered as alarms.
3. The Hazard Extraction System (HES), which extracts the hazard report information out of the basic remote sensing imagery layers, using advanced image interpretation techniques.
4. The Imagery Collection System (ICS), which collects the required remote sensing imagery with a suit of both spaceborne and airborne platforms and different types of sensors, conform the monitoring priorities. In the ICS all these means are scheduled optimally conform the specified priorities of the pipeline operators and the weather and season conditions. Here also the data are pre-processed to remote sensing basic imagery layers.

The four components in principle can be independent of each other so that maximal flexibility exists. Also each system component in itself is set up as much as possible in a modular and flexible way. By doing this, new technologies on sensors, platforms, data processing, data storage and transfer can be integrated and the system easily can be extended to other operators or areas.

3. HIGH RESOLUTION OPTICAL SATELLITE OBSERVATION

This required flexibility also holds for the Information Collection System. Given the high costs of the imagery collection part, optimisation is essential for the overall feasibility of the pipeline monitoring system.
Clear is that the ICS will be a hybrid system consisting of different type of sensors and platforms (both commercial available services and/or own operated dedicated systems) complementing each other for different areas (network density, cloud coverage and light conditions in northern regions) and different conditions (cloud coverage, snow and vegetation coverage etc.). The required flexibility of the imagery collection is also related to the flexibility of the Hazard Extraction System to combine different types of imagery layers in the extraction process, see also (Dekker, 2004)

In the Information Collection System optical satellites will play an essential role given the high spatial resolution and good interpretation capabilities. Limitation of optical systems however is the dependence on weather conditions, especially cloud cover. Therefore in this study special attention is given to the capacity and effectiveness of the high resolution optical satellite component of the ICS.

Within PRESENSE the National Aerospace Laboratory NLR performs a study to the optimisation of the high-resolution optical satellite constellation as part of the data acquisition system. The extent and effectiveness of a constellation of optical satellites is analysed and simulated in relation to the orbit configuration, the sensor/platform capabilities (swath, pointing), the form of the network, light/season conditions and the relation with the other sensors and platforms. Special attention is given to minimise the negative impact of cloud cover on the effectiveness of the system by using the pointing capability of the system to actively select cloud-free areas in combination with intelligent tasking based on actual cloud information.

4. CLIMAS SIMULATOR

For the analyses the Cloud Impact and Avoidance Simulator (CLIMAS), as in development at NLR, is used to support the analyses (Algra, 2004). An overview of the CLIMAS simulator is shown in figure-2.

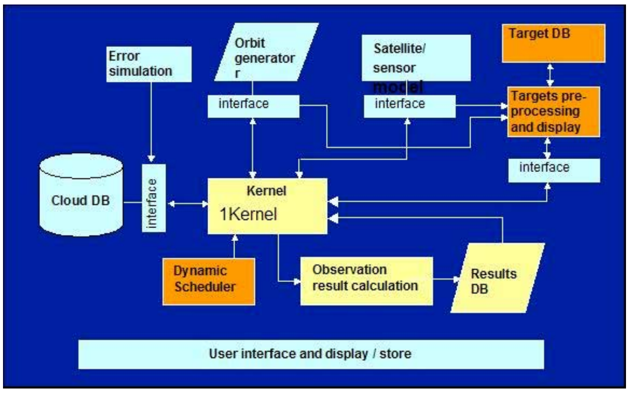


Figure-2: CLIMAS architecture

Various types of missions can be simulated, including constellations, with and without cloud avoidance scheduling. Satellite orbit parameters and instrument parameters can freely be chosen. Target area information can be imported from a GeoTIFF file, or from XML-format file in which target areas are described and observation priorities can be specified. Other major simulation input parameters are the maximum accepted cloud percentage in a target area and the minimal required solar elevation. As a result of a simulation run, CLIMAS generates a data file with for all targets the times of imaging request and the actual time(s) of capturing. CLIMAS supports statistical analysis of this information: e.g. average delivery time, effective revisit time, distribution of delivery times, number of targets successfully recorded per month, etc. CLIMAS uses the global CHANCES cloud database which is derived from real satellite data with high spatial and temporal resolution. The spatial resolution is 5x5km and the temporal resolution is one hour (Haar, 1995).

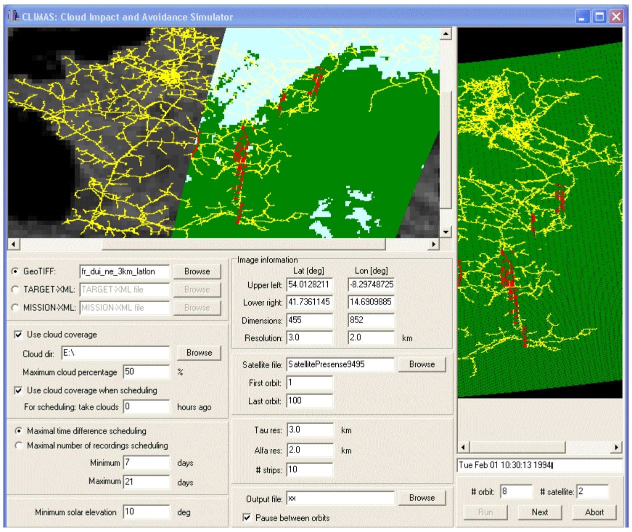
Different types of satellite tasking strategies can be implemented for simulation. The simulator allows the user to define target areas in any Area Of Interest (AOI). For each pass over the Area Of Interest the area is divided into rectangular sub-areas called strips, with a width equal to the swath of the optical sensor. The length in along-track direction is an independent input parameter. Basically, with two-dimensional pointing, after each strip any other strip in the AOI can be imaged. However, the order and number of imaged strips are limited by a set of constraints such as slew time, across track and along track pointing capabilities, the simulated time dependent satellite position, and the locations of candidate strips within the AOI.
Whether a strip is put on the task schedule depends on the number of target area elements it contains, the priority and

history of the elements, and the expected cloud cover situation for them. Different formulas for computation of the weight factor can be specified. If Cloud Avoidance Scheduling is enabled, then target elements with predicted cloud cover are not taken into account.

The scheduler starts with the selection of the strip with the highest priority that does not violate the imaging constraints. Subsequently strips with the next highest priority are selected, etc. Note that during the selection process the imaging constraints are becoming stricter due to the increasing amount of time needed for imaging and slewing to already selected strips. Although this procedure does not necessarily result in the most optimal selection, it leads to a rather efficient task list. Especially the adoption of a fixed strip length is not optimal. However the simulator can easily be extended with alternative scheduling algorithms due to its modular architecture.

The capturing of a target element is recorded to be successful if the element appears to be not cloud covered at the acquisition moment. Of each element, the co-ordinates, the imaging times and the imaging results are stored in the observation results database.

In figure-3 an overview of the graphical user interface of the CLIMAS simulator is shown.



● GeoTIFF: fr_dui_ne_3km_latlon
○ TARGET-XML: TARGET-XML file
○ MISSION-XML: MISSION-XML file

☑ Use cloud coverage
Cloud dir: E:\
Maximum cloud percentage 50 %
☑ Use cloud coverage when scheduling
For scheduling: take clouds 0 hours ago

● Maximal time difference scheduling
○ Maximal number of recordings scheduling
Minimum 7 days
Maximum 21 days

Minimum solar elevation 10 deg

Image information

	Lat [deg]	Lon [deg]	
Upper left:	54.0128211	-8.29748725	
Lower right:	41.7361145	14.6909885	
Dimensions:	455	852	
Resolution:	3.0	2.0	km

Satellite file: SatellitePresense9495
First orbit: 1
Last orbit: 100

Tau res: 3.0 km
Alfa res: 2.0 km
strips: 10

Output file: xx
☑ Pause between orbits

Tue Feb 01 10:30:13 1994

orbit: 8 # satellite: 2

Figure-3: Overview of the CLIMAS GUI

5. SIMULATION RESULTS

Simulations have been made for several satellite configurations with varying number of platforms and sensor parameters. First the simulation of a defined ‘standard’ satellite configuration is discussed, after which the effects of variations of several of the parameters are described.

The features of the standard satellite configuration are described in table-1. In general this configuration consists of 4 high resolution optical satellites as currently operational. The area for which the simulations are made covers 3400x2150km of the European continent. The simulation is run on a grid of 2x3km elements (1700x750=1.275.000 pixels).

First an ideal situation is simulated in which no constraints due to cloud coverage or minimum sun elevation are taken into account. A scheduling strategy is applied for monitoring of the network with a frequency of 14 days. This is filled in by weighting the pipeline elements with factor 0 to 7, depending on the number of days since the last observation (minus 7 days and with a maximum of 14 days).

Table-1: Used ‘standard’ satellite constellation parameters

Parameter	**Value**
Platforms	
Nr satellites	4
Altitude	500 km
Inclination	97.3785 degrees
Orbits/day	15.225
Ascending node crossing time	94013 12:23:00.0 (sat 1)
Ascending node crossing longitude	0.0 (sat 1)
Track direction	descending
Agility:	
Max pointing angle along track	33 degrees
Max pointing angle across track	33 degrees
Slew speed	2.0 degrees/sec
Stabilization time	2.0 sec
Scheduling:	
Nr of sub-strips	10
Monitoring frequency: 14 days	14 days
Tasking parameters LSETmin, LSETmax	7, 14
Observation strategy	max monitoring days
Sensor:	
FOV: 10km	1.4 degrees (10km)
Atmosphere conditions:	
Cloud period	1994/1995
Use of cloud information for scheduling	yes
Cloud info time delay	0 hours
Use of cloud information for collection	yes
Sunlight elevation constraint	> 15 degrees

The simulation resulted in the observation of 932.209 network elements, or 36.3 times the network. The total area of all these network element observations is 9.7% of the maximal system observation capacity. This means that the inefficiency due to the line structure of the network is more than 90%.

In a next step the constraints of sun elevation and clouds are introduced. The results of the simulations are shown in table-2.

Table-2: Simulation results for basic cases

	observations total		observ. 7-14 days		monitoring days	
	number	times	number	times	number	% full
case	elements	network	elements	network		monit.
No clouds, sun>0	932.209	36.3	607.521	23.7	5.346.013	57.0%
No clouds, sun>15	911.206	35.5	589.409	22.9	5.183.592	55.3%
Clouds, sun>15	582.860	22,7	274.909	10,7	2.717.495	29.0%

For describing the effectiveness of the observation system several parameters have been defined, as shown in table-2. First one can look at the total number of observed elements. This number is shown in the first column, with next to it the times the network can be covered by this number of elements. Not all observations are relevant however, for the required two weekly monitoring frequency only the observations taken after 7 to 14 days after the last observation of the element are taken into account. The number of these relevant observations is listed in the second column, also accompanied with the times the network can be covered by this. A factor of 26 times the network covered by relevant observations does not mean that 100% monitoring takes place however, because many of the observations does not take place after 14 days, but after a shorter period of up to 7 days. Therefor a third parameter is defined: the number of monitoring days. This means the sum of each relevant observation multiplied by the number of days after the last observation of this element. In fact the last parameter most correctly denotes the effectiveness of the system.

From the table it can be seen that about 30 – 50% of the observations done are not relevant, not within 7-14 days after the last observation. Further that the influence of the sun elevation constraint of 15 degrees is very limited for the total system effectiveness. It locally may have large impacts however for the northern regions. The influence of the cloud conditions above Europe is significant, as may be expected. The monitoring capacity is reduced from 55.3 to 29.0%. In general this means that with the defined constellation of 4 high resolution satellites only 29% of the European gas pipeline network can be monitored!

In figure-4 an overview is given of the monitoring period of each observation (the number of days passed after the last observation). The scheduling algorithm targets at a monitoring period between 7 and 14 days. The dip at 9 days is caused by the orbit pattern. By investigating more advanced scheduling algorithms possibly a some higher effectiveness can be obtained.

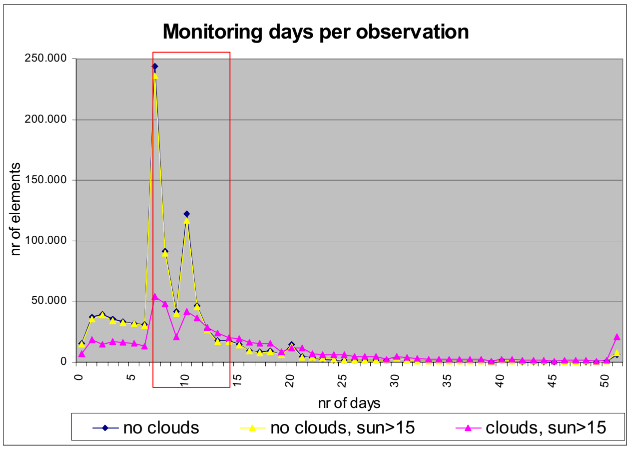


Figure-4: Distribution of monitoring period per observation

In order to get an impression of the spatial distribution of this monitoring capacity in figure-5 an overview is given of the number of days that each element is not monitored during the year, this means all days extending the 14 day monitoring periods. It can be seen that dense network areas and network trajectories in the north-south track direction are monitored best.

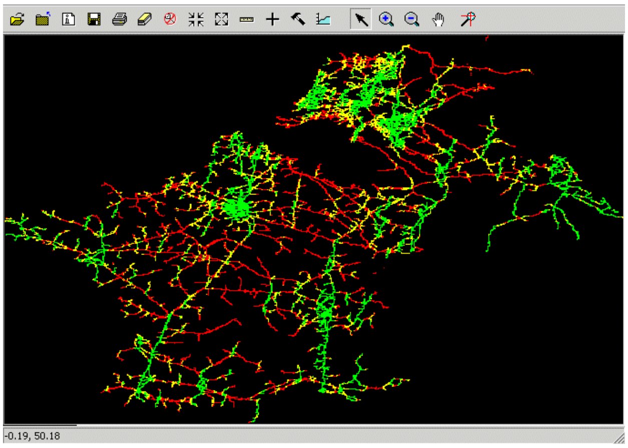


Figure-5: Number of days a network element is not monitored, green ≤2 days, yellow ≤21 days, red > 21 days.

In a next step several system parameters have been varied in order to get a feeling of the influence of the sensitiveness of the system to these parameters. Here attention will be paid to the availability of cloud information for the scheduling, the number of satellites, the swath width and the pointing range.

Use of cloud information

The simulation results of the situation with clouds as shown in table-2 and figure-4 have been generated for the case that ideal information on the cloud situation is available for the satellite scheduling. In case no information on the cloud situation at time of observation is available for satellite scheduling, the results are much weaker, as can be seen in table-3.

Table-3: Simulation results related to use of cloud information

case	observations total		observ. 7-14 days		monitoring days	
	number elements	times network	number elements	times network	number	% full monit.
Full cloud info	582.860	22,7	274.909	10,7	2.717.495	29,0%
1 hour old cloud info	492.099	19,1	208.716	8,1	2.088.109	22,3%
No cloud info	344.288	13,4	133.981	5,2	1.334.648	14,2%

The effectiveness of the system drops from 29% to 14.2%. In case cloud information of 1 hour old can be used the effect of this information still is significant: 22.3%. The effect of the use of cloud information also is shown in figure-6, where the distribution of the number of yearly cloud free observations is shown.

Different options and strategies for the use of cloud information are thinkable. They are dealt with in more detail by (Algra, 2003).

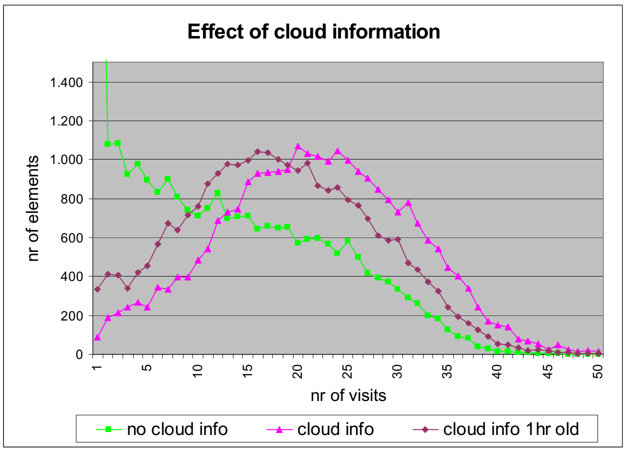


Figure-6: Distribution of the number of cloud free observations for different situations of cloud information.

Number of satellites

As described, with a number of 4 satellites only 29% of the fully required monitoring capacity are obtained. Additional simulations with constellations of 1, 2, 6 and 8 satellites have been made. The result is shown in figure-7. With 8 satellites the capacity increases to 49%. When also observations after 15 to 21 days are accepted the capacity would reach to 68%.

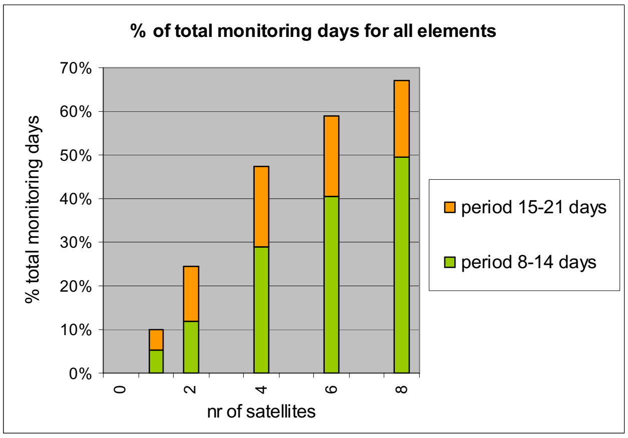


Figure-7: Monitoring capacity in % of required monitoring days for different number of satellites

Swath width

With a broader swath width the capacity of the satellites is also increased. In fact a 4 satellites with a swath of 20km can cover the same area as 8 satellites with 10km swath. The effect of the swath is shown in figure-8. It can be seen that the effectiveness of a wide swath drops after a swath width wider than 15km. When the situation of 8 satellites with a 10km swath is compared to

A constellation of 4 satellites with 20km swath results in 43% of monitoring capacity, while a constellation of 8 satellites with 10km swath has a capacity of 49%. The higher value probably is an effect of the more detailed following of the pipeline trajectory and the more frequent observation opportunities.

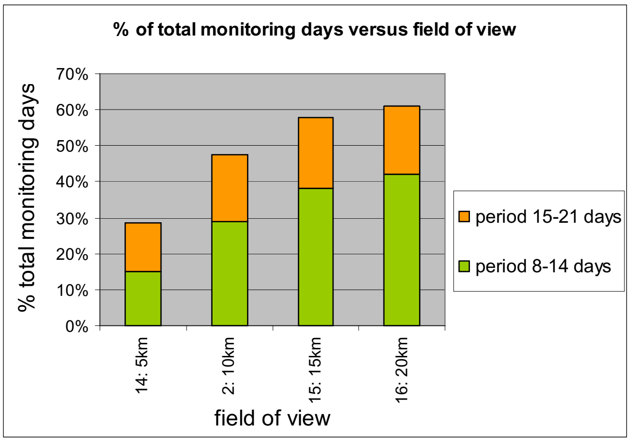


Figure-8: The effect of different swath widths in % of total required monitoring capacity.

Pointing range

Finally different ranges for the pointing in along and across track direction are simulated. See figure-9. As expected the effectiveness of the system increases with larger pointing ranges. This as a consequence of the wider area in which pipeline trajectories can be selected and clouded regions avoided, and as a consequence of the longer observation time as a consequence of the larger forward/afterward pointing range. From an interpretation point of view a pointing range wider than 33 degrees is not realistic however.

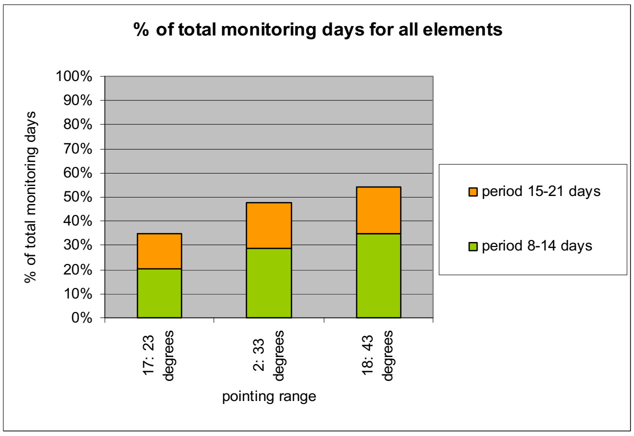


Figure-9: The effect of the pointing range in % of total required monitoring capacity.

6. OUTLOOK

The simulation results provide good insight in the use of high resolution optical satellites for monitoring of the European gas pipeline network. Additional simulations will be carried out in order to obtain answers to several questions. In the first place simulations with constellations of larger number of satellites and some wider swathes. Theoretically in a non clouded situation the network should can be covered with 8 satellites. As the found effect of cloud cover is about 50% this means that simulations with constellations up to 15 satellites are required.

Secondly attention will be paid to the combination of high resolution optical satellites with other collection assets like SAR satellites and airborne platforms with optical or SAR sensors, either manned 'platforms or UAV's (Hausemann, 2003). For this the less suited pipeline trajectories (non dense areas and east-west directed lines) can be filled in by this other platforms and left out of the scheduling. As a consequence the high resolution optical satellite effectiveness may increase.

A third point of interest is to simulate situations for higher monitoring frequencies of 10 or 7 days.

Finally attention will be paid to the satellite scheduling strategy. It is expected that by optimising the scheduling algorithms the results can be improved.

7. CONCLUSIONS

It can be concluded that for the two weekly monitoring of the extended European pipeline network with high resolution optical satellites a large constellation is required. The simulations learn that in case of optimal use of cloud information 29% of the monitoring work can be obtained with 4 satellites and 49% with 8 satellites.

A wider swath, better scheduling algorithms and proper co-ordination with other SAR and airborne collection assets can obtain further optimisation of the constellation.

The use of proper cloud information is essential for the effectiveness of the optical satellite constellation. The simulations shows an increase of 104%

The CLIMAS simulation tool is a powerful tool for simulation of the capabilities of an optical satellite constellation related to a specific application and with realistic cloud coverage conditions.

8. REFERENCES AND AKNOWLEDGEMENTS

8.1 References

Algra, T.; Kamp, A van der; Persie, M. van. Results with CLIMAS, a simulation tool for cloud avoidance scheduling in optical remote sensing missions. SpaceOPS Conference 2004, Montreal, Canada, May 17-21, 2004

Algra, T. Real-time cloud sensing for efficiency improvement of optical high-resolution satellite remote sensing. Proc. IGARSS'03, Toulouse, 2003

Dekker, R.J.; Lingenfelder, I; Brozek, B.; Benz, U; Broek, A.C. van den. Object-based detection of hazards to the European gas pipeline network using SAR images. 2004

Haar, T.H. von der; et al. Climatological and Historical Analysis of Clouds of Environmental Simulations (CHANCES) Database – Final report. PL-TR-95-2101, Philips Laboratory, Hanscom Air Force Base, Mass., (1995) Hausamann, D; Zirnig, W.; Schreier G. Monitoring of gas transmission pipelines – a customer driven civil UAV application. ODAS Conference, 2003

Persie. M. van; et.al. PRESENSE Report D3.1 Part-I System Concept, NLR-CR-2003-374-PT-1. Marknesse, 2003 (Confidential)

Pride, R., 2004. PRESENSE Pipeline Remote Sensing for Safety and the Environment website, http://www.presense.net

8.2 Acknowledgements

This work has partly been accomplished in the frame of the EU projects PRESENSE (http://www.presense.net/), Contract No. ENK6-CT2001-00553.